THE ENVIRONMENTAL IMPACT EVALUATION OF A WIND FARM IN VIETNAM

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Certificate of Authorship/Originality

I certify that the work in this thesis has not been previously been submitted for a degree, nor has it been submitted as part of the requirements for a degree, except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and preparation of the thesis itself has been acknowledged. In addition, I certify that any information sources and literature used indicated in the thesis.

Signature of Candidate

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Abbreviations

LCA	Life Cycle Assessment
RECTERE	The Research Centre for Thermal Equipment and Renewable Energy
US EPA	United States Environmental Protection Agency
$	United States dollars
AC	Alternating Current
AP	Acidification potential
CF	Capacity factor of wind farm
CH_4	Methane
CO	Carbon oxide
CO_2	Carbon dioxides
DFAG	Doubly Fed Asynchronous Generator
DFIG	Doubly Fed Induction Generator
EIO-LCA	An economic input-output analysis based LCA
EIO-LCA	An economic input-output analysis based Life Cycle Analysis
EU	European Union
EVN	Electricity Group of Vietnam
FL MD – 77	Fuhrlander 1.5 MW wind turbine, rotor diameter 77m
fU	Functional Unit
GHGs	Greenhouse gases
GWP	Global warming potential
GWP_{100a}	Global Warming Potential 100 years applied in this thesis
HVAC	High Voltage Alternating Current
IE	Institute of Energy, Vietnam
IEA	International Energy Agency
IEC -IIA	International Electro-technical Commission of wind Turbine under turbulence intensity distribution class IIA
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organization
Kg C_2H_4-eq	Kg of ethane equivalent
Kg CO_2-eq	Kg of carbon dioxides equivalent
Kg SO_2-eq	Kg of sulphur dioxides equivalent
kV	Kilo voltage
kW	Kilowatt
kWh	Kilowatt-hour
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Category
m	Meter
m/s	Meter per second

MGh	Megawatt-hour
MJ	Mega-Joules
MoIT	Ministry of industry and Trade
MVA	Megavoltage – Ampere
MW	Mega Watt
N_2O	Nitrous oxide
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
NP	Eutrophication potential
OECD	Organization for Economic Co-operation and Development
PLCA	Process analysis based Life Cycle Assessment
POCP	Photon Oxidant Chemical Potential
Project site	Binh Thuan Vietnam
REVN	Renewable Energy company in Vietnam
SO_2	Sulphur dioxides
t.km	Ton × kilometre
TCVN 5844:1994	Vietnamese Standard No 5844, year 1994
TR-XLPE	Tree-retardant cross-linked Polyethylene
USA	United States of America
VNRE	Vietnam Renewable Energy Joint Stock company
WB	The World Bank
XLPE	Cross linked Polyethylene, insulation polyethylene

Abstract

This research conducts an in-depth analysis of the environmental impact assessment of a wind farm in Vietnam, with a view to identifying the various environmental stressors and then assess them under suitable impact categories. Although wind power releases no emissions during operation, there is an environmental impact related to the wind turbine during the entire life cycle from manufacturing to dismantling. In this study, a Life Cycle Assessment is carried out to quantify the environmental impact of twenty existing 1.5 MW wind turbines. The assessment analyses emissions in different unit processes and compares the means of different emissions during the lifetime of a wind farm. Furthermore, at the end of the thesis, the energy payback time is determined based on the cumulative energy requirements for a 20-year life period.

For the quantitative analysis of the material and energy balances over the life cycle, all unit processes based on life cycle assessment are determined, and many matrix series are designed and calculated. Moreover, the environmental impact categories are set to match the conditions in Vietnam and the aims of the research.

This study also shows that while the comprehensive life cycle inventory of a wind farm is heavily dependent on the unit processes, the impact can be divided into three categories: raw material data input, energy consumed in each unit process, and the emission outputs such as CO2, SO2, CH4, etc.. The three impact categories allow the classification of the emissions and give results for all life cycle assessment.

Finally the findings shows that the largest emission contribution is mainly derived from the manufacturing phase, which varies from 60 % to 80 % of the total life cycle stages. The totalCO2 equivalent emissions in the climate change category is around 14 g for every kWh of electricity generated from the wind plant and the primary energy return is 5 months.

This research is a good example that proves that a wind plant is one of the best options for mitigating climate change and for providing electricity in rural areas that are not connected to the grid. It can be stated that wind energy is among one of the cleanest sources of energy available today.

Chapter 1

Introduction

1.1 Introduction

1.1.1 *The current global wind energy situation*

It is predicted in a report from the World Energy Council (World Energy Resources: 2013 Survey) that in the near future the Global Economy will slowly become more dependent upon alternative energy sources as the supply of oil and coal becomes more limited (Gadonneix et al. 2014). At the same time, there is also public concern about the environmental impacts associated with increasing energy use, e.g., burning coal causes CO_2 emissions, which is the primary Greenhouse Gas that is causing climate change and global warming. Furthermore, this concern and the growing wish for people to live in an environmentally friendly manner has gained global appeal so that many governments are addressing these issues. Researchers and policy makers are investigating ways to apply clean technology in order to protect the environment. However, it is difficult for alternative energy sources to meet all energy demands. These alternative energy sources most comprise of solar energy, wind energy, and bioenergy. There is also hydro energy which is more traditional. Wind energy harnessing technology, i.e., wind turbines, has matured in the last two decades, and wind energy has emerged as a primary energy source. Wind energy can make a substantial contribution to the total global energy, but it does face challenges in terms of meeting strict environmental protection conditions.

Figure 1.1 is taken from the Global Annual Wind Energy Report 2013 (GWEC 2014). It shows that the increase in total installed capacity of wind energy worldwide is significant, from around 6,100 MW in 1996 to approximately 320,000 MW in 2013. There is a fivefold increase in the total of installed capacity in 2013 compared to 2005. Although there is only a total of 35 GW of new wind power installation in 2013, this can be compared to less than 10 GW in 2012 (Figure 1.2). The sharp decline in 2013 is due to several factors, but it is mainly due to a decrease in the investment in wind farm projects, i.e., the total budgets dropped from US$ 80.9 billion in 2012 to US$ 80.3 billion in 2013. However, this is against a year-on-year increase over several years up to this point.

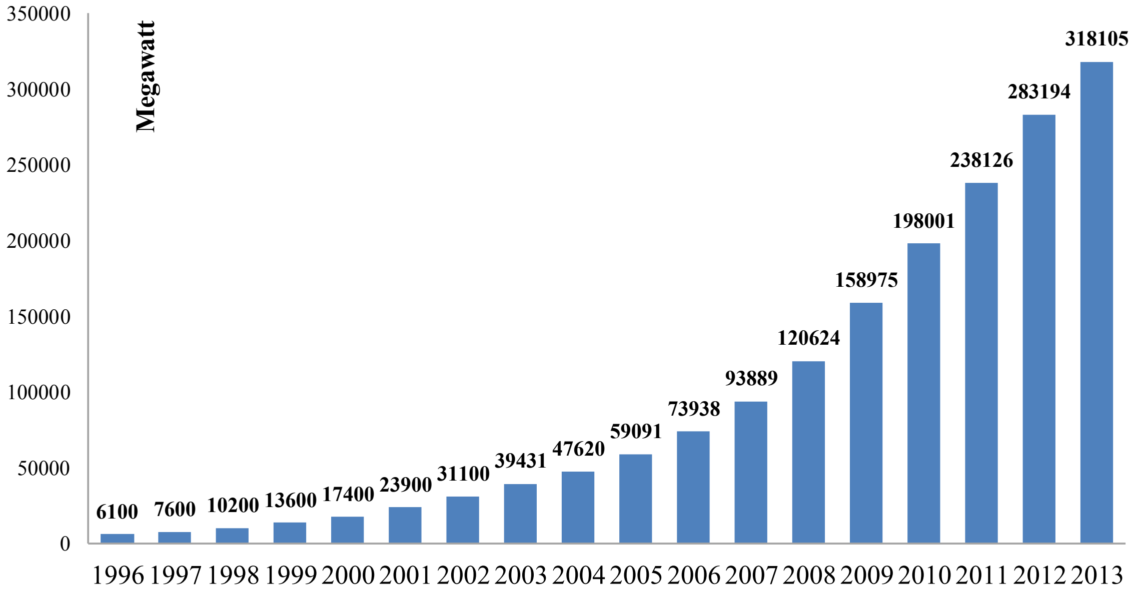


Figure 1.1: Global cumulative installed wind capacity in Megawatt from 1996-2013.

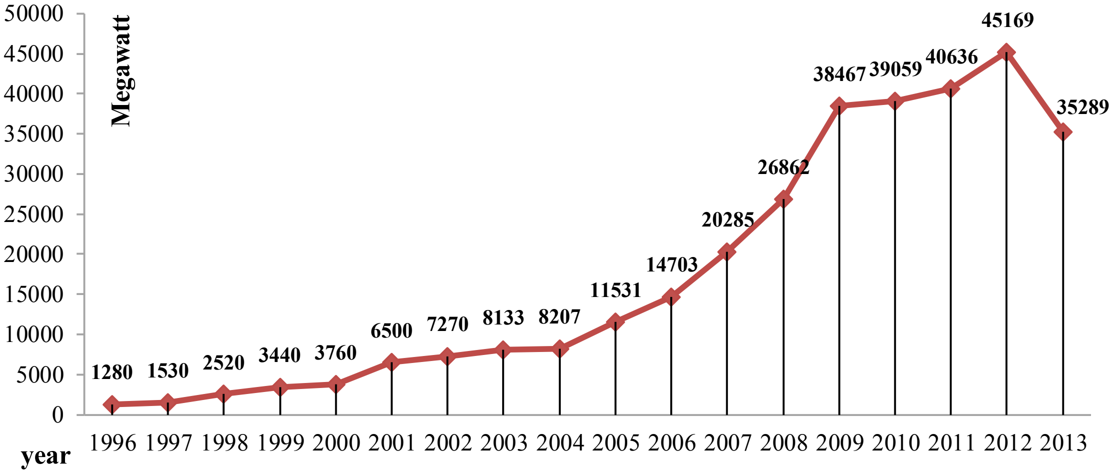
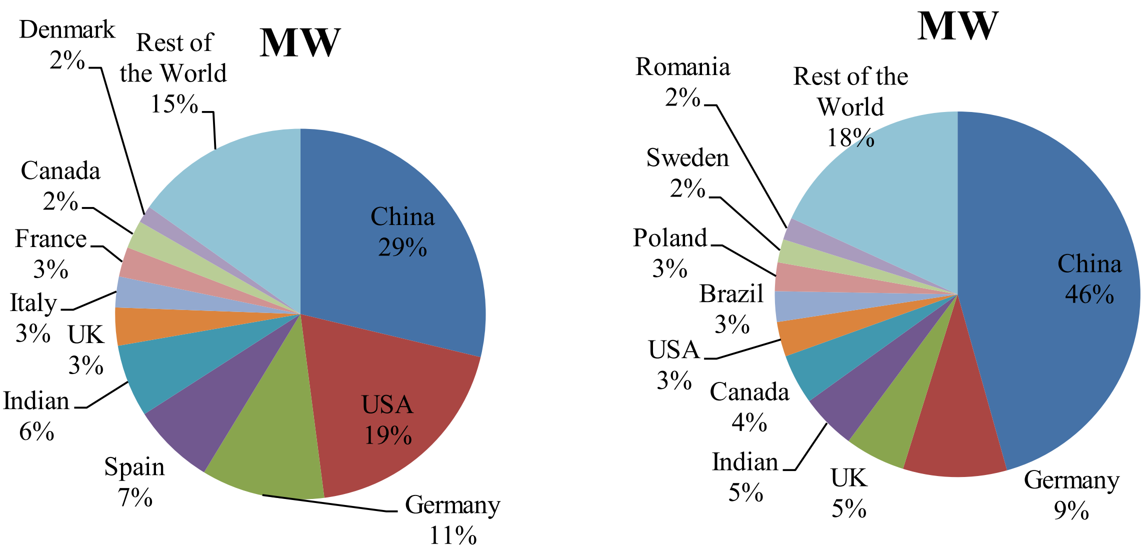


Figure 1.2: Global annual installed wind capacity 1996 -2013.

Asia has become the largest regional wind market, in which China has grown its wind energy industry and turned itself into the market leader with 16 GW of wind power capacity added in 2013. In the same year, India held the second position among Asian countries, with approximately 1.7 GW added to its wind power capacity. In South East Asia, there was 111 MW of wind power generation installed by Thailand, in 2013, bringing its total installed capacity of wind energy up to 223 MW.



Top 10 cumulative capacities 1996 - 2013

Country	Megawatt
China	91,412
USA	61,091
Germany	34,250
Spain	22,959
Indian	20,150
UK	10,531
Italy	8,552
France	8,254
Canada	7,803
Denmark	4,772
The rest of the World	48,332

Top 10 cumulative capacities 1996 - 2013

Country	Megawatt
China	16,088
Germany	3,238
UK	1,883
Indian	1,729
Canada	1,559
USA	1,084
Brazil	953
Poland	894
Sweden	724
Romania	695
The rest of the World	6,402

Figure 1.3: Top 10 cumulative and new installed capacities 1996 -2013.

To sum up, the overview of wind power development shows that wind resource is still a potential alternative which needs to be exploited around the world, and the investment for research and development of wind technology will continue to be increased to improve the energy efficiency of generator, aerodynamic of blades, and wind component materials.

1.1.2 *Wind energy scenario in Vietnam*

Vietnam is still a developing country in which the poor technology has been applied with high frequency on electricity. Moreover, although Vietnam possesses vast potential alternative energy resources which are spread over a wide area (i.e., alternative power generation will be distributed across the power system infrastructure), the utilization of these energy recourses is still limited. In the following decades, the renewable energy is decided to be necessary to allow the country to develop a sustainable energy programme in Vietnam. For that reason, since 2005 Vietnamese government has taken the form of both wind and solar energy sources (IE 2008).

Table 1.1: Wind energy potential of Southeast Asia.

Countries	Characteristic	Poor < 6 m/s	Fair (6 - 7 m/s)	Good (7 - 8 m/s)	Very good (8 - 9 m/s)	Excellent < 9 m/s
Vietnam	Land area (km^2)	197342	100361	25679	2187	113
	% of total area	60.6%	30.8%	7.9%	0.7%	0.0%
	MW potential	NA	401444	102716	8748	452
Cambodia	Land area (km^2)	175468	6155	315	30	0
	% of total area	96.4%	3.4%	0.2%	0.0%	0.0%
	MW potential	NA	24620	1260	120	0
Laos	Land area (km^2)	184511	38787	6070	671	35
	% of total area	80.2%	16.9%	2.6%	0.3%	0.0%
	MW potential	NA	155148	24280	2684	140
Thailand	Land area (km^2)	477157	37337	748	13	0
	% of total area	92.6%	7.2%	0.2%	0.0%	0.0%
	MW potential	NA	149348	2992	52	0

(*wind energy resource atlas of Southeast Asia* 2001)

The development of renewable energy in general and a focus on wind energy in particular are currently a priority of Vietnam in order to meet future energy demand given the depletion of traditional energy resources in the following years (MOIT 2005a). In early 2001, with the sponsor from World Bank, the wind atlas of Southeast Asia countries (Vietnam, Thailand, Cambodia, and Laos) has been prepared the first time for the wind power usage in the near future (*wind energy resource atlas of Southeast Asia* 2001). Based on the available input data gathered from different sources such as the Vietnam National Institute of Hydro and Meteorology (VNIHM) and the US National Oceanic and atmospheric Administration (NOAA), and the advanced wind mapping method - Messo Map simulation - Vietnam has assessed a good wind energy for the development (Table 1.1). In 2007, one important study on the average wind speed measured at many particular points in Vietnam was published by the Electricity of Vietnam (EVN). Although the data collected from EVN and WB shows minor differences (Table 1.2), the wind development in Vietnam is expected to further investment in order to replace the indigenous energy sources depleting (EVN 2007).

Table 1.2: Comparison of average wind speed estimated by EVN and the Wind atlas from WB.

No.	**Region**	**Site selection**	**Annual average win speed at 65 m above ground (m/s)**	
			EVN	WB
1	**North**	Mong Cai, Quang ninh	5.80	7.35
2		Van Ly, Nam Dinh	6.88	6.39
3		Sam Son, Thanh Hoa	5.82	6.61
4		Ky Anh, Ha Tinh	6.48	7.02
5	**Central**	Quang Ninh, Quang Binh	6.73	7.03
6		Gio Linh Quang Tri	6.53	6.52
7		Phuong Mai, Binh Dinh	7.30	6.56
8		Tu Bong, Khanh Hoa	5.14	6.81
9	**South**	Phuoc Minh, Ninh Thuan	7.22	8.03
10		Da Lat, Lam Dong	6.88	7.57
11		Tuy Phong, Binh Thuan	6.89	7.79
12		Duyen Hai, Tra Vinh	6.47	7.24

Researchers from the Vietnam Academy of Science and Technology (VNAST 2007), simultaneously published the results of multiple-year statistical collection and analysis of the wind resource. This aimed to evaluate wind mechanisms so that the development of this energy source can be carried out more effectively in Vietnam. The data shows that the strongest wind blows are found in the Eastern islands with the average speeds of 7.6 m/s in Bach Long Vi, 6.8 m/s in Phu Quy Island, Binh Thuan province, 4.9 m/s in Hon Dau- Hai Phong city and 4.4 m/s in Co To, Quang Ninh province. In some mountainous areas, the annual average wind speed is measured at 4 m/s. However, according to The Master Plan IV, published by The Institute of Energy (IE) (IE 2006), there is no detailed evidence of the wind energy collection methods or any specification of the databases used for the calculation in capacity and power of this source. Although the data outputs do not reflect accurately the potential of wind energy in Vietnam, they provide an overview of the wind energy potential in many specific sites in Vietnam.

Based on the information above, the Vietnamese government has set targets to increase the contribution of wind power from 3.5 % of the total of electricity consumption in 2010 to approximately 5 % in 2020 and to 6 % in 2030 (MOIT 2004). Recently, in March 2011, the total of installed capacity of wind farms in Vietnam accounted for approximately 19 MW connecting to national grid (Khanh 2011). Furthermore, among these wind plant projects, the Vietnam Renewable Energy Joint Stock company (VNRE), which is known to run the largest wind projects in Vietnam, has made massive investment in wind power in Tuy Phong District, Binh Thuan province after Government legislation aimed at supporting and developing wind power sectors. The government has imposed requirements on studying new technologies and developing expertise in terms of training academic advisors, essential experts and workers. Also, the investments in manufacturing related to wind energy is needed to create many sub and supporting industries in Vietnam. This will allow for a gradual and organized increase in wind turbine deployment.

All of these essential wind conditions have been boosting wind farm prospects ahead to provide the green power to meet electricity demands in Vietnam. However, to achieve this growth, there have been a number of challenges needed to be addressed. Although the evaluation of wind potential in many general areas around the world and particularly Vietnam has been completed recently, the effects and challenges of wind farms and turbines on technological performance, the shortage of skilled workers and maintenance services, the fluctuation of a wind power output, and the conflict between the wind farm areas and the environment and local population were almost totally neglected. Renewable energy policy for wind energy development is unclear in this respect. Together with the development of wind farm, these environmental issues will be challenged as key issues including: (a) the natural environmental influences such as soil erosion, weather change, depletion of wildlife habitat, plants, and (b) social-economic effects in the particular areas which instructed the wind farms. In order to deal with these challenges, it is vital to have an analytical framework for assessing the environmental impacts in different stages of wind projects' operation.

1.2 Research objectives

The aim of this study is to assess the influences of the recently completed large wind energy plants in Vietnam on the environment indexes on a national scale from 2009 up to the present and the primary objective of the study is to evaluate the life cycle environmental impacts of a current wind power industry in Vietnam? The study will employ a mathematic method, Life Cycle Assessment (LCA) which is a comprehensive mathematical methodology used for quantifying the environmental impacts throughout the lifetime of wind farm.

The objectives of this study are to address two questions as discussed below. These have yet to be addressed coherently in Vietnam.

First, what and how are the primary effects on the environment of the wind turbines that have been from manufacturing the wind turbine components to operating since 2009?

- Vietnam has built its first wind power plants in some places such as Binh Thuan province. Earlier, environmental research and the associated relevant data gathered were based on work conducted in foreign countries such as USA, Germany and China. The data for assessment of wind energy is inaccurate and insufficient in Vietnam.

Second, how can we interpret and compare the different parameters of wind turbine?

- Current legislation for renewable energy is based on legislation that is currently enacted in developed countries. However, legislators sometimes do not account for the fact that populations do vary in terms of their traditional employment and lifestyle; this is especially true for farming and livestock, habitat interaction and the local geographic information systems. Weather conditions between Vietnam and industrialized countries will also be very different. This means that Vietnam does require further research which includes an in-depth analysis addressing these two questions and considers the associated problems so that future renewable energy policy can be developed and refined.

To be more specific for doing research:

- To review the current large wind farm projects conducted in Vietnam to identify existing environmental and social-economic affects both their strength and weakness to propose an appropriate framework for this study.
- To develop an analytical framework for wind plant assessment in Vietnam, taking into account important factors that have potential to influence local environment.
- To develop a Life Cycle Assessment (LCA) framework, such as the input of material required, energy input to wind system during the length of wind farm life and use of this framework, to investigate the long-term potential impacts of wind power in terms of the total output from life cycle stages and a variety of potential environmental impacts, such as habitat erosion, noise, CO_2 emission when delivering 1 kWh of electricity to the national electrical grid.
- To assess the policy significance of the impacts quantified above in terms of discussion on environment cost and benefits for improving system design and strategies for better environment.

1.2.1 *Scope of research*

This research is to investigate the particular environmental issues and to assess the wind farms related to sustainable development in Vietnam. The data collection is analysed in terms of its **environmental assessments (EA)** and wind project analysis. The environmental impacts will be evaluated in different stages of planning, site selection, construction, and operation (decommissioning if possible). These effects of wind power are evaluated in terms of energy efficiency, and emission of CO_2 reduction. Furthermore, the following framework for discussion by policy makers will be built based on beneficial environmental conservation.

1.2.2 *Research framework*

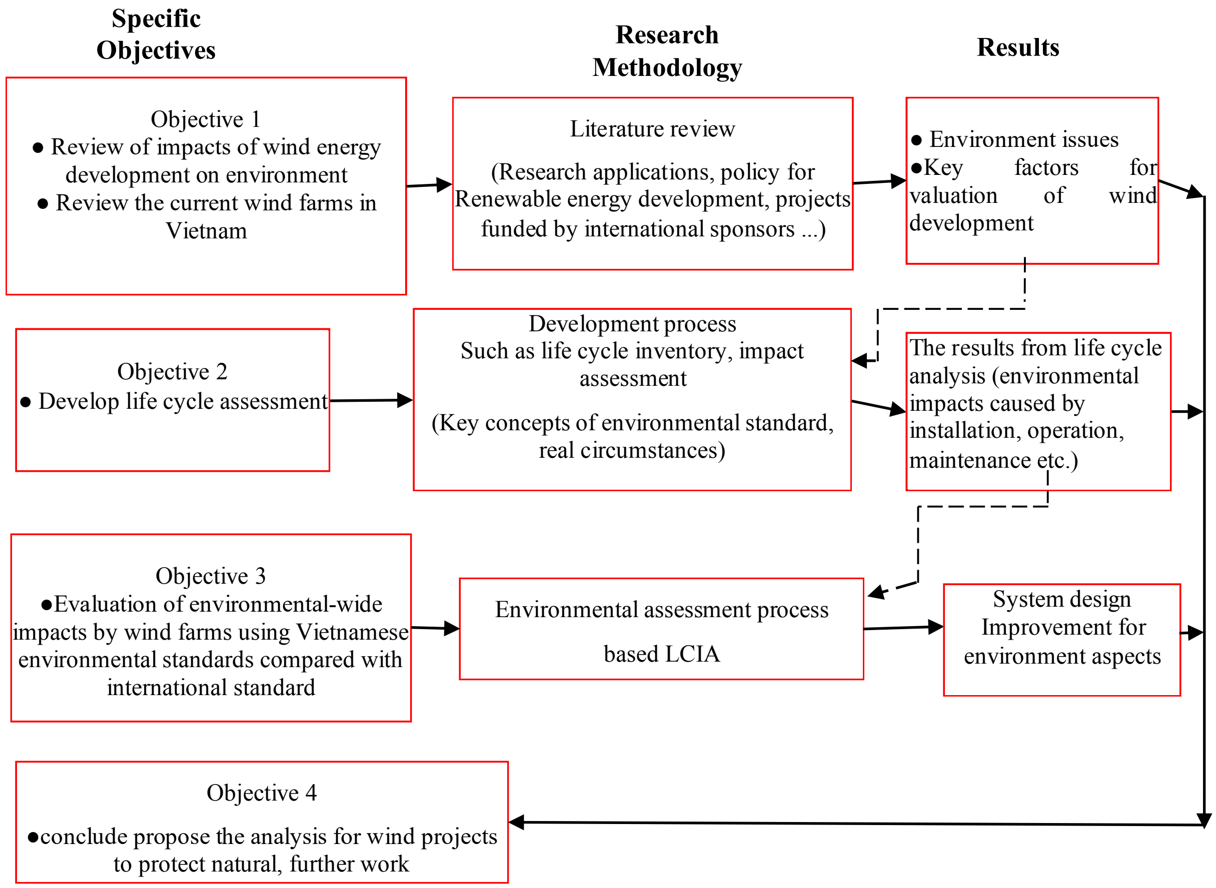


Figure 1.4: Research framework.

Chapter 2

Literature Review

2.1 Review of existing wind farm projects in Vietnam

Vietnam has the best wind resource out of the three Southeast Asia countries which includes Lao and Cambodia (TrueWind Solutions LLC 2001). The areas that are suitable for wind energy development, which have average wind speeds between 8 m/s and 9 m/s, is about 2187 km^2 giving an estimated capacity of 8748 MW.

Khanh Nguyen (Khanh 2007) reported on the evolution of Vietnamese wind energy technology. The first wind applications were quite simple, with turbines used to pump water for farming irrigation. There were low efficiency systems of a rudimentary mechanical design. The next generation of water pumping systems had improved efficiency and more technical sophistication and these were developed in the 1980s. In addition, from the late 1980s, about 900 small wind turbines with capacity ranging from 150 to 200 W peak (Wp) were installed by the Research Centre for Thermal Equipment and Renewable Energy (RECTERE) of Ho Chi Minh City University of Technology (HCMUT). These were installed in remote areas, especially in rural locations which were difficult to connect the national grid. These programs were funded by the Vietnamese government, who funded 90 % of the cost whilst the remaining 10 % was purchased by end user. The price of a wind turbine with 150 Wp was about US$ 270, which was quite reasonable for a remote family. The turbine was able to supply electricity to run basic electrical appliances such as a television and a radio, and was able to supply lighting (EVN 1999).

Other research and development programs were run by the Institute of Energy (IE) in Vietnam under supervision of Ministry of Industry and Trade (MoIT). Their mission was to review wind turbine electrical generation in order to install wind farms on islands and in rural areas. With the sponsorship from Electricity of Vietnam (EVN), small wind turbines with a capacity of 150 Wp have been manufactured and installed in more than thirty-five locations. Simultaneously, the Hanoi University of Technology (HUT), known as being the leading renewable technological innovation centre in Vietnam, has installed twenty 150 Wp wind turbines. Table 2.1 gives an overview of the wind power situation in Vietnam from 1999 up to the current time.

Table 2.1: Wind farm development in Vietnam.

Application	Capacity	Quantity of wind turbine	Operation start	Area of installation
Household wind turbine	100-200 W	About 1000	Counted from 1999	Central coastal area
Grid-connected REVN wind farm	30 MW (1st)	20 (Furhländer 1.5 MW)	Operational from 2012	Tuy Phong Dist, Binh Thuan Province
Gird- connected Congly wind farm	16 MW (1st phase)	10 (GE 1.6 MW)	Under construction	Vinh Thanh Dist, Bac Lieu province
Hybrid wind-diesel PV Power corporation (Petro VN)	9 MW (6 MW wind +3 MW diesel)	3 (Vestas 2 MW)	Soon to connect into the Grid	Phu Quy Island, Binh Thuan province

Source: updated from (Khanh 2007)

Wind energy in Vietnam has received support in terms of industrial manufacturing. GE was the first American company set up a representative office in Vietnam and this was 1993 even before the US Embargo was lifted. In 2009, GE made a decision to invest in a wind generator manufacturing plant that is located in Hai Phong city in the north of Vietnam. The products manufactured are then exported to other GE manufacturing and service centers around the world (GE 2014). Currently, the generator manufacturing capacity is up to approximately fifteen hundred generators annually.

There are another three heavy industrial manufacturing plants. The largest has 100 % capital investment from the South of Korea. They manufacture wind towers in Vina Halla with a capacity of four hundred units per year. The second largest is the UBI Tower Co Ltd located in Hai Duong province, North Vietnam, which produces three hundred towers per year. The third plant is the CS Wind Tower plant which exports about one hundred and fifty units per year (Tuan 2012b).

Some observations

Vietnam is still a developing country with a low level of technology compared to a developed country. It has been faced with many challenges relating to the development of green energy, and in particular wind energy technology. The difficulties can be listed as:

- Large wind farms mostly depend on the foreign technology and maintenance.
- Wind turbine operation is affected by the instability of the wind velocity, which can be a problem in Vietnam.
- The electric infrastructure such as the power transmission lines and voltage control of the national grid in the project areas are of low quality.
- Transportation of heavy plant in remote locations can be difficult.

All of the above points mean that it takes more time to respond to the operational needs, or to stop and replace the parts of a wind turbine. This additional time leads to additional costs in running a wind farm.

Wind farms require large areas and substantial amounts of raw material from manufacturing to end-of-life. For this reason, they may have a wide environmental impact on the local population during the twenty-year life span of the farm. For example, at the construction site of the first phase of the REVN scheme, the area that needed to be cleared for construction was 350 hectares, which is approximately 3.5 km^2 (Khanh 2012a). At present, there is no standard for carrying out a wind energy Environmental Assessment in Vietnam (Tuan 2012a), leading to difficulty in assessing, reviewing and predicting environmental issues for wind farm projects. In the social context, nearly 70 % of the population in Vietnam (FAO 2014) lives in remote and rural areas, a large proportion is poor and have insufficient awareness of complex environmental problems. Hence, the population living near a wind plant are often easily convinced that wind farm projects will bring the electricity into their home and create more jobs whilst not realising the importance of environmental preservation. Although this study is focused on the environmental interaction of a wind farm over its life cycle via gas emissions, and the environmental impacts on the land and water are not addressed (due to time limitations), land and water usage still raise issues that must be discussed by policy makers before forming wind farm regulations in Vietnam.

Other potential barriers which wind energy projects have encountered include:

- The absence of appropriate regulatory framework and no specific incentives;
- Insufficient technology (manufacture, conversion energy, etc.);
- Shortage of reliable data on wind energy sources;
- High importation cost and lack of factory to produce the equipment such as blade, controller, generator, services; and
- Limited access to capital for consumers, entrepreneur and project developers.

2.2 Review of the major impacts on wind farm analysis

To date there is no information related to the environmental impact assessment of a wind farm in Vietnam that has been published, including international and academic publications. Furthermore, in 2012, circulars on “Wind development plans”, “Wind power investment”, and “power purchased agreement for Wind power” are still at the drafting stage (Tuan 2012a). Due to this reason, there is only academic literature sources outside Vietnam employed to serve the review purposes.

In 2000, Schleisner (Schleisner 2000) presented an interesting study on the Danish wind farm Tunø Knob using a life cycle assessment model developed by the Danish Risø National Laboratory. This study concluded an emission of 16.5 kg CO_2-equivalent per GWh electricity generated. In addition, this study provided many primary data related to the production and disposal processes that are used for many life cycle inventory assessments such as the study by Yun-Minh Lee in Development and Life Cycle Inventory Analysis of Wind Energy in Taiwan (Lee & Tzeng 2008b), and the study by Rooke concerning a 5 kW turbine (Rooke 2012). Some of the data is also used in this study when data for materials and processes are not available.

Data from seventy wind farms that were constructed from 1981 to 2000 around the world was published in 2002 (Lenzena & Munksgaard 2002). The aims of that study was to analyse the energy and CO_2 intensity, and to investigate the interaction between the wind farm parameters in terms of the wind farm energy and CO_2 values. The parameters included a life cycle up to 30 years, a load factor that varied from 7.6 % to 45.9 %, and different rated powers from 0.3 kW up to 3000 kW. Different particular methodological approaches and boundaries were identified. After examination, Lenzena concluded that although most modern wind turbines only have small technology differences through the different power ratings, the life cycle assessment results conducted have significant differences in their CO_2 emissions and energy intensities. For example, the energy intensity varies in the range of 0.014 to 1 $kWh_{used}/kWh_{electricity}$ and the CO_2 intensity ranges from 7.9 to 123.7 g CO_2-equivalent per kWh generated. Based on the scatter plots, the finding is that while the differences of energy intensities were derived from the assumptions of the Goal and Scope definition, the recycling stages and overhaul maintenance time periods, the CO_2 intensity values differ and are strongly dependent upon national fuel mix.

An important technical report on the life cycle assessment of a V90 3 MW turbine was undertaken by Vestas in 2006 (Vetas July, 2006). It found a contribution to climate change of 5.3 g CO_2-equivalent per kWh of electricity from an offshore wind farm with the mono-pile type of foundation. According to this study, the environmental performance of onshore and offshore wind turbines are equal within expected uncertainties. The higher material consumption for an offshore wind turbine is offset by improved energy performance. Another report also from Vestas (Vetas 2011) with a different type of wind turbine (V80 2 MW) shows that the manufacturing stage prevails in this impact category; the production of the tower, site cables, nacelle and blades take 38 %, 20 %, 16 %, and 5 % respectively. The emissions of SO_2 (sulphur dioxide) and NO_x (nitrogen oxides) are mainly related to the production of steel and iron and these contribute 64 % and 32 %, respectively. The recycling phase contributes significantly to the environmental credit with a value of -30 % for metals such as copper and steel. It helps to minimize these materials.

In 2008, many studies associated with wind farm life cycle assessment were published. Research on the life cycle assessment for large wind turbines installed in Spain and France were published. The Spanish study presents the results in units of eco-points taken directly from the commercial software SimaPro (Martınez et al. 2008). The highest scoring impact is from the turbine foundations and this impact is termed “inorganic respiration" (IR), presumably, referring to breathing and inhalation of pollutants such as particular matter and substances from manufacturing. As the source of the high score is not disclosed, it can only be surmised what the impact details are. The inventory data applied from the Ecoivent 2.2 database shows the fact that cement manufacturing process generates a large amount of emission. However, if correct precautions are taken both in manufacture and manpower during the construction phase, a substantial decrease in emission can be achieved. To conclude, Martinéz stated that a contribution of 6.6 g CO_2-equivalent per kWh of electricity from offshore wind power (Martınez et al. 2008) was calculated using computational software, while a life cycle report in 2004 by Elsam found a contribution of 7.6 g CO_2 per $kWh_{electricity}$ (only contribution of CO_2) from the Horns Reef wind farm in Denmark (Elsam Engineering A/S 2004). There is a certain amount of correlation here.

Also in 2008, a life cycle assessment of a large-scale floating offshore wind farm was performed. Parameters important to this wind farm design, such as capacity factor, life cycle time, transmission distance and maintenance demand, were analysed (Tveten 2008). The study also stated an emission of 9g CO_2-equivalent per kWh of wind power generated. The sub-processes that were found to contribute most to the overall impact were mainly the production of the wind power plant, which was responsible for almost 50 % of the total costs. This was dominated by steel production for the wind turbine tower. The production of the cable system was responsible for almost 20 % of the total emissions, which is dominated by the large amount of copper. The emissions from operation and maintenance had a considerable contribution corresponding to more than 10 % of the total emissions; this was dominated by fuel consumption and production of material for replacing broken parts.

Ardente (Fulvio Ardente 2008) used a traditional life cycle method for assessing an Italian offshore wind farm. This study concluded a more uncertain result for emissions between 8.8 and 18.5 g CO_2-equivalent per kWh-electricity and the measurement of the actual power factor in one year was 0.19 which is quite small compared to the typical design capacity factor of 30 %, for example, in the Guezuraga study (Davidsson, Höök & Wall 2012).

In 2009, a life cycle study for offshore wind power was published and this addressed the environmental impacts of a floating offshore wind farm located off the Norwegian coast. This used a process-based life cycle. In this study, Weintzettela found a contribution to climate change of 11.5 g CO_2-equivalent per kWh generated for a floating wind turbine, and concluded that the largest contribution to climate change came from the low-alloyed steel in production of the tower, followed by the cable production and chromium steel in production of the wind turbine (Weinzettela et al. 2009). It can be noted that the study conducted by Weinzettela is of a floating offshore wind farm, and hence, there will not be any emission impacts linked with the foundation. Instead, much more steel will be used in the tower, thus the large contribution from steel (Sørensen 2011).

Some observations

- Since the life cycle assessment conclusions as mentioned above are mainly based on the scope and boundary definition of the collected the data, the data should be considered carefully. Any slight changes of these data between one study and another, which is used to approximate the wind farm data, could lead to large errors in the final results. Therefore, in this research, specific data for the Goals and Scope was gathered clearly and thoughtfully. In some particular circumstances, the data is not available but it was possible to use previous results from reliable sources. This discussion will be continued in Chapter 3 Methodological Approach and Chapter 4 Case Study Selections.
- In the scope and boundary of one life cycle study, the capacity factor and lifetime assumption have the most impact on the results (Jungbluth et al. 2004). For instance, if there are two wind turbines with the same rated power and similar operating conditions, but one turbine has a higher capacity factor then it will generate more power than the other will. However, the installation and decommissioning costs are the same. Further discussion about the capacity factor is presented in details in Chapter 4.
- In addition, the lifetime assumption is quite interesting. Generally, a wind farm will be assessed as having a life expectancy of twenty years but in some special cases it can be longer, say thirty years (Lenzena & Munksgaard 2002). Extending the operational life by ten years obviously affects the results of

environmental analysis due to the increase in maintenance services and part replacement. However, there are fixed-costs as previously mentioned.

- No studies have been carried using the Input-Output method for investigating the environmental impacts derived from the installation of either onshore or offshore wind power. All the studies reviewed above are process-based life cycle assessments with limited system boundaries. The reason for this is the large amount of input data in the Input-Output approach which is based mostly on monetary flow which differs depending on the country and multilateral trade agreements between countries.
- For all these reasons, the selection of an appropriate environmental assessment framework for this research is crucial. The input data must be strictly handled to achieve accurate results because of the different kinds of data input involving in a wind farm impact assessment, and because critical material is sourced from a variety of domestic and international sources and organizations. Some data sources should be classified and characterized before using as a data input. This includes sources such as international energy agencies and national wind energy information administrations (some operating data is very difficult to obtain and its publication is limited in the public domain), and project impact assessments and environmental impact assessments of wind plants.
- Although the field of life cycle assessments is wide, from environmental assessment to political perspective (ISO 14040 2006), the relevant legislation, administrative documents, and policy making are not discussed in this study in order to focus on maintaining the objectives.

Life Cycle Assessment of environmental impacts are adapted for this research because of following reasons:

- One of the objectives of this research is to investigate and quantify the environmental effects of a diverse set of factors related to wind turbine manufacture. The outputs of this method of investigation are relevant to a wind power project, and they address the air emissions and other various potential factors. These quite closely satisfy the research objectives. For this purpose, the application of life cycle assessment to an existing wind farm will be beneficial in terms of the development of new wind power projects and the reduction in cost of new public investment.

- Based on the findings of the investigation, the research will choose matching environmental impact categories for assessment. Furthermore, the results will be used in the planning of future wind farm projects which have the same or similar conditions to plants that have already been developed and that are currently operational in the Binh Thuan region.

Chapter 3

Life Cycle Assessment Methodology

3.1 Introduction

In this research, the environmental aspects and potential impacts are determined using the Life Cycle Assessment (LCA) method. The theory and completed stages used in the full Life Cycle Assessment are presented in this chapter. LCA is currently regulated by the International Standard Organization by ISO 14040 and 14044 (ISO 14040 2006; ISO 14044 2006) and is defined by "the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle". This includes the materials and emissions associated with the extraction of raw materials, manufacturing of those materials, transportation of items, assembly of the product, maintenance or operation, and its final decommissioning. To date LCA has been used to model many different systems in terms of "product" which can refer to a number of things, including business strategies, specific objects, and policy makers.

3.2 Life cycle theory

LCA is a standardized methodology for product tracking and reporting analysis based on full Life Cycles.

Firstly, Giudice in 2006 stated that life cycle progression of a product is linear and irreversible. Since Life Cycle Theory deduces that each process of a product's life contributes to the final product, and must occur in a predetermined order (Giudice., Rosa & Risitano 2006). The completion of one process or product influences the next stages and depends upon the one before it. For a synthetic product, these processes could consist of different steps such as: from raw material extraction and processing; transportation to manufacturing factory; manufacture; transportation or distribution; the use or operation in service; and the last decommissioning including recycling, waste management, and disposed (Elcock 2007).

Secondly, Giudice postulates that for the *"in Life Cycle, generating force consists of a predefined program, inherent in the entity that evolves, which is regulated by the environment in which the entity is conceived and develops"* (Giudice., Rosa & Risitano 2006). For man-made products, this statement suggests that industry requirements or total final demand should be converted into terms of physical production, usage, and the dismantling of the product. This principle refers to the fact that the design required for a product is the momentum for the various physical materials or sub-subcomponents. Hence, if one or more of the system criteria are concerned with environmental aspects, the design will have to address the minimization of the environmental impact; and to do this, the physical steps during design can be adjusted to meet these requirements. This characteristic identifies the fact that some driving force has created the physical product and that if the driving force is able to change, the product will change.

Life Cycle Theory has been used in manufacturing for decades as part of the design process. LCA, however, has only recently started to be more robust and more precise about the impact of a product on the environment, as mounting environmental concerns call for scientific data.

3.3 Life cycle assessment

3.3.1 *Life Cycle Assessment structure*

LCA has been commonly applied to the comprehensive quantification and investigation of the direct and indirect environmental effects of variety of products, processes, and services through their life cycle (Hendrickson et al. 2006). LCA can be the starting point to undertake studies which aim to serve several purposes (Kuemmel, Nielsen & Sørensen 1997). These can be described by the following:

(a) To improve the energy usage for different processes of a product which are used to constrain the industrial production? One common method for LCA is to account for the energy demand from the sourcing of the raw material until the end of product's life. This is usually called a product LCA.

(b) To determine all impacts of a technical system. For instance, an onshore wind farm and its associated effects on the power transmission line and connecting switchgear and transformers, and on the sector economy, socio-economic system and related activities. All of these define a systems level LCA.

ISO 14040 creates the typical framework for an LCA analysis as shown in Figure 3.1. In this section, the different stages in the LCA framework are discussed step-by-step in order to understand the variety of LCA applications that are possible in many LCA studies. Whilst the following discussion on the LCA framework is as detailed as possible, there are specific circumstances based on the purposes of the LCA that will be slightly modified, or adjusted, in a specific framework.

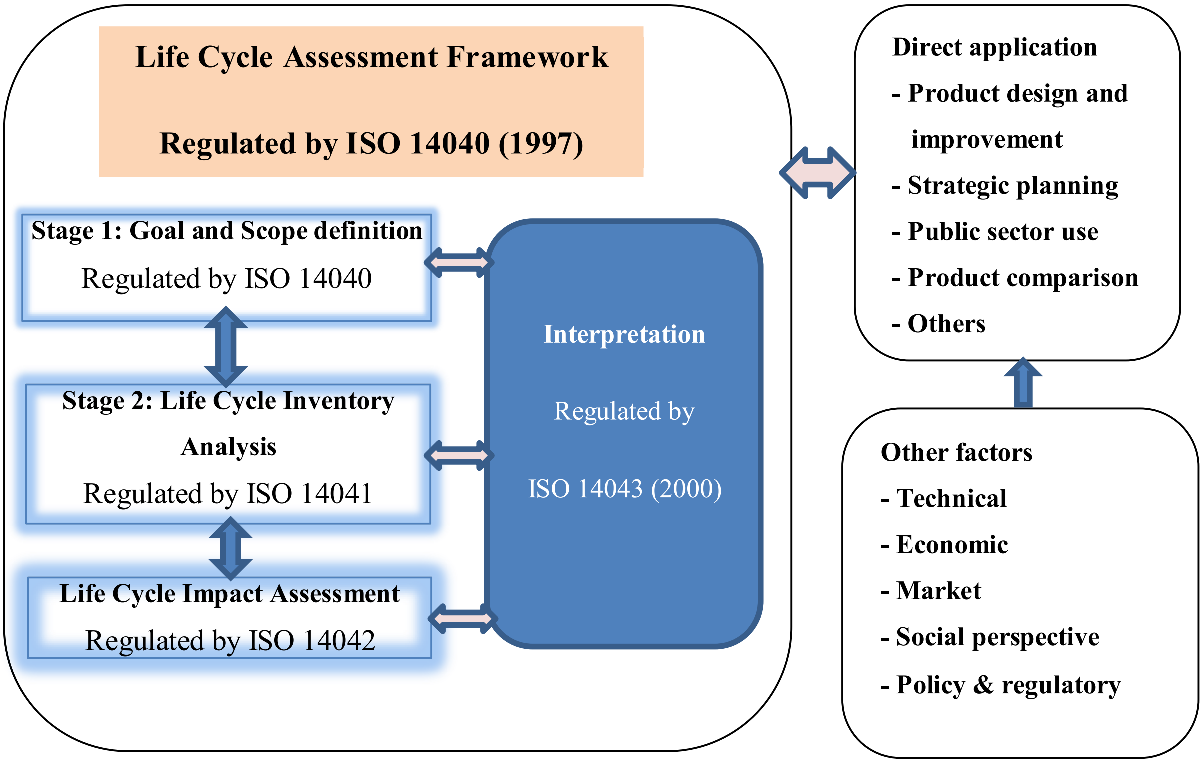


Figure 3.1: Various phases and applications of an LCA (based on ISO 14040, 1997).

Many LCA approaches have used three methodologies, namely: firstly, a process analysis based LCA (PLCA), secondly, an economic input-output analysis based LCA (EIO-LCA), and thirdly, a hybrid LCA. Table 3.1 describes the advantages and disadvantages of the three models.

The LCA methodology generally has four main stages, including goal and scope definition, Life Cycle Assessment Inventory (LCI), Life Cycle Impact Assessment

(LCIA), and improvement assessment based on Life Cycle Interpretation (Ciambrone 1997; Curran 1996; SETAC 1993b). A full LCA flow chart is given in Figure 3.1 and these shows in detail the regulation by ISO 14040 to 14044.

Table 3.1: List of the key features of various LCA methodologies.

Model	**Description**		
	Main characteristics	**Use**	**Limitation**
PLCA	- Inputs: raw materials - Outputs: the environmental impacts assessed at various processes	- Very specific analysis at particular process - Apply for assessment process, product and services	- The boundary and scope is difficult because of too large data collected at different stages. - Making comparison between PLCAs is hard.
EIO-LCA	- Input-output table data compiled. - Inputs: material, energy use, - Output: emission, waste generation factors per monetary unit - Based on the standard of regions or country	- Use comprehensive analyses of many products and services	- Not provide a detail in many stages in one process.
hybrid LCA	- The combined method - Input: all life cycle stages (e.g., energy, raw materials, water, etc.) - Output: emission to air, noise, visual impacts, Bird and bat effects, etc.	- Use to assess the environmental impacts related cost and time effective (spatial and temporal)	- Comprehensive data gathered - Choosing an appropriate stage is difficult.

3.3.1.1 Goal and Scope definition

LCA Goal and Scope provides a fundamental description for the study of LCA, a description of the expected definitions in terms of the system boundary conditions, and the assumptions for a functional unit (SETAC 1993a). This step is defined by the ISO 14040 series (1998) (ISO 14041 1998.); it is the first important main part of Life Cycle Inventory (LCI) since setting system boundaries and defining the Functional Unit is necessary for LCI. The following is a detailed illustration about Goal and Scope definition.

(a) The LCA Goal is regulated by ISO 14040 and 14044 and defines the analysis of the project. This is based on a series of questions. These questions will be about:

- the environmental impacts of processes or products;
- what is intended by the application or what the objectives of the study are;
- what is the reason for doing the research;
- for whom will the LCA be conducted (the targeted audience); and
- in what form will the final comparative study be couched, such as by internal publication or by public comparative products (Klöpffer & Grahl 2014a).

The parameters of the goal are the backbone of a study. An LCA conducted for internal purposes would be carried out differently compared to one publicly comparing two or more products and processes. Furthermore, some particular cases must comply to additional ISO Standards, and early knowledge of these is key (Goedkoop et al. 2008). The goal must be adhered to during the entire LCA and, if needed, input data updated to accurately align with the current study.

(b) The LCA Scope based upon ISO 14044 requires the definition of what is included in and excluded from the analysis. The parameters which have specific requirements are then defined. Note that the LCA also describes the most vital methodological selection, which includes the assumptions and limitations for the research project (Goedkoop et al. 2008).

Firstly, the priority stages in the life of the product should be determined. Although this study could be called a life cycle assessment, sometimes the overarching questions do not require some aspects of the product's life to be included. In a typical life cycle of a product or process, consideration is usually given to the raw material requirements, manufacturing, transportation, use, maintenance, and management of waste (United States Environmental Protection Agency (EPA) 2006). A complete life cycle assessment should include all phases, but the goal of a project needs often only to be related to a particular stage of the life of the product. The scope should define which stages will be included. The scope of an LCA includes four steps which are presented below in points (c) to (f). These steps are adapted from ISO 14044 (ISO 14044 2006).

(c) **Functional Unit (fU)** is especially important in an LCA. It will compare two or more products or processes as described in the performance and unit of analysis. Defining the fU is not always simple, especially when comparing different options. The fU defines a unit of analysis that consists of quantity, quality, and duration of the product, or provided services (Goedkoop et al. 2010b). For instances, the environmental impacts associated with different power plants are typically identified based on a Functional Unit of 1 kilowatt hour, or 1 kWh. Take an example of comparison between a solar power plant and a wind farm, to do this, putting the all impacts of both a solar power plant and a wind farm into this functional unit, 1kWh, and then the comparisons between the environmental impacts of both systems can be carried out.

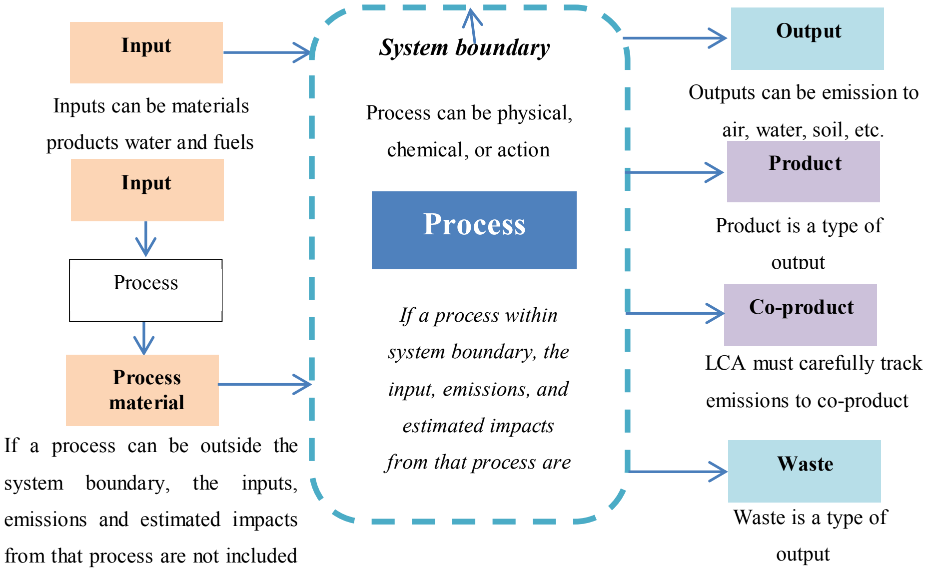


Figure 3.2: System boundary of generic process.

(d) **The system boundary** is a key consideration within the scope stage. It will ensure that the product or process of the research is transparency and has clear definition. It will define which of the part or sub-components of the product are to be included in this study, and which parts or sub-components may be not. The system boundary can be between system and environment or between the system under study and other related systems (Elcock 2007). In some cases, certain objects may be located outside the system boundary due to the expected minimum impacts. For example, in a wind farm, if raw material was quantified to only contribute a small percentage of the total impact of the wind turbine, this material could be neglected (Goedkoop et al. 2010b).

A general system boundary flow chart in a graphical representation of the scope of an LCA is illustrated Figure 3.2. It shows the generic process of the study in which the inputs and outputs have been traced.
The following processes are excluded in typical LCA (Simonen 2014a):

- Employee commuting
- Hygiene related waste water such as toilets and site access such as paths for workers
- Manufacture of fixed equipment such as the manufacturing plant
- Manufacture of transport equipment (boat, truck, etc.)

(e) **Methodical selections** are also part of the clarifying procedure for the scoping of an LCA. The standardized LCA will allow several methods to be used, provided that the analysis clearly documents the methods used in the study. For this reason another critical point that must be addressed in the Scope are issues related to allocation, impact assessment metrics and methods, and interpretation methods.

The allocation is relevant to most of the processes and often relates to more than one product or output. The environmental impacts of the entire system must be allocated appropriately to a variety of products. Two approaches that can be used in order to avoid allocation problems is to broaden the boundaries of the appropriate system, or to separate the process into several LCAs (Goedkoop et al. 2010b). If allocation is necessary, it is suggested that the environmental impacts are allocated based on the percentage of weight or economic value of the different outputs for the entire life cycle of the system.

(f) **Analysis details** must also be determined in the scope of definition. Three items in the details of analysis can be highlighted here. These are the quality of data sources collected, the differences of geographical and temporal aspects in the study, and technological trends. Since the different items will change the outcome, it is important to decide which type will be analyzed. The scope should also adequately address the consistency, completeness and reproducibility of the data gathered (Goedkoop et al.

2010b). Furthermore, the scope definitions involve detailed processes. These definitions must be done thoroughly and solve as many characteristics of the project as possible to ensure both quality and consistency during the conducting of the research.

3.3.1.2 Life Cycle Inventory Analysis

As the parameters of the project have been well defined in the Goal and Scope stages, the Life Cycle Inventory can be created. The Life Cycle Inventory Analysis (LCI) is a methodology for calculation of resource material consumptions and quantification of the input-output process of the product. This stage is an important part since tracking material flows over all stages of a life cycle is required for a comprehensive LCI. The data gathered in the LCI is often large with multifunctional factors such as multiple sites, different fractions of total emission at one site, time variety, and different time periods. It leads to all data collation and action in the LCI and any further steps which are appropriate through the decision making in determining the Goal and Scope of the project. According to ISO 14044, the inventory database should be spilt into four categories:

- The input including energy, materials, and auxiliary materials.
- The product category consisting of co-product and waste.
- The emission category relates to the releases into the air, soil, and water.
- The final category of environmental impacts such as effect on human health as shown in Figure 3.3; this is related to the Life Cycle Inventory data classification.

It should be noted that there are two important points of LCI that have to be considered. The first is data collation and the second is the calculating of further data to obtain results for the system under research. The calculations in the LCI stage may lead to the potential changes to the Goal and Scope focus. Therefore, it is essential to create a flow diagram for the project. These flow diagrams are used to describe an outline structure and the relationship between the inputs and outputs for the product life cycle as shown in Figure 3.3.

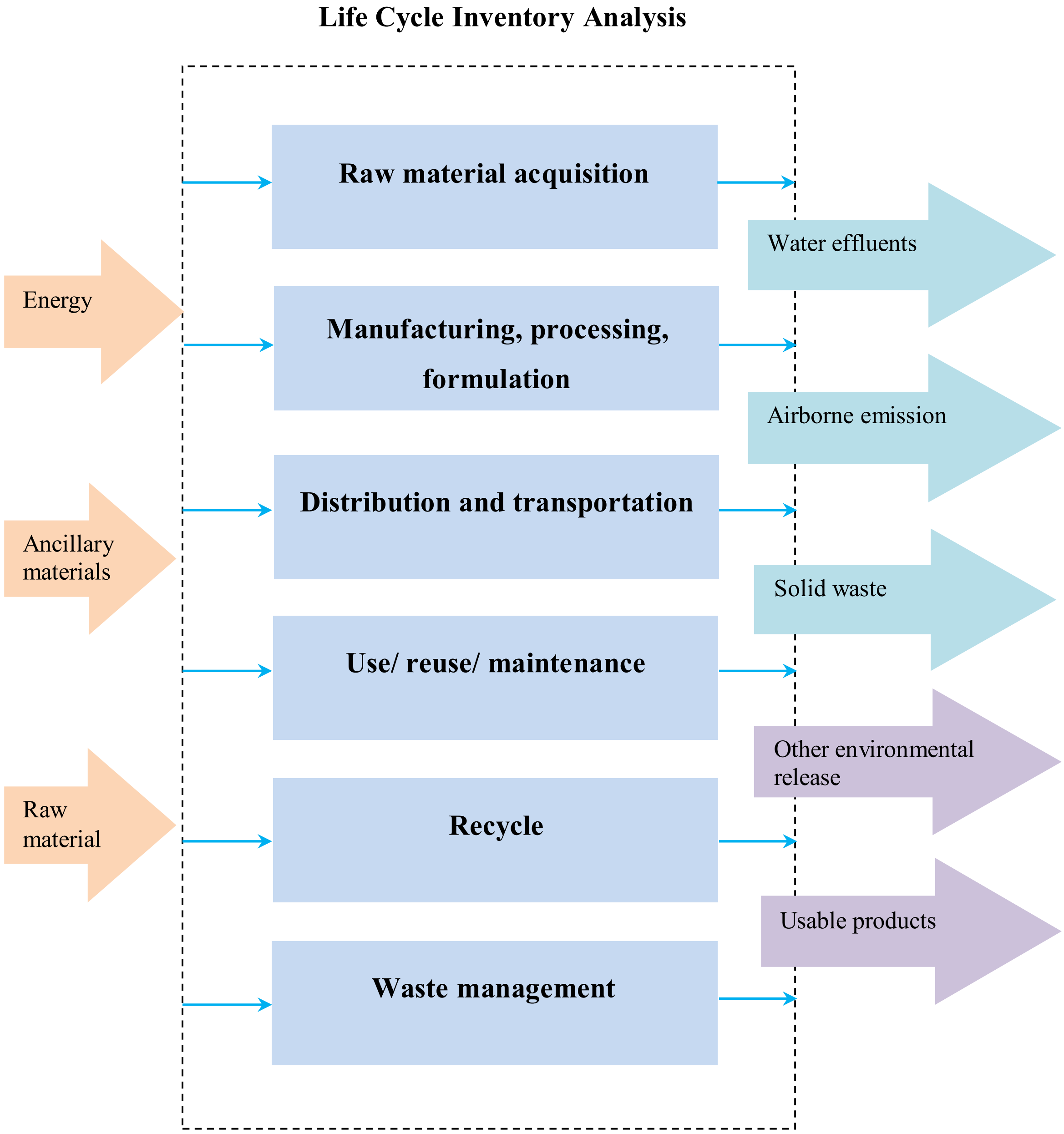


Figure 3.3: Life cycle inventories account for material use, energy, wastes, emissions, and by products over all of the stages of a product's life cycle.

The next step is to create a data collation plan. The data, for example, can be collated via measurement during manufacture or on-site, or calculated or even estimated. However, it is often not simple to collect actual data due to access restrictions during manufacture. For that reason, the plan for data collation should be identify which data must be collected, where the data sources can be found, and how to approach it. For the life cycle data approach, there are two types of data collation: foreground data and background data.

Foreground data, which is stored specific information for particular processes or products necessary to model the project. It is very difficult to collect due to the confidentiality issues. In most cases collating foreground data from specific companies is almost impossible since the data contains technically or commercially sensitive material (Goedkoop et al. 2010b).

Background data is the information related to basic materials. This data is also stored information but it is more generic than foreground data. To date, up to 80 % of the data required for LCA research is considered as background data and can be collected from non-primary sources (Goedkoop et al. 2010b). These data sources are known as "databases" or "libraries" when contained within various Life Cycle Analysis software packages. Basically these databases include the background data from LCA calculations based on standard materials, transportation costs, typical manufactured materials and energy input. If the Scope of a study and a flow chart indicates a certain input as background data, the software databases can be employed to estimate the emissions, energy usage, and material mass with a degree of accuracy. Furthermore, most databases now contain detailed explanations of the input and should be classified carefully to ensure that the process being used appropriately represents the Scope of the study.

When the LCA study team has determined how to collect the different and necessary data through the data collation plan, the process for the data collection can be initialized. This LCI stage can be time consuming and iterative. It is very important to remain organized because a large quantity of data information will be imported. The final outcome of this stage is a quantitative list of emissions and raw materials (Goedkoop et al. 2010b). Whilst the results of the LCI is very simple and able to be utilized for decision making from policy makers, some LCAs do skip this stage, and go straight to the Life Cycle Impact Assessment (LCIA) stage. They convert the amount of emissions into useful impact categories.

3.3.1.3 Life Cycle Impact Assessment

Since the Life Cycle Inventory (LCI) provides the data inputs (raw materials, energy and water, etc.) and outputs (emission to air, soil, water, etc.) in terms of lists, they contain many different chemical emissions that can be hard to explain or use. Therefore, in order to translate all the collected data from the LCI into potential environmental impacts, the next stage, named Life Cycle Impact Assessment (LCIA), converts the LCI data into impact assessments. It can be noted that the LCIA does not assess or quantify the environmental issues of a product, process or service. Typically, the LCIA consists of two types of the Impact Assessments: mandatory structure and optional structure. In this thesis, the mandatory elements of an Impact Assessment are chosen, the optional elements are omitted.

The mandatory elements of the Impact Assessment have got a structure which is compiled from three stages (SETAC 1993a):

- the choice of the impact categories, category indicators and classification, and characterization models;
- classification of the results; and
- calculation of category indicator results or characterization.

There are hundreds or even thousands of emissions coming from the LCI. In addition, there are numerous impact categories such as acidification, climate change, stratospheric ozone depletion, aquatic toxicity, human toxicity, fossil fuel depletion, and water depletion (ISO/ TR 14047 2012). It is important to identify which environmental impact categories are appropriate for the study, and then establish which emissions affect which impacts. The final operation is to compute the total relative impacts (ISO 14044 2006). Furthermore, the impacts in the study should be chosen first, before knowing outcomes of the LCI, in order to avoid the temptation of impact selection based on preliminary results (ILCD 2010). Table 3.2 presents two sample lists for selection of impact categories. On the right side of the table, the impact categories can be assigned using the LCI results, hence the mid-point categories and damage categories.

Table 3.2: Two sample lists for chosen impact categories [a].

Impact category	Impact category	
	Mid-point category	**Damage category**
Human toxicity Ecotoxicity Eutrophication (aquatic) Land use Ozone formation (near surface) Resources demand Ozone depletion (stratospheric) Greenhouse effect Acidification	Human toxicity Impact on respiration Ionizing radiation Photo chemical oxidation	Human health
	Aquatic ecotoxity Terrestrial ecotoxity Aquatic acidification Aquatic eutrophication Terrestrial acidification and eutrophication Land use	Quality of ecosystem
	Global warming	Climate change
	Non-renewable energy Mining minerals	Resources

The second step of the LCIA is classification. Classification is obviously a correlation between the inventory results and the impact categories. Once the appropriate impact categories have been selected, the LCI results are classified and put into the different categories. It can be noted that several emissions may affect one particular environment impact and a single emission might cause more than one environmental impact. For example, multiple emissions such as CO_2 (carbon dioxide) and CH_4 (methane) have been classified to be greenhouse gases (GHGs) and affect the climate change. Moreover, multiple classifications for one emission are permitted but should be managed carefully to ensure that it is not over calculated. Goedkoop 2010 (Goedkoop et al. 2010b) proposed two ways to manage the one emission allocation with multiple impacts. Firstly, the emission could be divided between the two impact categories using a logical percentage. This scenario would be applied in cases in which the emission has an impact on a certain impact category, which can be quantified, and then the remainder is then allocated to another category. An example for this method is the amount of SO_2 (sulfur dioxide) released which is inhaled by a person; this would not contribute to acidification. In this

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[a] Adapted from (Klöpffer & Grahl 2014b)

case, a certain percentage of SO_2 emissions will be reserved for human toxicity, and the remaining percentage to acidification. The second allocation scenarios can be related to a chemical allocation, 100 % of these emissions may affect two allocations simultaneously. An example of this may be related to the emission of NO_2 (nitrogen dioxide), which contributes to both ground level ozone and acidification (Elcock 2007). This is shown in Figure 3.4, which illustrates the principles of classification and characterization in an LCIA. Since the same particles of NO_2 will affect both categories, 100 % LCI emissions are used in both.

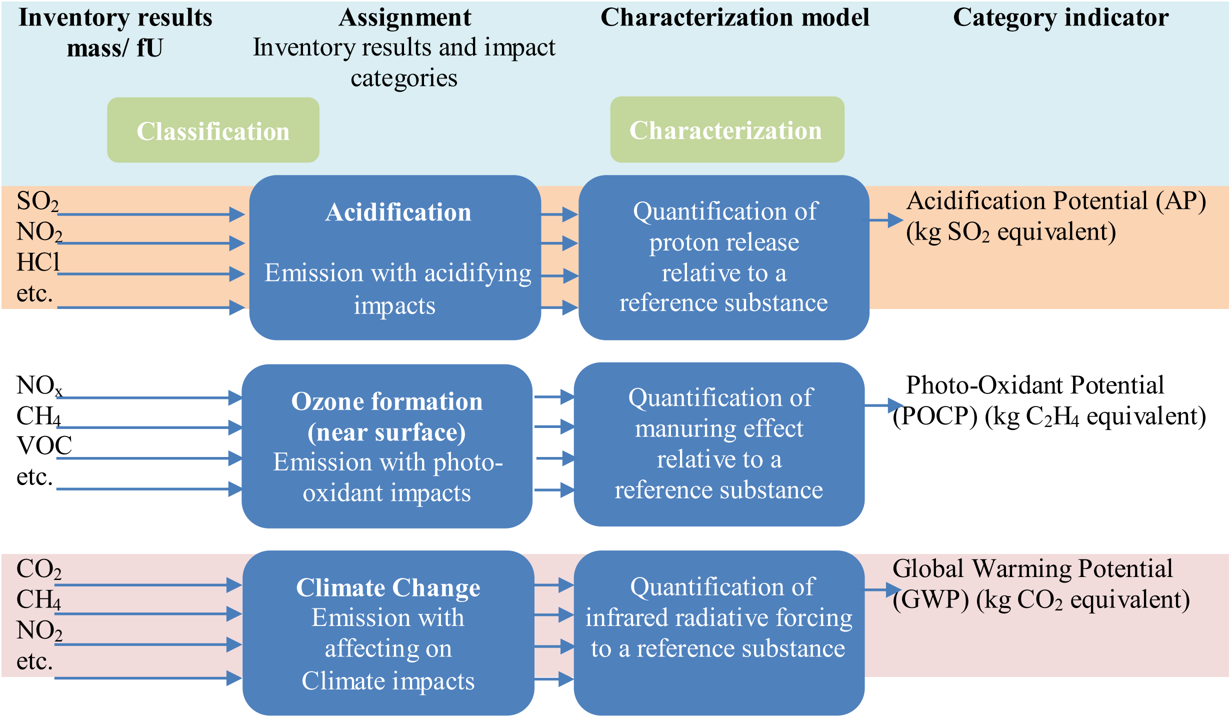

Figure 3.4: Principle of classification and characterization in the phase of Life Cycle Impact Assessment.

Finally, the last stage is emission characterization in the LCIA when all LCI's outcomes have been classified into the selected impact categories. This stage is responsible for translation of the emission outcomes in one category into an equivalent impact. This is done by multiplying each emission by a characterization factor in order to determine the total impact of the product on climate change (Goedkoop et al. 2010b). In the Life Cycle Assessment: Principles and Practices report prepared by the Scientific Applications International Corporation (United States Environmental Protection Agency (EPA) 2006), the characterization stage can be carried out by putting the different chemical quantities on an equal standardized scale. For example, as mentioned earlier, CO_2 and CH_4 contribute to the climate change impact category; however, they will have different contributions that need to be quantified. The impact assessment evaluates the relative contributions of multiple GHGs to the climate change: one kg of CH_4 has 25 times the impact of one kg of CO_2. This is because CH_4 emissions affect smog but carbon dioxide does not. In terms of GHG, the impact is quantified in terms of equivalent is CO_2 written $kgCO_2e$ (e means Equivalent). Table 3.3 illustrates the basic calculation approach for chemical emissions based on anticipated characterization factor.

Table 3.3: Calculating impacts of some greenhouse gases with Global warming potential (GWP_{100}) or characterization factors (time period 100a)[a].

Substance	Formula	Emission (kg)	Characterization factor, GWP_{100} (kg CO_2 -eq/kg GHG) [b]	Impact (kg CO_2 -eq)
Carbon dioxide	CO_2	1.96000	1	1.9600
Methane	CH_4	0.00050	25	0.0125
Carbon monoxide	CO	0.00013	0	0.0000
Nitrous oxide	N_2O	0.00160	298	0.4770
Total climate change estimated impact				2.45 kg CO_2e

The characterization stage in the LCIA is mainly based on the characterization factors. For that reason, these characterization factors must be high quality and be appropriate for the case study. Generally the applicable characterization factors are the best choices for doing LCA research; but in some particular cases, the scientific study data are limited and not available for calculating correct impacts (United States Environmental Protection Agency (EPA) 2006). In these cases, the LCA expert must ensure that they are employing characterization factors that are in agreement with the scientific community.

The development of global scale determination of environmental impacts for a product, process, or service needs the data stored in the LCI to be converted into environmental impact prediction (Boustead, Hancock & Sons 1979).

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[a] Time period 100a means impact assessment in 100 years

[b] GWP_{100} data is selected from IPCC fourth assessment report

3.3.1.4 Life Cycle Interpretation

This stage is related to interpreting the findings of the Impact Assessment in order to compare products. This includes the recommendations for the objectives of the study, which are presented in the stage 1 Goal and Scope definition. Interpretation is performed with reference to the three preceding phases of the LCA. If the outputs of the Inventory Analysis do not fulfill the requirements in the Goal and Scoping stage, the inventory analysis must be improved by: i) revising the boundary conditions; ii) obtaining further collated information data; iii) by analyzing further processes or products.

Figure 3.5 presents the significant items identified in the results from the three previous stages of the LCA, and the interaction with the evaluation of stage 4. According to ISO 14044 (ISO 14044 2006), there are three main steps in the Interpretation stage, as listed and shown in Figure 3.5:

(a) **Identification of significant issues:** This is mainly based on the resulting data from the LCI and LCIA stages; the aim of the identified significant issues step is to determine the significant quantitative differences related to data uncertainties that are contained in the LCI and LCIA. A solution can be presented using ISO 14044. If the resulting data from the LCI and LCIA, stages 2 and 3, respectively, have been found to meet the requirements of the Goal and Scope definitions shown in stage 1, the significance of these results will be identified.

(b) **Evaluation:** This is to verify the trusted results of an LCA and the significant parameters. There are three ways to carry out the evaluation of data, these are completeness, sensitivity and consistency check; these can be defined by:

- **Completeness check** *is to assess data information of an LCA to ensure that it is a complete and entire LCA; this means that there is no missing data which could affect the environment. If information is found to be missing, which can heavily impact the study, new data and processes need to be employed for completion of the full LCA (United States Environmental Protection Agency (EPA) 2006). Another way to deal with this is that the Goal and Scope from the LCA could be modified and adjusted if the data is still not available. This* *could be due to budget and time pressures. This limitation should be included in the conclusion.*

- **Sensitivity check** *is to estimate the uncertainties of the LCA results. This is mainly based on data quality, cut-off criteria, and selection of allocation rules and choices of Impact categories. For highly matched LCI data, and for particular cases, classical mathematical error methods can be used. This uncertainty can be assessed using Gaussian distributions and standard deviation* (Klöpffer & Grahl 2014d). *To alleviate the data error, a sensitivity analysis is performed by simply altering the old assumption within the model and then re-computing to identify that how the significant changes affect results. If the small changes in the inputs cause major effects on the outputs, the assumptions related to these inputs should form a critical discussion in the conclusions of the LCA study* (Goedkoop et al. 2010b).
- **Consistency check** *is to evaluate the LCA study to ensure that the analysis is internally consistent and matches the Goal and Scope set up at the* 1st *stage.*

(c) Final conclusions, limitations and any recommendations that are based on the LCA study are only appropriate with the goals of the research. It should be ensured that the final results have been assessed for significant issues which should have been clearly specified and discussed; with further data input evaluated via a sensitivity analysis model.

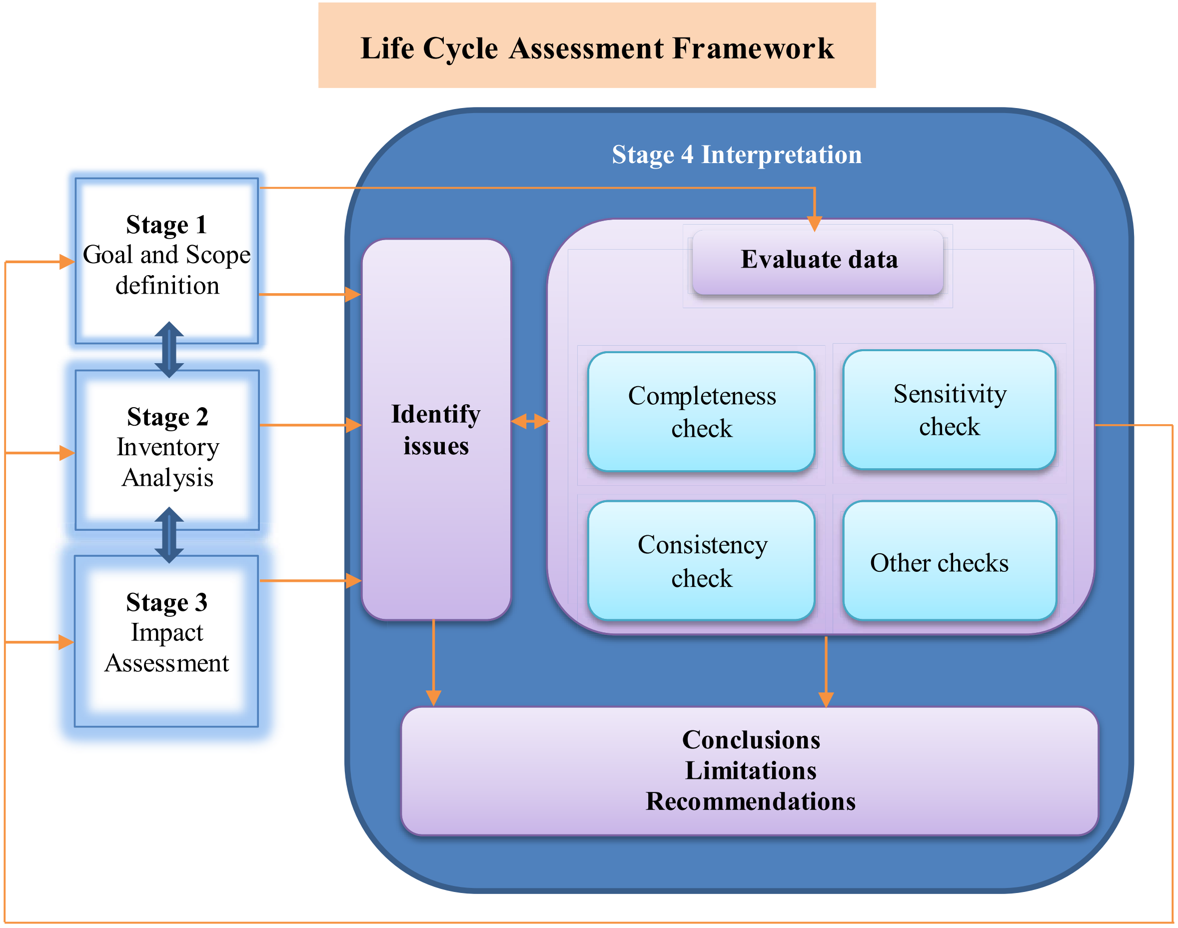

Figure 3.5: Main components of stage 4 Interpretation and other stages regulated by ISO 14044.

Chapter 4

Practical life cycle inventory of the wind farm in Vietnam

4.1 Case study description

This study will focus on the first industrial-scale wind farm in Vietnam (Khanh 2012b) and will address the environmental impact assessment. The wind project is owned by the Vietnam Renewable Energy Joint Stock Company (REVN) and known as Wind Power Plant No 1. It is located in the Tuy phong District of Binh thuan Province, Central Vietnam. Figure 4.1 give a pictorial layout of the wind farm and Figure 4.2 shows the farm as AutoCAD illustration which is used for estimation of relevant distances, such as the distance of the twenty wind turbine units from the 110 kV step-up transformers.

To be more specific about the wind farm development, in September 2008, the first five wind turbines were completed and connected to the national grid; the total capacity was 7.5 MW. A further fifteen wind turbines were erected and came on line in March 2012. Currently in this first phase of investment, there are twenty industrial wind turbines with a combined installed capacity of 30 MW connected to the Vietnam national electricity network (Khanh 2007). The capacity of this wind farm project is predicted to increase up to 120 MW by 2020 if the next phase is implemented.

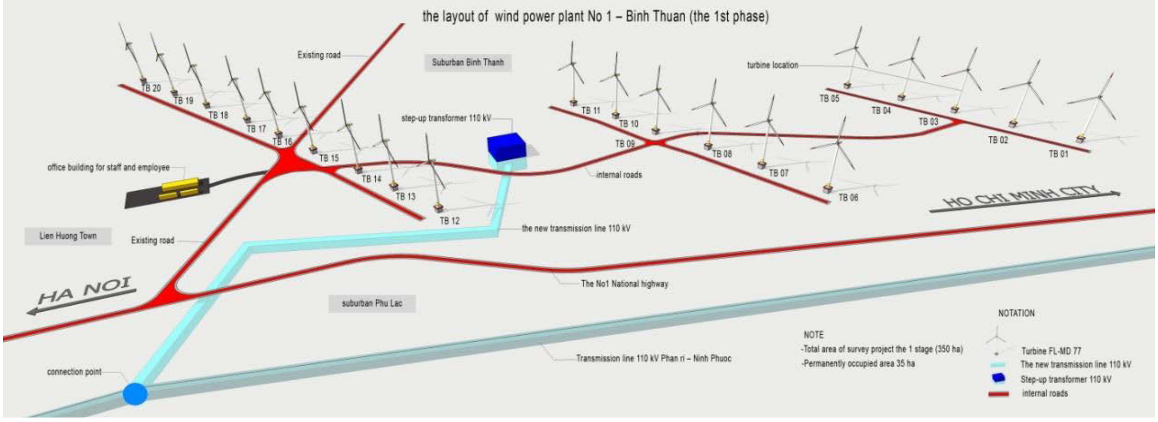

Figure 4.1: The illustration of the wind farm in 3-D map in Binh Thuan province.

The step of the project development had several intensive stages. These are either related to planning (site selection, construction, design, finance support, insurance, and consultation) and implementation (operation and maintenance cost, and power purchase) and it has to be ensured that these have beneficial outcomes in relation to the environment and the local community (ICONTEC 2012).

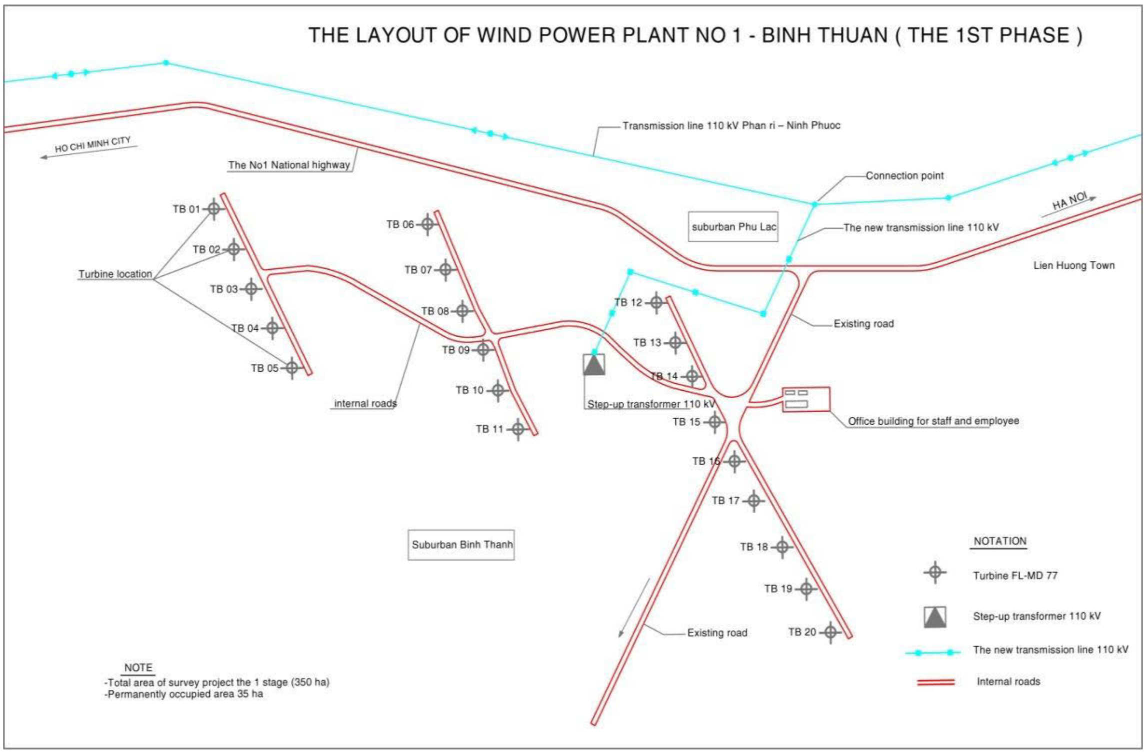

Figure 4.2: The layout of wind farm in Binh Thuan province [a].

4.2 Goal and scope definition

4.2.1 *Goal*

The goal of this Life Cycle Assessment is to comprehensively determine the environmental impacts of the generation and transmission of wind energy from the local wind power plant to the national grid in Vietnam. The best wind resource is concentrated

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[a] 1.Khanh, N.Q., *first wind farm at industrial scale in Vietnam – lesson learned.* 2012, Vietnam Renewable energy company: Hanoi, Vietnam.

in central Vietnam near the sea shore (TrueWind Solutions LLC 2001) so that in the near future it is predicted that many wind projects will be developed in these areas. However, there are currently no wind power standards in Vietnam for either wind power generating systems or the resultant necessary environmental assessment. This causes difficulty in getting investment certification and technical review of the wind projects. Furthermore, for this project, after a period of monitoring, the local city power transmission line was found to be still low in quality in terms of voltage and this operating instability influences the wind power generation plant. For these reasons, this study sets out to analyse the total environmental effects of wind energy in terms of both generation and transmission to load centres.

4.2.2 *Scope definition*

4.2.2.1 System boundary

Figure 4.3 shows a flow chart for the major components in the life cycle of a wind farm. This assumes that the total lifecycle of the wind turbine from the cradle to grave is 20 years. The entire LCA has to be considered, from the manufacture of different components of the wind turbine, up to the end of life of the wind farm. There are boundaries between the different stages: main component production of wind turbines, delivery of these components from their manufacturer to site, and then the construction phases (called the installation step). After these, the next step is the power generation stage which should consider power transmission to substation including the step-up transformer before the connection point to the grid. The internal network transmission to the national grid needs to be considered. The final steps are the decommissioning phases with sub-phases including recycling and landfill.

The chosen boundaries are also suitable for defining the aims of this research. This is because the work conducted in this research is related to the assessment of the total environmental impact of the wind farm so that the data related to the grid system power quality is not addressed in this thesis.

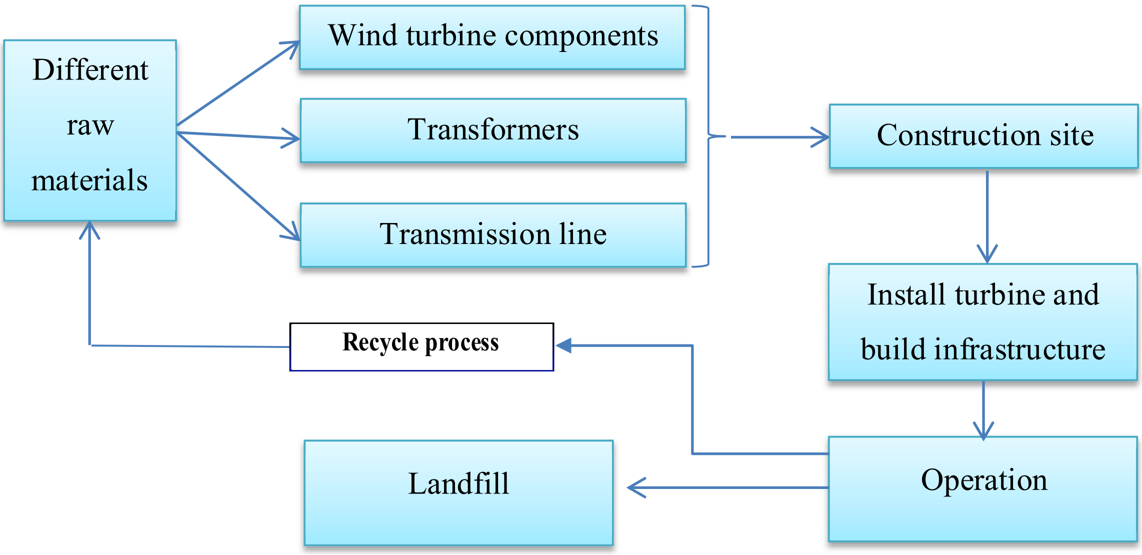

Figure 4.3: The basic system boundary for the life cycle assessment of a wind turbine.

4.2.2.2 Functional unit

In addition to the determination of the LCA system boundaries, the reference units of measurement must be chosen. According to Giudice, 2006, the *"reference unit of measurement used to treat and present the data and information of an LCA"* (Giudice., Rosa & Risitano 2006) is called a functional Unit (fU). If there are more than two processes or products which need to be analysed, the fU will then play an important role in the comparison of the different processes or products since it is the fixed unit of measurement. In this study, the functional unit is 1kW of power output for a wind farm. For research related to electrical cable, the fU will be kWh/kg materials and to assess the transportation of various parts the fU is 1kg/km. These illustrate some of the fundamental fUs.

4.2.2.3 Data sources

The quality of data has a great impact on the result of the life cycle assessment. Researchers often have a difficulty in getting primary-level real data; this is known as a primary data input for academic purposes. This is because the refined material requirements for an individual component, and the percentage of different materials and processes contained within the component, are usually considered as proprietary and available to the manufactures only, so that detailed input data for manufactured components cannot be reported (Wilburn 2011). Another reason related to the environmental impact assessment of the material used in manufacturing is that manufacturers have to be careful handling collected manufacturing data; it has to be treated as confidential information because the public knowledge of their own data could affect their market share price. Their competitors could also exploit the data when operating in an intensively competitive market (Hendrickson et al. 1998).

To deal with these issues in this research, the first set of energy and environmental impacts related to the raw material in the production of a wind turbine have been calculated using estimations of weight. The material percentages in a common arrangement of a wind turbine is investigated, with suitable percentages being picked out and used as the data source. This data may come from industrial sources, literature review, academic reports or government technical paper review. The parameter value is finally chosen based on this estimation. This is used to approximate the practical processing and used as input data in this study. However, it is not a straightforward process selecting which parameter is an ideal sample. To reduce the error in the selection procedure, one model is built up with standard deviation so that it has minimal effect on the final input data; this method will be shown in later sections. The output data was checked in order to determine any data that had significant impact on the end results, and to make sure that the processes that do have affected results are reported in a transparent manner and well understood.

Finally, the data collected for this case study can be used for optimization; however, optimization relies on accurate inputs so that it should be ensured that it comes from various reliable sources such as research literature, commercial databases, and information provided by industrial representatives.

4.2.2.4 Uncertainty

Due to the uncertainty of the data input in an LCA model, an uncertainty analysis needs to be undertaken in order to make sure that the error is reduced to a minimum so that the output results are as accurate as possible. Typically, there are three main categories of possible uncertainty. These are: the input data uncertainty which is based on ISO 14044 requirements (ISO 14044 2006) and includes different types of raw material; the output data which includes the amount of environmental emissions with the energy payback time; and a representative model of uncertainty with the latest uncertainties caused by an incomplete model of data and processes. For the first point, the quality of input data gathered for the Life Cycle Inventory is normally inherently inconsistent. This is due to the fact that not all measurements are obtained using the same geographical and technological standards, which leads to uncertainty and inconsistency in the input data. Furthermore, as mentioned earlier, a number of the process data, that are required to complete the entire LCA, are not available. The solution for these issues is that the data for these processes has to be obtained from other sources (Goedkoop et al. 2010b). This means that uncertainty is unavoidable in every model assessment due to practical circumstances. In order to mitigate the error in the model performance, multiple examinations of the data can be carried out using sensitivity analysis models. These can affect the data input in both the LCI and LCIA. The third uncertainty is due to the incompleteness of the study. This refers to the data differences between the various system boundaries, incomplete data sheets and mismatches between data inventory and impact assessment method. To deal with these, an uncertainty analysis will be built up, and the analysis of the uncertainty model will be presented in a later section.

4.2.2.5 Key assumptions

There are a number of assumptions made in this analysis. In general, these are:

- The wind velocity distribution is based on Weibull's distribution. With this assumption, the wind turbine capacity factor will be calculated.
- Turbine lifetime has been assumed to be 30 years.
- This study accounts for regular turbine maintenance and component replacement. Material required for maintenance has been included, i.e., change of oil and lubricant every five years.
- The quality of data is inherently inconsistent. Since not all metrics were obtained from the same geographical and/or technological standards, so the uncertainty is inherent in these input data. This leads to an uncertainty analysis.

- Because the example wind turbine is produced by Fuhrländer in Germany, the main estimated data was based on the European database. The transportation of these turbines from Germany to Vietnam was by ship based on international standard of shipping cargo, and from the Vietnam port to the construction site by local trucks so a local database was used.
- Environmental impacts of diesel transport fuel were estimated based on a Vietnamese standard. This data were in an aggregated format, which includes fuel extraction, refining, and transportation to service stations.
- There are some assumptions made for special processes in the construction phase and other phases.

4.3 Inventory analysis of case study

4.3.1 *Methodology*

In this section, the Life Cycle Inventory analysis (LCIA) is carried out in a step-by-step manner. To begin, a capacity factor for the wind farm must be calculated. All generating plants must have a capacity factor which is defined as the ratio between the real power over the operating period (based on the measurement of actual power during the actual operating period, for example, the power can be averaged to operate for six hours per day at rated power) during a specific period of time such as 24 hours per day or 8760 hours annually.

The power capacity factor in this case is determined using the report from a wind farm project (ICONTEC 2012). The total real hours of operation was measured as approximately 2715.6 hours, which means that there are 7.44 hours daily when power is generated. The rated power of one wind turbine is 1.5 MW so that the capacity factor is

$$\text{CF}=\frac{\text{real power capacity in a year}}{\text{rated power capacity in year}}=\frac{\text{rated power}\times\text{real hours a year}}{\text{rated power}\times\text{total hours a year}} \qquad (4.1)$$

$$=\frac{2715.6}{8760}=0.314=31.4\ \%$$

The figures in Table 4.1 show the average capacity factors for several wind farms located in the USA from 1998 until 2005. It can be seen in Figure 4.4 that these capacity factors vary from approximately 20 % up to around 40 % (Wiser & Bolinger 2006). If these farms are compared with the wind farm studied here, it was that a CF of 31.4 % it could be acceptable.

Table 4.1: Capacity weighted average 2006 capacity factors by region and commercial operation date [a].

Capacity factor	Heartland			Texas			California			Mountain			Northwest		
	No[b]	MW[c]	CF[d]	No[a]	MW[b]	CF[c]	No[a]	MW[b]	CF[c]	No[a]	MW[b]	CF[c]	No[a]	MW[b]	CF[c]
Pre 1998	1	26	0.255	1	34	0.196	17	870	0.224	NA	NA	NA	NA	NA	NA
1998-99	6	447	0.301	3	139	0.301	4	174	0.3	3	68	0.352	1	25	0.301
2000-01	4	197	0.326	7	911	0.318	1	67	0.374	4	123	0.301	3	338	0.295
2002-03	10	602	0.349	2	198	0.37	4	287	0.301	3	510	0.303	2	105	0.311
2004-05	9	1042	0.387	3	341	0.389	3	130	0.342	3	208	0.41	4	424	0.315
Total	30	2314	0.32	16	1623	0.31	29	1528	0.31	13	909	0.34	10	892	0.31

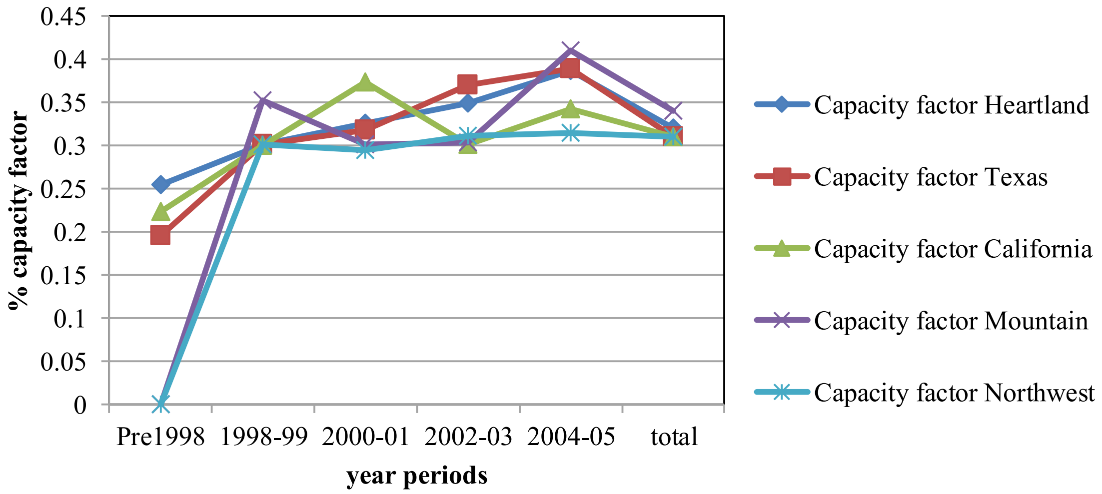

Figure 4.4: Average capacity factors in US region.

In the Life Cycle Assessment of the entire wind farm, the functional unit for energy is one kWh of electricity generated from the land-based wind power plant and delivered to the national grid. In addition to the functional units, further technical data is needed and

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[a] (Wiser & Bolinger 2006)
[b] No – Total numbers of wind farm plants
[c] MW – Total capacity of wind power in regional scale
[d] CF – capacity factor in average

this is given in Table 4.2. From this, the total number of energy units generated per year can be calculated.

The wind farm is split into different stages through its lifecycle as illustrated in Figure 4.5. This breaks down the LCA into smaller manageable sections, which is more straightforward than considering the LCA in its entirety. After breakdown, these new stages will be analyzed in the following manner. First, the manufacturing stage of the wind turbine components or sub-components, and transmission cable, or whatever additional component products produced for the wind project must be calculated. Some processes for components and subcomponents will have data available, but some will be not. For these latter cases, a second stage will consist of a quasi-process, which will be built up an analysis under the similar conditions to develop the necessary calculations. The third stage will be transportation calculations linked with the construction. In this stage, ship transportation is required to deliver the large turbine components (e.g., blades) and heavy components (turbine nacelle and tower); these were manufactured in Germany but are on-site in Vietnam. The energy input and emissions during the transportation by the ship will be estimated and calculated. Furthermore, the transportation of the foundation materials, such as concrete and reinforcing steel, has to be included. This comes from local suppliers since both of these materials are common and standard. During the delivery and construction phases, a crane and an excavator are also considered. All of these input requirements will be explained in detail later. Finally, the power generation, maintenance and decommissioning phases will be presented in detail.

Table 4.2: Wind turbine main characteristics.

Parameters	Specifications	Sources
Rated power output/wind turbine	1.5 MW	(Khanh 2012b)
Number of wind turbines	20 Units	(Khanh 2012b)
Total installed capacity	30 MW	(Khanh 2012b)
Turbine manufacturer and models	Fuhrländer – Germany, FL MD - 77	(Khanh 2012b)
Location –town and state	Binh Thuan, Vietnam	(Khanh 2012b)
Wind farm owner	REVN	(Khanh 2012b)
Predicted life of nacelle (years)	20	(Khanh 2012b)
Capacity factor	0.31	Calculated
Full load hours	2715.6 h	Calculated
Cut –in wind speed (m/s)	4 m/s	(TrueWind Solutions LLC 2001)
Cut-out wind speed (m/s)	25 m/s	(TrueWind Solutions LLC 2001)
Average wind speed of specific site (m/s)	7.2 m/s	(TrueWind Solutions LLC 2001)
Hub height	60 m	(Khanh 2012b)
Blade length diameter	77 m	(Khanh 2012b)
Losses in Transmission	0.03	(ICONTEC 2012)
Lifetime of transformer	35 years	ABB 2003
Capacity of transformer	1x 45 MVA, 20x1.8MVA	(Khanh 2012b)
Annual production (excl. losses)	85 GWh	(Khanh 2012b)
Annual production (incl. losses)	82.45 GWh	calculated
Production over the life time (incl. losses)	1292.58 GWh	calculated
Length of transmission line 110 kV	1500 m	(Khanh 2012b)

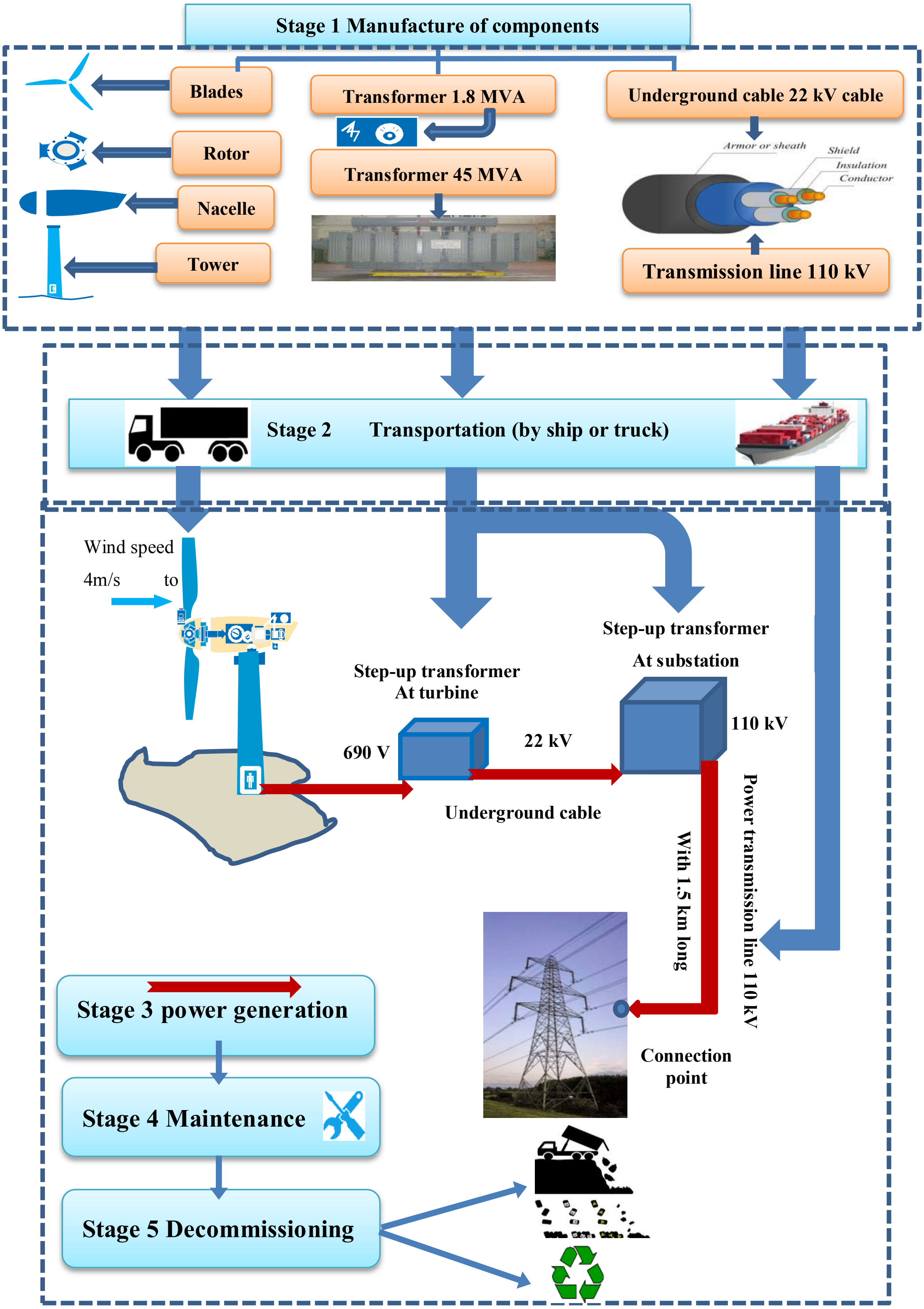

Figure 4.5: The inventory of the wind farm for the case study in Vietnam.

4.3.2 *Stage 1- manufacture of wind turbines, transformers, and electrical cable*

4.3.2.1 Stage 1 - Wind turbines production inventory

This section covers the first stage as described in Figure 4.5. This includes the manufacturing process and sub-processes of the main turbine components. The turbine in this study is a horizontal axis wind turbine type FL MD – 77. There are three main components: the rotor, nacelle, and tower, as shown in Figure 4.6. If the wind velocity is between the cut-in speed and the cut-out speed, which is referred to as the operating condition, power will be generated. The principles of operation can be simply presented. The wind energy is transmitted from the rotor hub to the gearbox via a low speed shaft and from the gearbox to the generator via a high-speed shaft. In this process, the wind energy is converted from the kinetic energy to mechanical energy. Inside the nacelle mechanical work is converted to electrical energy by an electrical generator (the generator used in the wind turbine here is Doubly Fed Induction Generator, DFIG (Fuhrlaender 2014)). This energy is then transmitted to the grid through step-up transformers.

The wind turbine inventory schematic description is modeled as an electricity production chain in Figure 4.7. The energy input and emission impacts from the resourcing of all the raw materials required to manufacture the turbine components have been calculated under this unit process. The construction of fixed and moving components has been separately displayed. All the inventory data is based on the material life cycle. The main components of nacelle, rotor and tower are described below.

a. The **nacelle** (Sterzinger & Svrcek 2004) is the covered plant room at a top the tower containing the main shaft, gearbox, generator, etc. It also contains all the internal electronic components. The yaw system is required to keep the turbine aligned with the wind direction. This requires the changes in wind speed and direction to be monitored.

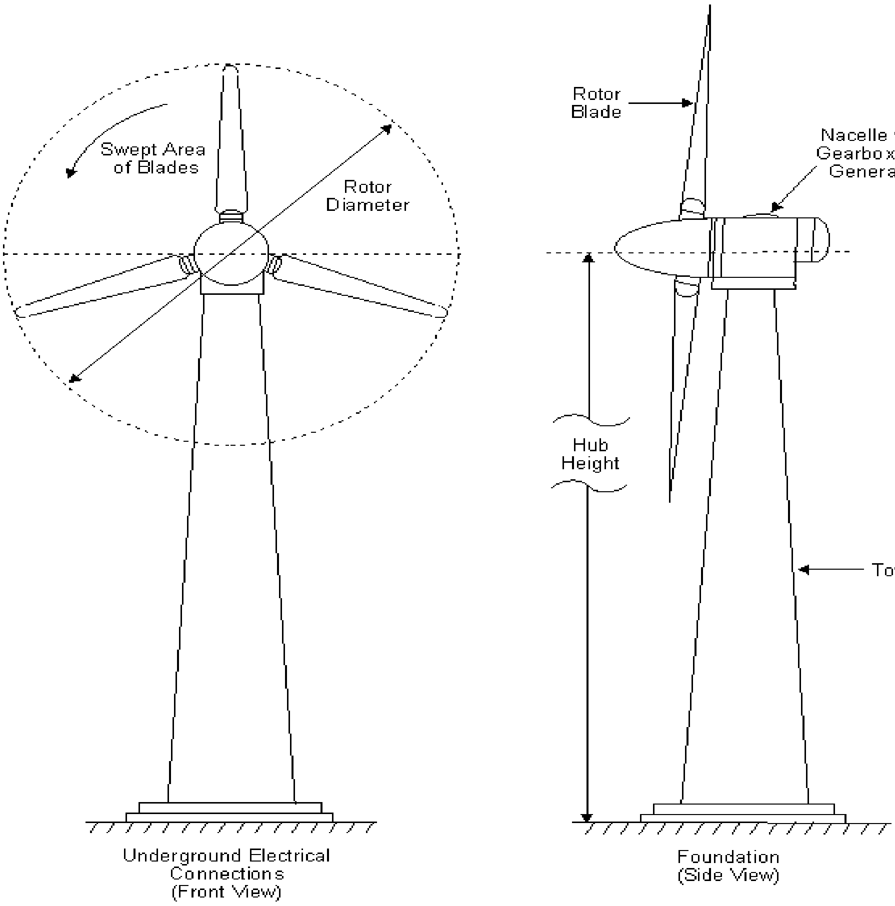

Figure 4.6: Wind turbine main components (source: wind turbine development: location of manufacturing activity- 2004 (Sterzinger & Svrcek 2004)).

The nacelle includes subcomponents:

- **Nacelle Cover** protecting the machinery inside from the weather.
- **Breaking System** with a mechanical friction brake and a **hydraulic system** to stop the turbine blades during maintenance and overhaul
- **A generator**: a DFIG to convert mechanical energy into electricity
- **A main shaft** including a low speed shaft and a high speed shaft which transmits the rotational energy to the generator via gearbox
- **A gearbox** which converts low-speed rotation from the input shaft of the rotor to high-speed rotation, which drives the high-speed shaft of the generator assembly. It is usually a spur/planetary type with 3 stages and a ratio of 1:104 (Fuhrlaender 2014).
- **Resolving systems** include electronics to control and monitor operation with sensors

Gear boxes, source: http://www.machinedesign.com/ASP/vie

b. **The rotor (Sterzinger & Svrcek 2004)** comprises of four main sub-components: the three blades, the blade extender, the hub and pitch drive system. In this study, the rotor diameter 77 m with a swept area 4657 m2. The subcomponents can be briefly described:

Hub with blade extenders

- **Blades** convert wind energy to mechanical energy. The main materials are fiberglass with reinforcing products, such as epoxy resin with steel.
- **Blade extenders** these steel components that to support the blades and secure them to the hub.
- **Hub** is the base for the blades and blade extenders and it contains the pitch control systems. It rotates and is attached to the nacelle using a shaft and bearing assembly. It is manufactured from cast iron or steel.
- **Pitch drive** this system controls the blades to achieve the optimum angle for the wind speed and desired rotational speed. Generally, there are three motors which are used to control the three blades. The power is either electrical or provided by hydraulics in the nacelle, and supplemented by a hydraulic accumulator in the event of system failure.

Pitch control systems source: internet

c. **The Tower** is primarily made from rolled steel tube or concrete depend on the size of the turbine**.** It is connected in a series of stages:

- **The Tower** is typically made of tubular steel, and built and shipped in sections because of its size and weight. Common tubular towers incorporate a ladder and lift within the hollow structure to provide maintenance access. The height of the example here is about 85 m with a weight of around 260 tons[a].
- **Flanges and bolts** are used to join each section.
- **A concrete base** supports the tower and delivers the loads to the foundation. The foundation size and type depends on the foundation conditions but is typically it is made from steel and reinforced concrete.

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[a] Source: *http://en.wind-turbine-models.com/turbines/357-fuhrl-nder-fl-md-77*

The other components or sub-components, including the transformers, circuit breakers, small lift or crane, electronic controllers, sensors, fiber optic cables, bolts, and ground-mounted electrical equipment are described here due to space constraints; however, if the amounts of these materials used are available from the manufacturing sources, these materials will also be calculated for energy input and emission output. The mass of paint used in the rotor, nacelle and tower is also excluded from the scope of this analysis because it was impossible to obtain secondary data sources from the manufacturers and it has of little effect on the final result.

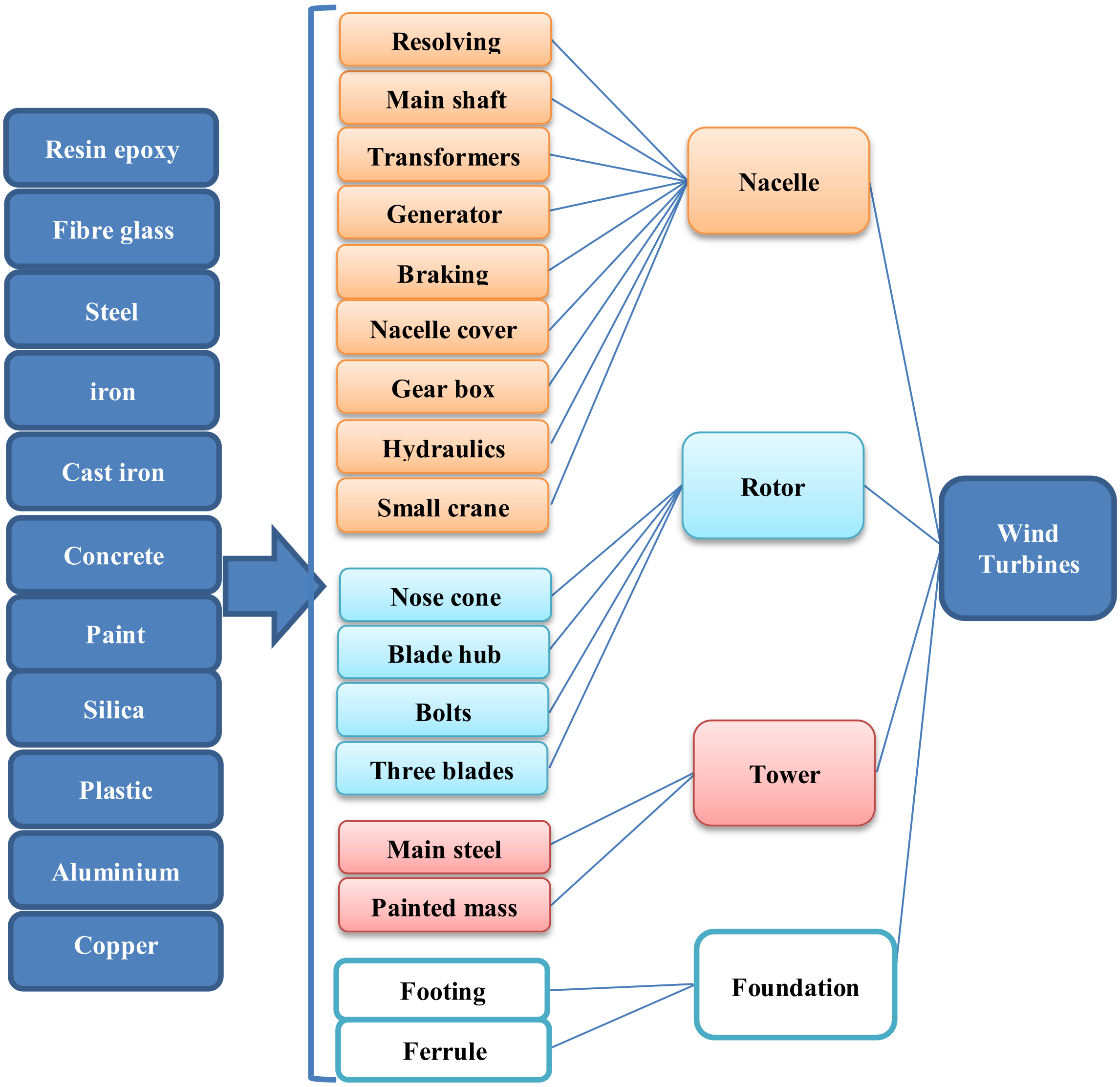

Figure 4.7: Life cycle inventory of wind turbine based the unit processes.

For the aim of this study, the detailed contribution of mass from the raw materials was considered. Table 4.3 shows the average weights of the nacelle, tower and rotor based on the data from Fuhrländer, Germany. The particular turbine used here, the FL MD – 77, is in the third column and it is compared with different wind turbines with the range of capacities, from 800 kW up to 2.3 MW, and from different manufacturers.

Table 4.3: The component weights from the manufacture[a].

Component	Sample Standard 800 kW[b]	FL MD – 77 1.5 MW[c]	IEC - IIA 2MW[d]	Siemens 2.3 MW[e]
Unit	weight (tons)			
Nacelle	20.2588	56	61	82
Rotor	14.7	33.4	37.85	62
Tower (85 m)	118.55	129.57	181.34	NA

The flow chart in Figure 4.5 shows the unit process of how the raw materials are formed to make the wind turbine components. The individual amount of raw material input for calculation comes from different academic references. Although there is a difficulty in accessing confidential data required for unit processes from some manufactures, one method in dealing with this is to collect data from standard suppliers and industrial sources; in addition, sometimes, academic literature publishes data that can be used in lieu of manufacturers' data. After this data is collected from reliable sources, it can be averaged and used as background data in a database; however, it should be understood that this data has not be collected from on-site construction or from a manufacture. This means the data requires careful assessment to see how well the database data meets the requirements that appear in the Goal and Scope conditions.

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[a] (Fuhrlaender 2014)

[b] The mass calculation based on table 4.4

[c] The mass calculation based on industrial sources http://www.fuhrlaender.de/en/fl-1500-gb

[d] The mass calculation based on (Guezuraga, Zauner & Pölz 2010)

[e] The mass calculation based on industrial sources http://www.energy.siemens.com/hq/en/renewable-energy/wind-power/platforms/g2-platform/wind-turbine-swt-2-3-101.htm#content=Technical%20Specification

For the LCA community, a full Ecoinvent database with more than 4000 processes is the most important reliable data source (Goedkoop et al. 2010b). This package has been well developed through prolonged work by a group of Swiss institutes. The Ecoinvent project was first made public in 2003 with the support from many Swiss Federal Offices, and then quickly became a database which LCA analysts use for their assessments.

To calculate the contributions of the individual amounts of input material for the FL MD - 77 1.5 MW turbine, some basic unit processes of the 800 kW turbine were taken from the Ecoinvent database 2.2 and used as sample standard units. With the calculated percentages of materials from the various wind turbine components in the sample 800 kW, the input data was calculated for the FL MD – 77 using scaling based on the percentage of the sample.

The following reasons explain why the 800 kW wind turbine was selected:

- Due to time and cost limitations of the time and cost, it has to be accepted that some assumptions regarding to the components have to be made, and data is obtained from non-direct means when the specific data for a wind turbine component or sub-subcomponent is not available, However, similar data is available from SimaPro 7 and Ecoinvent 2.2 for alternative turbines, and there is a degree of standardization in wind turbine design.
- The LCA of twenty land-based FL MD - 77 wind turbines has been investigated in Vietnam; however, the major wind turbine component production was in Germany. The sample standard turbine 800kW turbine was also produced in Germany so that the data between the two should be similar.
- According to a report from Sima Pro 7 2010, the 800 kW wind turbine has been benchmarked as the average onshore wind turbine in European countries. In addition, both wind turbines were produced in the same period in 2007 with similar technology levels. Hence, the sample can meet the requirements for temporal correlation of FL MD - 77 data in order to mitigate the error of estimation in the LCA methodology.
- The 800 kW turbine has a three-bladed rotor which is 50 m in diameter and a tower that is 85 m high (Swiss Centre for Life Cycle Inventories 2007). These are

similar to the characteristics of FL MD – 77 (Fuhrländer AG), although there is some scaling to carry out. There is some correlation between the weight and the power output of a wind turbine; the output power is given by Burton (Burton et al. 2011)

$$P = \frac{1}{2} C_P A U^3 \tag{4.2}$$

Where: ρ is the density of air (1.25 kg/m^3);

C_P is the power coefficient defined as a fraction of the wind power that can be converted into rotational work by the turbine; and

A is the rotor swept area; U is the wind speed.

As can be seen from (4.2), the turbine output power is obtained using ρ, C_P, A and U. Under similar conditions, ρ, U in the same wind regime are considered as constant. Therefore, the rated power has to be calculated using the power coefficient and the swept area of the rotor. While improvement in the power coefficient is possible by design change, this is a slow iterative process in the evolution of the technology (and limited by the Betz constant). The other obvious way to raise the output power is to increase the swept area of the rotor (Burton et al. 2011). The swept area A is governed by the blade length:

$$A = \pi r^2$$

Where r is the length of one blade

The increased output power obviously leads to a larger size of wind turbine. This can be seen when comparing the weights and the rated powers in Table 4.3. When the power capacity rises from 800 kW to 2.3 MW, the mass of the total wind turbine also increases considerably. The assumption is that the tower is of the same height but the weight changes when the rotor diameter increases – it needs to be heavier and stronger in higher power turbines. For this reason, the particular material composition of the FL MD - 77 was calculated based on the percentage of mass in each material in main components of the 800 kW wind turbine.

Table 4.4: Material use for the main components of 800 kW onshore wind turbine.

Main components	Sub-components	Material	Mass [kg]	Per unit calc.
Rotor	Blades	Glass fiber reinforced plastics	8400[a]	**0.571**
	Blade extender	Chromium steel	3100	**0.211**
	Hub	Cast iron	3200	**0.218**
	Pitch drive	NA	0	**0**
Nacelle				**1**
Mechanicals parts	Shaft	Steel, low alloyed	3100	**0.265**
	Main bearing	Cast iron	251[a,b]	**0.021**
		Chromium steel	251	**0.021**
	Gearbox [c]	Cast iron	2200	**0.188**
		Chromium steel	2200	**0.188**
		Rubber	100	**0.009**
	Generator	Cast iron	828[d]	**0.071**
		Chromium steel	2173	**0.186**
		Aluminum 0% recycle	207	**0.018**
		Copper	242	**0.021**
	Brake	Chromium steel	150[e]	**0.013**
Casting	Frame Cover	Chromium steel	5652[f]	**0.818**
		Glass fibre reinforced plastics	1261[g]	**0.182**
Yaw system	Ball bearing	Steel, low alloyed	585	**0.539**
	Drive	Chromium steel	300[h]	**0.276**
	Brake	Chromium steel	200	**0.184**
	Hydraulic system	Chromium steel	500	**0.895**
		Lubricant	58.5	**0.105**
Tower (85 m)		Steel, low alloyed	69375[i]	**0.995**
		Epoxy resin	360[j]	**0.005**
Basement		Concrete	102m^3 [k]	**0.941**
		Reinforcing steel	14000	**0.059**

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[a] Mass from (Nordex 2001)

[b] Own estimation of shares of materials 50% cast iron and 50% chromium steel, materials from (Nordex 2001).

[c] Rubber estimated. Other materials from (Nordex 2001), assuming 50% weight for each.

[d] Mass of Generator from (Nordex 2001).

[e] Own assumption for mass and material.

[f] Total mass of nacelle from (Nordex 2001).

[g] 0.5% of total weight (incl. basement) of the turbine, (Communication with M.Lenzen, 17.6.02).

[h] Own assumption for mass and material.

[i] Mass of tower: 60300 kg (Nordex 2001), additionally 15% for internals, plus 30 kg for welding (as soldering metal).

[j] 0.25 kg paint per m^2 surface and coat (Hagedorn 1991); 2 coats (Nordex 2001).

[k] 4500 kg concrete/m height, 280 kg reinforcing steel/m height (Steinemann D.,29.11.2001, ABB Energie Services Switzerland), density of concrete: 2200 kg/m^3.

Table 4.4 shows detailed data of the main materials used for the manufacturing of the different sub-components in the 800 kW wind turbine. The data is available in a German report or can be retrievable directly from the Ecoinvent 2.2 database. The material weights are based on information from particular manufacturers, as given in the footnotes references to the table. For some parts, such as the nacelle, only the total mass is available so that estimates of its components are subject to high uncertainty. In the fourth column, the per-unit values of the different materials required to make main components and these proportions are used for FL MD – 77 when the scaling was carried out, with the total mass of rotor, nacelle and tower coming from Table 4.3.

Based on the per-unit values in Table 4.4, the input data for the FL MD – 77, which is a 1.5 MW turbine, were determined by scaling up with the same per unit of different materials. The input material ratio for turbines was taken as 1.5 and used in Table 4.5 when the actual vale is not known.

Table 4.5: The calculation of mass of different material in FL MD – 77 1.5 MW.

Main components	**Total Weight [Tons]**	**Sub-components**	**Material**	**Mass [tons]**	**Per unit cal.**[a]
Rotor	**33.4**	Blades	Glass fiber reinforced plastics	**19.071**	**0.571**
		Blade extender	Chromium steel	**7.047**	**0.211**
		Hub	Cast iron	**7.281**	**0.218**
		Pitch drive	NA	**0**	**0**
Nacelle					**1**
Mechanicals parts	**56**	Shaft	Steel, low alloyed	**8.568**	**0.153**
		Main bearing	Cast iron	**0.672**	**0.012**
			Chromium steel	**0.672**	**0.012**
		Gearbox	Cast iron	**6.104**	**0.109**
			Chromium steel	**6.104**	**0.109**
			Rubber	**0.28**	**0.005**
		Generator	Cast iron	**2.296**	**0.041**
			Chromium steel	**5.992**	**0.107**
			Aluminum 0% recycle	**0.56**	**0.01**
			Copper	**0.672**	**0.012**
		Brake	Chromium steel	**0.392**	**0.007**
Casting		Frame Cover	Chromium steel	**15.624**	**0.279**
			Glass fibre reinforced plastics	**3.472**	**0.062**
Yaw system		Ball bearing	Steel, low alloyed	**1.624**	**0.029**
		Drive	Chromium steel	**0.84**	**0.015**
		brake	Chromium steel	**0.56**	**0.01**
		Hydraulic system	Chromium steel	**1.4**	**0.025**
			Lubricant	**0.168**	**0.003**
Tower (85 m)	**129.57**		Steel, low alloyed	**128.922**	**0.995**
			Epoxy resin	**0.648**	**0.005**
Basement	**NA**[b]	**NA**	Concrete	**NA**	**0.941**
			Reinforcing steel	**NA**	**0.059**

Based on the measurement of the foundations of one wind turbine, the volume of one base is about 200 m^3, with main materials being concrete and reinforcing steel. It is assumed that the density of concrete is approximately 2360 kg/m^3 and that the total mass of the base is obtained from

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[a] Per unit cal. – per unit of component calculated by this study

[b] NA – Note Available

$$\begin{aligned}&\text{mass} = \text{density} \times \text{total volume}\\&\text{mass} = 2360\ [\text{kg/m}^3] \times 200^3 = 472000\ \text{kg}\end{aligned} \qquad (4.3)$$

The mass of a base is 472 tons, based on the per-unit contribution of the base in Table 4.5, the concrete weight will be 444.15 tons, and 27.85 tons of reinforcing steel.

To conclude with this section, Table 4.6 lists the mass distributions for both individual wind turbines and the wind farm as a whole.

Table 4.6: Material distribution in wind turbine.

	Rotor mass [ton]		**Nacelle [ton]**		**Tower [ton]**		**Basement [ton]**	
Material	**A**[a]	**B**[b]	**A**	**B**	**A**	**B**	**A**	**B**
Glass fiber reinforced plastics	19.071	381.42	3.472	69.44				
Chromium steel	7.047	140.94	31.620	632.4				
Cast iron	7.281	145.62	9.072	181.44				
Steel, low alloyed			10.192	203.84	128.922	2578.44		
Rubber			0.28	5.6				
Aluminum 0% recycle			0.56	11.2				
Copper			0.672	13.44				
Lubricant			0.168	3.36				
Epoxy resin					0.648	12.96		
Concrete							444.152	8883.04
Reinforcing steel							27.848	556.96

4.3.2.2 Stage 1 - transformer production inventory

In this life cycle research assessment, there are twenty medium step-up transformers, one at the base of each wind turbine. They step the voltage from 690 V up to 22 kV before transmitting electricity to a step-up transformer sub-station which further steps up the voltage to 110 kV (called the collection sub-station (Negraa, Todorovicb & Ackermann July 2006)) which supplies the national grid.

As previously mentioned, the base transformers are 1.8 MVA and considered medium in size. The large substation transformer is 45 MVA. The life cycle of both transformer types is predicted to be up to 35 years. They are manufactured by ABB Vietnam who are part

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[a] - one turbine unit 1.5 MW

[b] - twenty wind turbine units of 1.5 MW each

of the worldwide ABB group (ABB Vietnam 2014). To determine the production assessments of these transformers, there are many modeled unit processes in their life cycle inventory as illustrated in Figure 4.8.

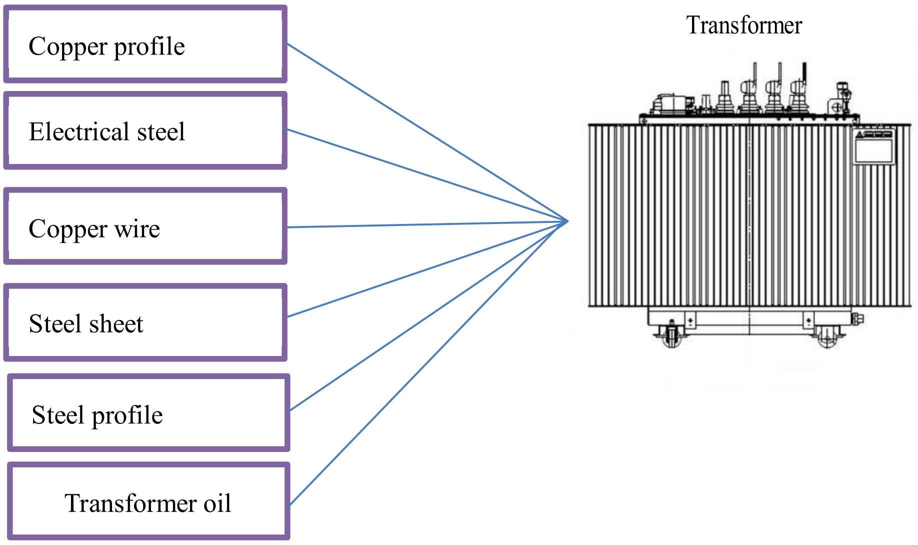

Figure 4.8: The life cycle inventory of one standard transformer.

For the substation transformer, according to ABB (ABB T&D S.p.A. Unità Operativa Trasformatori 2003), the design and manufacture of their transformers with the range capacity from 40 to 50 MVA is derived from the concept of TrafoStar. This is considered to be a common technology design system. The transformer is tailored to fit the application from standardized components and modules. More recently they have been producing a completely new concept ABB transformer. However, in this study, in order to calculate the raw material required to produce an ABB transformer, the standard TrafoStar transformer is used to estimate the environmental impacts which have a significant level of ± 5 %**.** If the amount of materials in this transformer is less than 2 % of the total weight of transformer, these materials are ignored in the life cycle assessment because of their small impact on the final results. The functional unit of a transformer, generally is 1 MVA, are referred to in PSR 2000:6 (Product Specific Requirements for "Liquid- or gas-filled and dry type transformers within the range of < 1000 MVA" version 1.1 dated 2001-02-21) and MSR 1999:2 (ISO TR14025 27-03-2000).

Turning to the medium sized 1.8 MVA transformers, the data collection from two ABB transformers was used. These were 1.6 MVA and 20 MVA. It is assumed that the weight of transformer increases linearly with MVA rating so that the weight of the 1.8 MVA transformer could be determined as an interpolation between 1.6 MVA and 20 MVA.

Table 4.7: List the main material required in manufacture phase of the transformer 45 MVA calculated from Environmental Product Declaration Power Transformers 40/50 MVA, 2003[a].

Materials	Kg/transformer [b]	kg/MVA [cal.][c]	P.U. mass [cal.]
Copper profile	8788	195.29	0.146
Electrical steel	20050	445.56	0.333
Steel sheet	8258	184.11	0.137
Steel profile	7600	168.89	0.126
Transformer oil	15500	344.44	0.257

Table 4.8: List main materials required in manufacture phase of transformer 1.8 MVA[d].

Materials	Kg/transformer [e]	Kg of 20 TBs	kg/MVA [cal.][f]	P.U. mass [cal.][g]
Copper profile	566.685	11333.7	314.825	0.126
Electrical steel	1497.668	29953.35	832.0375	0.333
Steel sheet	791.56	15831.2	439.7556	0.176
Steel profile	683.62	13672.4	379.7889	0.152
Transformer oil	960	19159.35	314.825	0.213
Total weight	4497.5	49972.222	89950	1

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[a] (ABB T&D S.p.A. Unità Operativa Trasformatori 2003)

[b] The weight of transformers with the range from 40-50 MVA is unchanged while the contribution of different materials changes with the power capacity.

[c] Cal. Calculation based on this thesis

[d] Calculation based on the mean of both values of the 1.6 and 2.0 MVA transformers, and the total transformer base.

[e] The weight of the 1.8 MVA transformer is calculated based on the average mass between 1.6 and 2.0 MVA

[f] Cal. calculation based on this thesis

[g] Per-unit estimate based on the statistical averages of 40-50 MVA (ABB T&D S.p.A. Unità Operativa Trasformatori 2003)

4.3.2.3 *Stage 1- manufacture of transmission line 110 kV and underground cable 22kV*

The electricity is generated in an AC form and transmitted to the national grid network through several voltage stages. From the report about this wind farm (Khanh 2012b), the cables were chosen to be 22 kV with an underground installation method. This can be seen in Figure 4.2 and this is due to the turbines and 22/110 kV collection substation being very close in proximity.

The manufacturing life cycle inventory for transmission line is given in Figure 4.9. All the raw materials and manufacturing unit processes used to make the 22 kV and 110 kV transmission lines are presented. The assumptions made were that the lifetime of both cables is 30 years. Both cables were made from three copper conductors; the density of copper of wire is 8.93 kg/cm^3.

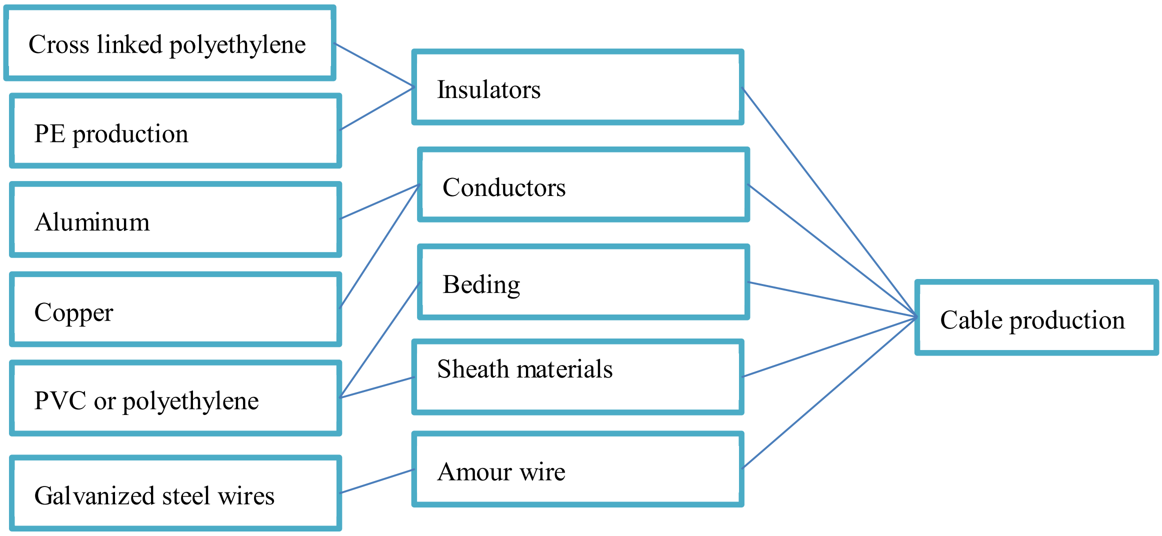


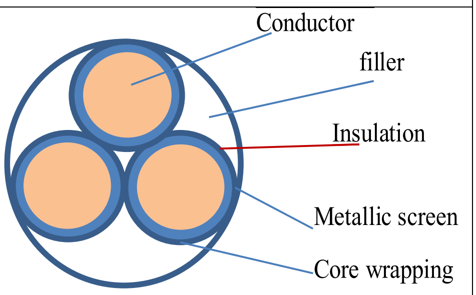
Figure 4.9: Life cycle inventory of basic cable in manufacture stage.

The cables studied here are the 22 kV cable and the 110 kV cable:

<u>22 kV cable</u>

Sheathed 22 kV high voltage alternating current (HVAC) cable is used extensively in this project and there are three main categories in the manufacturing of this component. The outer protective sheath, which is typically a different type of plastic or nonmetallic sheath from the individual conductor insulation, is polypropylene. The insulation layer uses common fire-retardant cross-linked polyethylene (TR-XLPE) which complies with TCVN 5844:1994 (Ministry of Science and Technology Vietnam 1994). The conductor is made from copper. The function of the outer layer is to prevent damage to the cable from its environmental surroundings as well as to offer some fire protection. It is also required to offer protection from insects such as the ants (Ergon Energy Corporation Limited). This cable is only used to transmit power between the base transformers at wind turbines and the 45 MVA high voltage transformer in the substation. Although the material requirements for the 22 kV cable are taken from a product sheet in a report on the first wind farm in Vietnam, it is not possible to obtain the raw data for manufacturing this cable. As mentioned above, a quasi-process needs to be set up in order to estimate the appropriate value of the material inputs. To do this, the published material data for a 20 kV underground cable from an existing ABB project in 2010 [24] was employed. This was for a cable in Europe. The technical data is given in Table 4.9.

Table 4.9: Technical data for the 22 kV used in the study.

Technical data	**Specification**
Cable type	HVAC
Voltage ± 22 kV	 22kV three core copper conductors
Voltage max	24 kV
Insulation	XLPE (cross linked polyethylene)
Conductor	Three core copper conductor
Life time assumption	30 years
Cross sectional conductor	630 mm^2
Cross section of metallic screen	16 mm^2
Insulation thickness	5.5 mm
Diameter of conductor	29.8 mm
Diameter over insulation	43.6 mm
Outer diameter of cable	134 mm
Cable weight of copper	38.5 kg/m
Density of copper wire	8930 kg/m^3

The mean length of the 22 kV cables used in wind farm using the lay-out map of wind farm is designed in Figure 4.1 and via personal communication with representatives (Khanh 2012b). There are three wind turbine lines on the map with the distance between two consecutive rows being about 1000 m. The spacing between two wind turbines in one row is estimated to be approximately 500 m. After calculation, the average length of one 22 kV underground cable is approximately 10,500 m. The weight per meter of underground cable was considered to be a functional unit, so that the definition of the density of the material is its mass per unit volume. The solution for calculation of mass of total copper is

$$\text{Mass of copper [kg]} = \text{density [kg/m}^3\text{]} \times \text{volume [m}^3\text{]} \tag{4.4}$$

According to Table 4.9, for one copper conductor, the area is nearly 630 mm^2 (0.00063 m2), so the volume of a 1 meter long section of conductor is $0.00063 \times 1 = 0.00063$ m^3 From (4.4) we have:

$$\text{Mass of copper/conductor} = 8930 \text{ [kg/m}^3\text{]} \times 0.00063 \text{ [m}^3\text{]} = 5.63 \text{ kg/m} \tag{4.5}$$

That leads to the total weight of copper in 1 m of cable with three cores as 16.88 kg/m. The main materials in the 22 kV cable are given in Table 4.10, the calculation of the mass of the insulation of both XLPE and polypropylene can be carried out as follows. From Table 4.9, for one phase conductor, the diameter of the insulation layer is about 43.6 mm, while the diameter of one conductor is 29.8 mm. The area of XLPE can be calculated from π (43.6 -22)2/4 = 336.432 mm^2; for three phases this is then 1099.30 mm^2. The mass of XLPE in 1 m is approximately 1 kg/m. This assumes that the mass of polypropylene is equal to the mass of XLPE in 1 meter long.

Table 4.10: Cabling materials of 22 kV per metre.

Material	**Copper**	**XLPE**[a]	**Polypropylene**[b]	**Steel pipe** [c]	**Lead**[d]
Weight	16.88 kg/m	1 kg/m	1 kg/m	2.2 kg/m	4.52 kg/m

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[a] Density of XLPE is 0.93gcm $^{-3}$ in normal condition

[b] Density of Polypropylene is 0.855 g.cm^{-3} in room temperature

[c] Density of steel pipe is 7.850 g.cm^{-3} in normal condition

[d] Desity of lead is 11.34 g.cm^{-3} in room temperature

110 kV cable

Table 4.11 shows the detailed technical data collected from the product sheets of ABB in 2010 (ABB 2010). Figure 4.10 illustrates the typical construction of the 110 kV transmission line which is used to connect the 45 MVA transformer to the national grid connection point. There are three copper conductors in the cable in a trefoil formation with cross-linked polyethylene insulation (XLPE) and a lead sheath that is included with the steel armour. The length of the 110 kV transmission line in this study is approximately 1.5 km, from the collection substation location to the national connection point as shown in Figure 4.2. The manufacturing stage shows all of the raw materials and manufacturing processes applied to make the main components of the 110 kV transmission line. The material requirements for the 110 kV cable are given in Table 4.11.

Table 4.11: Technical data of 110 kV cables used in the transmission sytem with the performance of one conductor with wire amour.

Technical data	**Specification**
Cable type	HVAC
Voltage	± 110 kV
Voltage max	123 kV
Insulation	XLPE (cross linked polyethylene)
Conductor	Three core copper conductor
Life time assumption	30 years
Cross sectional of conductor	630 mm^2
Insulation thickness	13 mm
Diameter of conductor	29.8 mm
Diameter over insulation	58.6 mm
Lead sheath thickness	2.3 mm
Outer diameter of cable	176 mm
Cable weight of copper	60.7 kg/m
Density of copper wire	8930 kg/m^3

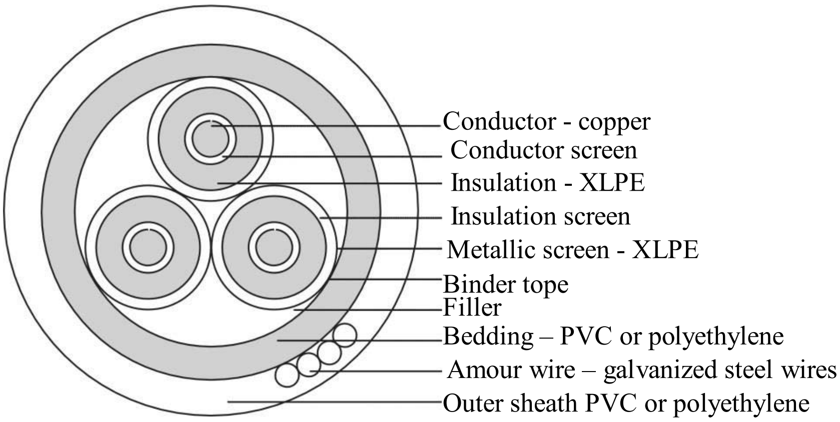

Figure 4.10: Illustration of the high voltage three core XLPE insulated power cable.

The material component amounts for the 110 kV cables are calculated using the technical data from ABB in 2010 [25]. The different material layers in the cable are given in the data sheets provided so that material amounts can be calculated by using the different material densities. When the cross-sectional areas are calculated as well as the every cable length then it is relatively straightforward to calculate the material amount. The calculation for copper assumes an area of 630 mm^2 and a conductor diameter of 29.8mm. Mass of copper per meter is 16.88 kg/m. Table 4.12 presents the input material data for manufacturing one meter of 110 kV transmission line.

Table 4.12: Life cycle inventory of 110 kV cable.

Material	Copper	XLPE	Polypropylene	Steel pipe	Lead
Weight (kg/km)	16.88 kg/m	9.06 kg/m	4.53 kg/m	16.88 kg/m	13.354 kg/m

4.3.3 *Stage 2 – Transportation and installation*

4.3.3.1 Stage 2 – Transportation of main turbine components

There are some assumptions that have to be made for the transportation and construction stages. It should be first mentioned that the transportation of raw materials and sub-components to the turbine manufacturer are not calculated in this section. For example, the gearbox manufacturer was Dorstener, Winergy and Eickhoff. While the transportation of the gearbox to Fuhrländer could be included in the Fuhrländer assessment it is not because it is impossible to trace with their movement. In addition, the complete raw material supply chain is difficult to assess and it is also relatively insignificant. A second point to make is that the movement of all components from the manufacturer to the ship transportation, and from the docked ship to the erection site, was estimated using road transport and standard diesel fuel usage in that particular country. For example, for delivery of the 45 MVA transformer from Australia to the substation, the fuel emissions were calculated from the Australian manufacturer to the Australian port for shipping using Australian fuel emission standards. From here to the Port of Nhatrang, international shipping standard emissions were used. These shipping standards were used no matter where the components were shipped from, including Europe.

As discussed earlier, the two main components of wind turbine, the rotor and nacelle, were manufactured in Germany and transported to Binh Thuan, Vietnam. Clearly, this is a substantial amount of transport. Their journey start is Liebenscheid in Germany and it is assumed that from there they delivered via diesel tractor to the Port of Rotterdam, and then moved by cargo ship to Nhatrang in Veitnam and then by road transport to the construction site. The calculated travelling distances given in Table 4.13 with further detailing in Appendix C. The foundations and tower, however, were manufactured in Vietnam in order to reduce the cost of investment. The tower was manufactured UBI in the Hai Duong province, Vietnam and turbine foundation constructed by HaSon JSC (Khanh 2012b), the transport distances are given in Table 4.14.

Table 4.13: Distance travelled of rotor and nacelle.

Main components		Departure	Destination	Mode of transport	Fuel	Distance travelled [km]	Reference
Rotor and nacelle	Step 1	Fuhrländer AG, GER[a]	Port of Rotterdam, NE[b]	Truck	Diesel	377	(Google Map 2014)
	Step 2	Port of Rotterdam, NE	Port of Nhatrang, VN[c]	Cargo ship	Diesel	17,422	(Petromedia Ltd 2014)
	Step 3	Port of Nhatrang, VN	Project site, VN	Truck	Diesel	243	(Google Map 2014)

Table 4.14: Distance travelled of tower and foundation.

Main components	Departure	Destination	Mode of transport	Fuel	Distance travelled [km]	References
Tower	Hai Duong province, VN	Project site	Truck	Diesel	1,587	(Google Map 2014)
Foundation	Nhatrang, VN	Project site	Truck	Diesel	243	(Google Map 2014)

To construct the foundations of the wind turbines, an excavator needed to dig the holes. After this, the concrete and reinforced steel bases were constructed. For the foundation construction and erection of the turbines, a 550 ton crane was required which was supplied by Urban Infrastructure Investment (UBI), Business JSC. The turbine foundation construction was supervised by Fuhrländer and the Big Bridge-Tunnel Design Company (TEDI) (Khanh 2012b). However, the data for construction and the total hours logged by the crane and the excavator were not published since it is proprietary information. For this reason, another quasi-process for construction phase must be implemented using the database and literature review of a full assessment of wind farm life cycle. According to Carbone 2009 (Carbone 2009), the average of foundation pour

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[a] GER stands for Germany
[b] NE stands for Netherland
[c] VN stands for Vietnam

per day was estimated using personal information collected from industry workers; this is given in Table 4.15.

Table 4.15: Construction data used for erection of turbines bases.

Process	Number of foundations	Number of foundations per day	Working hours assumed 8 hours/day	Average number of Equipment hours
Dig foundation hole (excavator)	20	1	8	160
Pour concrete (cement mixer)	20	1.5	8	240
Pour concrete (concrete pump)	20	1.5	8	240
Total hours				640

4.3.3.2 Stage 2 – Transportation and installation of transformers and cables

The turbine transformers and electrical cables were manufactured by ABB High Voltage and Medium Voltage Power Products factory in Bac Ninh. Therefore the transportation distance from the factory to the construction site was estimated using Google Maps with the assumption is that a truck was used in all transportation. Further details are in Appendix C. Table 4.16 gives the distance.

Table 4.16: The distance of transportation of transformers and cables.

Main components	Departure	Destination	Mode of transport	Fuel	Distance travelled [km]	References
Transformers	Bac Ninh, VN	Project site	Truck	Diesel	1578	(Google Map 2014)
Electrical cables	Bac Ninh, VN	Project site	Truck	Diesel	1578	(Google Map 2014)

There is no construction information for the erection of the turbine transformers. It was assumed that the transformer was installed using the 550 t crane already found on-site and in use for the day and the effective time for successful installation of one HV transformer was estimated from 48 to 72 hours by Rambo 2009 (Rambøll 2009). Hence the effective time for installation of the cables is estimated to be about 14 days for all the wind turbines as shown in Table 4.17.

Table 4.17: The total hours for installation of transformers and cable.

Installation	Number of units	Number of estimated hours per one unit	Average estimated hours per one unit	Total number of equipment installation hours
Transformers 1.8 MVA	20	48-72	60	1,200
Transformers 45 MVA	1	48 -72	60	60

4.3.4 *Stage 3 and 4 – power generation and maintenance*

4.3.4.1 Stage 3 and 4 – operation and maintenance of wind turbines

The wind farm is operated under remote control from a local control centre. During the life cycle assessment of the wind farm the environmental impact parameters associated with operation are quite small, the energy input required for the power production such as yaw and rotor pitch control, was estimated as 1 % of total electricity generated by the wind turbine (Guezuraga, Zauner & Pölz 2010). This is illustrated in Table 4.18.

Table 4.18: The total energy input for operation process.

Operation process	Total electricity output including annual loss	1 % of all wind farm annually
Energy input require	82.45 GWh	0.8245 GWh

For the maintenance process, there are three main types of maintenance services, namely inspection, repair systems and replacement of parts. For inspection purposes, a vehicle is used to and from the turbines twice per year. As can be seen in Figure 4.1, the utilized area of the wind farm is not large but it is spread over a large area. The travelled distances for maintenance were calculated as shown in Table 4.19.

Table 4.19: Total inspection and maintenance of wind farm.

Maintenance	Fuel	Distance			
		[km]	x 2 [km]	1 year [km]	30 years [km]
Inspection by car	Diesel	20	40	40	1200

Data for component replacement due to failure is needed. During the repair and replacement process, a car and small crane is assumed to be used and data can be compiled for this. However, there is little detailed information available about the maintenance approach for a wind turbine, so that the maintenance stage is mainly based on the local conditions for operational hours and weather, and the resultant maintenance schedule. According to the Elforsk report (Bertling, Tjernberg & Wennerhag 2012), the average lifetime of a gearbox is between eight and ten years, so the gearbox life in this study is assumed to be nine years, when it has to be replaced. In addition, the moving components, such as the rotor and hub, are estimated to be replaced after a twenty year period (Jungbluth et al. 2004). Therefore, the maintenance impacts must include the materials used, manufacturing processes used, the distances traveled, and the installation processes needed for the components of twenty turbines. The calculation of the materials, manufacturing processes and distances traveled are determined using the data as calculated previously for new manufacture and installation. The calculations for the maintenance and operations are presented in Appendix D.

4.3.4.2 Stage 3 and 4 – operation and maintenance of transformers

The transformers have a life cycle up to 40 years. They transit electrical power and also there are electric and magnetic fields associated with them. There is interest in the potential health risks presented by these magnetic fields. However, this is not main focus of this research. For this reason it is assumed that under operation and maintenance, the transformers have minimum impacts on the environment so they can be neglected.

4.3.4.3 Stage 3 and 4 – operation and maintenance of electrical cable

Although it is assumed that the cable and transmission line life cycle will be forty years, the documentation for the processes in the Ecoinvent 2.2 database indicates that the lifetime of underground cables is only thirty years and will therefore be scrapped when the wind farm is decommissioned. For inspection of the transmission line, an average of one week annually is assumed. The cabling system in SimaPro is shown in Appendix D.

4.3.5 *Stage 5 – decommissioning*

4.3.5.1 Stage 5 – decommissioning of wind farm

The dismantling of a wind farm has never been carried out in Vietnam, so that there is no database and supporting industry available for the task of dismantling, disposal and recycling. Another difficulty is the uncertainty of knowing how this will be done and what can be recycled and what will be reused. For that reason there are assumptions based on previous studies made for this stage. Firstly it is assumed that the decommissioning process is equal the construction process (Fulvio Ardente 2008), which allows the accounting of the impacts of the disassembly process. Since metal material, such as steel, copper and aluminium, are easy to recycle, as discussed in several European academic sources (Fleck & Huot 2009), it is assumed that all recycled metal components would be re-manufactured into other components such as future turbines. This can be treated as raw material. Furthermore, a recycling factory was assumed to be located in suburb of Ho Chi Minh City, with the distance between the project site and recycling plant estimated to be 450 km (Google Map 2014). The waste remaining after dismantling would be transported to landfill with assumption of distance from the wind farm to landfill being 50 km. Assumptions involved in data and the unit processes, the relevant data references, are shown in Table 4.20.

Table 4.20: Material type and disposal method considered.

Material type	Removal Scenario	Reference
Iron	90% Recovery 10% losses in landfill	(Vetas July, 2006)
Cast iron	90% Recovery 10% losses in landfill	(Vetas July, 2006)
Steel	90% Recovery 10% losses in landfill	(Vetas July, 2006)
Stainless steel	90% Recovery 10% losses in landfill	(Vetas July, 2006)
High-strength steel	90% Recovery 10% losses in landfill	(Vetas July, 2006)
Lead	90% Recovery 10% losses in landfill	(Vetas July, 2006)
Aluminum	90% Recovery 10% losses in landfill	(Vetas July, 2006)
Copper	95 % recovery 5% losses in landfill	(Martınez et al. 2008)
Epoxy	Landfill 100%	(Martınez et al. 2008)
Concrete	Landfill 100%	(Martınez et al. 2008)
Plastic PVC	Landfill 100%	(Vetas July, 2006)
Other plastics	Combusted 100%	(Vetas July, 2006)
Rubber	Combusted 100%	(Vetas July, 2006)
Fibre glass	Landfill 100%	(Vetas July, 2006)
Oil	Combusted 100%	(Vetas July, 2006)

4.3.5.2 Stage 5 – decommissioning of transformers

The transformers made mainly from copper, steel, concrete and oil while there is only the metal material recycled as shown in table 4.20. It is assumed that all recycled materials are transported to Ho Chi Minh City. The concrete foundation however, is sent to the nearest demolition landfill as previously presented. An estimate of 50 km is used from the wind farm to landfill.

4.3.5.3 Stage 5 – decommissioning of cable and transmission line

At the end of the life cycle of the cable, which includes the copper, steel, PVC, conducting wire and polyethylene materials, they can be recycled. For removal of the underground system, an excavator must be used; the impact of this uses the same calculation as construction process. It is assumed that all copper and steel can be recycled. The materials within the transmission lines are assumed to be disposed of in the following way. All aluminum from the conductor is salvaged and sold for recycling purposes. All steel from the wires is sold to scrap metal dealers for reuse purposes. The remainder of the materials is sent to demolition landfills. It is assumed that all materials are shipped to their various disposal locations via tractor-trailer. In addition to the transportation of the transmission line materials, the construction equipment used must also be transported onsite. The transportation is similar to transformer process. All necessary equations, and the processes used to represent them in SimaPro, are listed in Appendix C.

4.3.6 ***Inventory Analysis Calculation***

The calculation of the Life Cycle Inventory dataset mainly uses the “matrix method” via the process structure. How to calculate this is presented in the next section. The results are clearly presented in two tables; the input and output and the database of the inventory lists can be listed in a spreadsheet such as an Excel workbook, for Environmental Impact Assessment. The first step before calculating the inventory is to tabulate the emissions factors and energy values for every material in the various products. This must be calculated or estimated for 1 kg of material; each factor must be identified by summing the corresponding impacts for every material or product in the life cycle steps. The Table 4.21 shows the factors for the material manufacture, operation, recycling and landfill.

Due to the limitation of time and budget, some emission factors from the recycling processes were difficult to obtain but these were for processes with very small contributions to the entire life cycle impact assessment, and so had a negligible effect.

Table 4.21: Emission per kg material produced and energy embodied in the unit processes.

No.	Material (1kg)	CO_2 [g]	SO_2 [g]	NOx [g]	N_2O [g]	CH_4 [g]	NMVOC [g]	CO [g]	Sources
1	Steel carbon/low alloyed/ Chromium	2,306.50	14.50	9.50	0.070	0.040	0.160	0.930	(White & Kulcinski 2000)
2	Steel stainless	3,275.00	14.50	9.50	0.070	0.040	0.160	0.930	(White & Kulcinski 2000)
3	Rebar steel	2,163.83	6.62	2.88	0.070	0.100	3.740	26.530	(Schleisner 2000)
4	Aluminum	3,433.50	21	13.00	0.105	0.065	0.145	0.745	(Schleisner 2000)
5	Copper	6,536.00	35.61	23.19	0.190	0.160	0.250	1.570	(Schleisner 2000)
6	Plastic, glass fibre polyester/epoxy	3,941.00	22.91	14.71	0.120	0.080	0.200	1.100	(Schleisner 2000)
7	PVC	3,113.00	14.75	10.49	0.090	0.080	0.200	1.040	(Schleisner 2000)
8	Rubber	3,398.00	16.06	10.61	0.100	0.060	0.180	1.060	(Schleisner 2000)
9	Reinforced iron (rebars)	3,114.00	14.58	8.89	0.090	0.060	0.180	1.570	(Schleisner 2000)
10	Cast iron	3,114.00	14.58	8.89	0.090	0.060	0.180	1.570	(Schleisner 2000)
11	Concrete (construction)	703.00	0.01	2.50	0.000	0.000	0.000	0.000	(Schleisner 2000)
12	Lead	2,953.00	18.19	19.82	0.110	0.070	0.550	2.030	(Schleisner 2000)
13	Zinc	6,648.00	47.49	35.66	0.230	0.120	0.600	2.390	(Schleisner 2000)
14	Float glass	581.00	0.87	2.41	0.010	0.040	0.150	0.660	(Schleisner 2000)
15	Packing glass	551.00	1.58	2.48	0.010	0.030	0.140	0.640	(Schleisner 2000)
16	Insulations, rock wool (/m3)	1,042.00	6.08	2.82	0.030	0.020	0.060	0.820	(Schleisner 2000)
17	Insulation, glass wool [per m3]	1,008.00	4.98	3.96	0.030	0.030	0.080	0.360	(Schleisner 2000)
18	Concrete (foundation)	835.00	0.60	3.20	0.000	0.000	0.000	0.000	(Schleisner 2000)
19	**Recycle**	**CO_2 –eq**							
20	Steel	1819							(Martınez et al. 2008)
21	Aluminum	738							(Martınez et al. 2008)
22	Copper	3431							(Martınez et al. 2008)
23	**Emission per kg material disposal**								
24	Plastic (polyester/epoxy)	4680	3.6	6	0.16	0.24	0.36	87.52	(Schleisner 2000)
25	PVC	4680	3.6	6	0.16	0.24	0.36	87.52	(Schleisner 2000)
26	Rubber	3510	2.7	4.5	0.12	0.18	0.27	65.66	(Schleisner 2000)

4.3.6.1 General formulation of the basic model for inventory analysis

In this section, the calculation of inventory analysis is presented using the equation:

$$\begin{cases} a_{11}s_1 + \cdots + a_{1i}s_i + \cdots + a_{1n}s_n = f_1 \\ \vdots \\ a_{i1}s_1 + \cdots + a_{ii}s_i + \cdots + a_{in}s_n = f_i \\ \vdots \\ a_{n1}s_1 + \cdots + a_{ni}s_i + \cdots + a_{nn}s_n = f_n \end{cases} \qquad \mathbf{A} = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}; \ \mathbf{s} = \begin{pmatrix} s_1 \\ \vdots \\ s_n \end{pmatrix}; \ \mathbf{f} = \begin{pmatrix} f_1 \\ \vdots \\ f_n \end{pmatrix} \tag{4.6}$$

Then

$$\begin{aligned} &\mathbf{As} = \mathbf{f} \longrightarrow \mathbf{s} = \mathbf{A}^{-1}\mathbf{f} \\ &\mathbf{Bs} = \mathbf{g} \longrightarrow \mathbf{g} = (\mathbf{BA}^{-1})\mathbf{f} = \mathbf{\Lambda f} \end{aligned} \tag{4.7}$$

Where

Matrix $\mathbf{\Lambda}$ denotes the matrix intensity;

Matrix **A** represents the technology matrix;

Matrix **B** is the environmental intervention;

Vector **f** will be referred to as the final (external) demand vector, because it is an exogenously define set of economic flows;

Vector **g** is an environmental intervention in the inventory; and

Vector **s** denoted a scaling vector.

See Appendix E to understand how these equations can be applied to the formulations in this case study.

4.3.6.2 Inventory calculation applied in this study

(a) **Manufacturing calculations**: the aim of the inventory was presented earlier in Section 3.3.1.2 so the first thing to do before calculating the data from the life cycle inventory is to determine the input and output data for a unit process.

The limitation of this study is that the research was focused on the first unit process with the environmental emissions and the life cycle energy required being considered for this component in the turbine system life cycle. To calculate all process chains including the total energy used from all the different energy resources, the raw material energy requirement for the material extraction is very complicated and it may take time and cost much to obtain. For example, for the rotor, there is only a first unit process calculated in this case study. Although there are three main types of material in the rotor: glass fibre (19.071 t), chromium steel (7.047 t), and cast iron (7.281 t) - see Table 4.6 - the main boxed area in Figure 4.11 only describes the data of glass fibre (19.071t). This data comes from Table 4.21 with the column for the rotor mass tabulated. The unit process for the glass fibre blades is shown in Figure 4.11

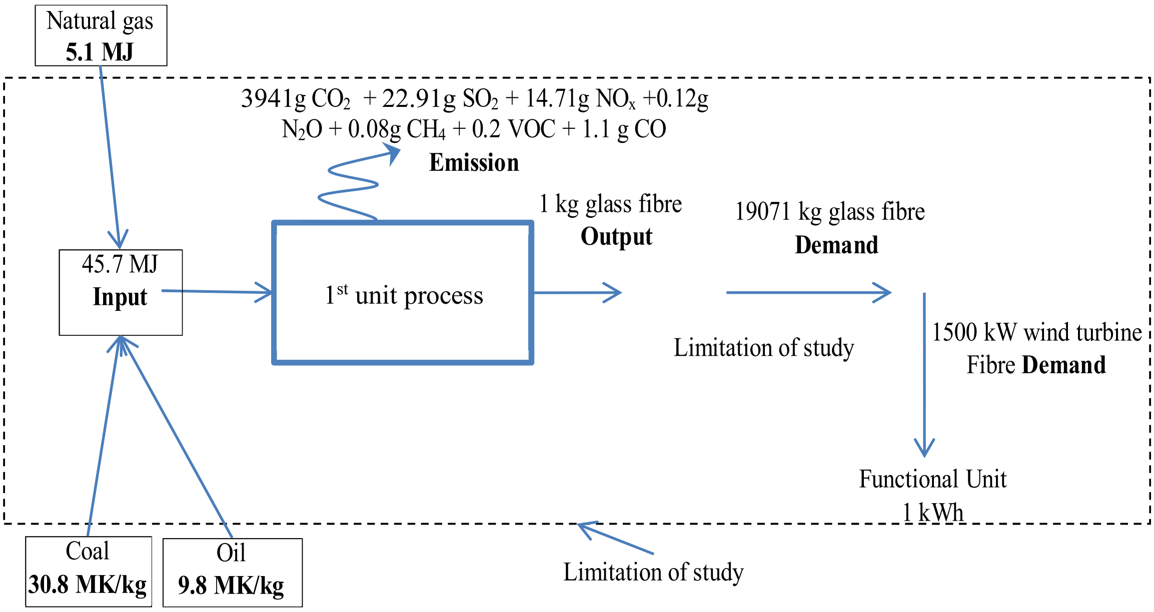

Figure 4.11: The unit process for the manufacture of glass fibre reinforced plastics used in rotor.

Figure 4.11 shows how the unit process chain of the glass fibre works in order to generate 1 kWh. The glass fibre unit process is applied to this example. The economic flow is calculated using the functional Unit (1kWh). The technology matrix $\mathbf{A}_1$, scaling vector $\mathbf{s}_1$, and the matrix $\mathbf{B}_1$ related intervention of environment, can be determined based on (E.5) in Appendix E.

$$\mathbf{p}_1 = \left[\begin{array}{c}\mathbf{A_1}\\ \hline \mathbf{B_1}\end{array}\right] = \left[\begin{array}{c} a_{11} \\ a_{12} \\ \hline b_{11} \\ b_{12} \\ b_{13} \\ b_{14} \\ b_{15} \\ b_{16} \\ b_{17} \end{array}\right] = \left[\begin{array}{c} -45.7\text{ MJ} \\ 1\text{ kg} \\ \hline CO_2 \\ SO_2 \\ NO_x \\ N_2O \\ CH_4 \\ VOC \\ CO \end{array}\right] = \left[\begin{array}{l} -45.7\text{ MJ} \\ 1\text{ kg} \\ \hline 3941 \\ 22.91 \\ 14.71 \\ 0.12 \\ 0.08 \\ 0.2 \\ 1.1 \end{array}\right] \tag{4.8}$$

Equation 4.8 has two meanings: the first is that A1 refers to the manufacture of 1 kg of glass fiber, which requires 45.7 MJ energy input (- 45.7 MJ); and the second is that the unit process also releases 3941 g CO_2 + 22.91 g SO_2 + 14.71 g NOx + 0.12 g N_2O + 0.08 g CH_4 + 0.2 g VOC g + 1.1 g CO (taken from Table 4.21, 6th row).

Therefore with the demand of 1 kWh of electricity output, 19071 kg glass fiber is required in order to manufacture for one 1.5 MW turbine which operates for 20 years (2715.6 hours full load per year). The electricity output of one turbine can be accounted for its life cycle:

$$\mathrm{E}_{output} = 1500\text{ kW} \times 2715.6\text{ hours } \times 20\text{ years} = 81468000\text{ kWh per turbine} \tag{4.9}$$

The whole capacity of the wind farm will be

$$\begin{aligned}\sum \mathrm{E}_{output} &= 1500\text{ kW} \times 2715.6\text{ hours } \times 20\text{ years } \times\ 20\text{ turbines} \\ &= 1.62936 \times 10^{-9}\text{ kWh}\end{aligned} \tag{4.10}$$

However, consider the manufacture of one turbine manufacture, the following formulation can be used to scale in order to meet the fU requirement. The flow chart in Figure 4.12 shows the way to estimate the final demand; this can be applied to all the material requirements in the manufacturing stage in this research. In this example, the final demand of mass is 2.34×10^{-4} kg.

The value of 2.34×10^{-4} kg is then called the final demand (equal 1 kWh of fU) for the glass fibre material. Mathematically, it is simple to determine the scaling factor for the fibre glass example; this is that illustrated in flow chart in Figure 4.11. The mass required is therefore:

$$\begin{aligned} \text{mass required} &= \left(\frac{19071 \text{ kg}}{1500 \text{ kW} \times 2715.6 \text{ hours } \times 20 \text{ years}} \right) \\ &= \left(\frac{19071 \text{ kg}}{81468000 \text{ kWh}} \right) = 0.000234 \left[\frac{\text{kg}}{\text{kWh}} \right] \end{aligned} \tag{4.11}$$

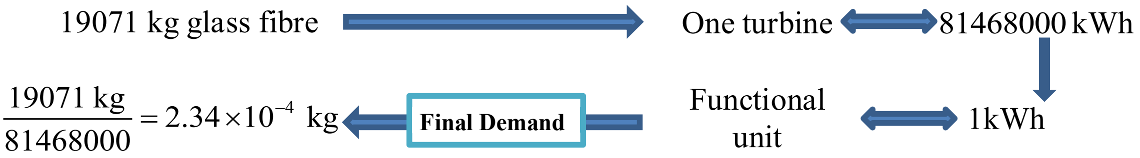

Figure 4.12: The scaling approach for mass of glass fibre in one turbine, corresponding to fU (1kWh).

Similarly for the calculation of chromium steel (7.047 t), and cast iron (7.281 t), which are in the rotor:

$$\mathbf{A}_2 = \begin{bmatrix} -34 \text{ MJ} \\ 1 \text{ kg} \end{bmatrix}; \ \mathbf{f}_2 = 0.0000865 \left[\frac{\text{kg}}{\text{kWh}} \right] \text{and}$$

$$\mathbf{B}_2 = \begin{pmatrix} CO_2 \\ SO_2 \\ NO_x \\ N_2O \\ CH_4 \\ VOC \\ CO \end{pmatrix} \left[\frac{\text{g}}{\text{kg}} \right] = \begin{pmatrix} 2306.5 \\ 14.5 \\ 9.5 \\ 0.05 \\ 0.04 \\ 0.16 \\ 0.93 \end{pmatrix} \left[\frac{\text{g}}{\text{kg}} \right] \tag{4.12}$$

$$\mathbf{A}_3 = \begin{bmatrix} -29.3\ \text{MJ} \\ 1\ \text{kg} \end{bmatrix}; \ \mathbf{f}_3 = \left(\frac{7281}{81468000} \right) = 0.0000894 \left[\frac{\text{kg}}{\text{kWh}} \right]$$

$$\text{and } \mathbf{B}_3 = \begin{pmatrix} CO_2 \\ SO_2 \\ NO_x \\ N_2O \\ CH_4 \\ VOC \\ CO \end{pmatrix} = \begin{pmatrix} 3114 \\ 14.58 \\ 8.89 \\ 0.09 \\ 0.06 \\ 0.18 \\ 1.57 \end{pmatrix} \left[\frac{\text{g}}{\text{kg}} \right] \tag{4.13}$$

The formulation for rotor calculation is obtained and the matrix calculation where:

$$\mathbf{A} = [\mathbf{A}_1 \mathbf{A}_2 \mathbf{A}_3] = \begin{bmatrix} a_{11} \\ a_{12} \end{bmatrix} \begin{bmatrix} a_{21} \\ a_{22} \end{bmatrix} \begin{bmatrix} a_{31} \\ a_{32} \end{bmatrix} = \begin{bmatrix} -45.7 \\ 1 \end{bmatrix} \begin{bmatrix} -34 \\ 1 \end{bmatrix} \begin{bmatrix} -29.3 \\ 1 \end{bmatrix} \begin{pmatrix} \text{MJ} \\ \text{kg} \end{pmatrix};$$

$$\mathbf{f} = [\mathbf{f}_1\ \mathbf{f}_2\ \mathbf{f}_3] = \begin{bmatrix} f_{11} \\ f_{12} \end{bmatrix} \begin{bmatrix} f_{21} \\ f_{22} \end{bmatrix} \begin{bmatrix} f_{31} \\ f_{32} \end{bmatrix} = \begin{bmatrix} 0 \\ 2.34 \times 10^{-4} \end{bmatrix} \begin{bmatrix} 0 \\ 8.65 \times 10^{-5} \end{bmatrix} \begin{bmatrix} 0 \\ 8.94 \times 10^{-5} \end{bmatrix} \begin{pmatrix} \text{MJ} \\ \text{kg/kWh} \end{pmatrix}$$

$$\mathbf{s} = (s_1, s_2, s_3) \text{ unkown} \tag{4.14}$$

Applying E.12, E.13, and E.14 from appendix E, for the first economic flow (first row), a balance equation can be set up for the fuel. For glass fibre:

$$a_{11} \times s_1 = f_{11}$$

$$\text{or } -45.7 \frac{\text{MJ}}{\text{kg}} \times \text{s}_1 = 0 \tag{4.15}$$

$$a_{12} \times s_1 = f_{12}$$

$$\text{or } 1\text{kg} \times \text{s}_1 = 0.000234 \text{ kg/kWh } \Rightarrow \text{s}_1 = 0.000234 \text{ kWh}^{-1} \tag{4.16}$$

From (4.16), s1 = f12 = 0.000234 (different unit). There are similar calculations for both chromium steel and cast iron. The scaling vector will be determined from

$$\mathbf{s} = (s_1, s_2, s_3)(0.000234)(0.0000865)(0.0000894) \text{ kWh}^{-1} \tag{4.17}$$

To calculate the vector **g**, which is the environmental intervention, the setup matrix **B** is the environmental interaction where if the emission values for 1 kg glass fibre are already known, the correspondent scaling vector of s_1 is 2.34×10^{-4} kg. Glass fibre will be calculated by taking the column for the mass of the emissions, multiplying by 2.34×10^{-4}, and modelling as shown in the Figure 4.13.

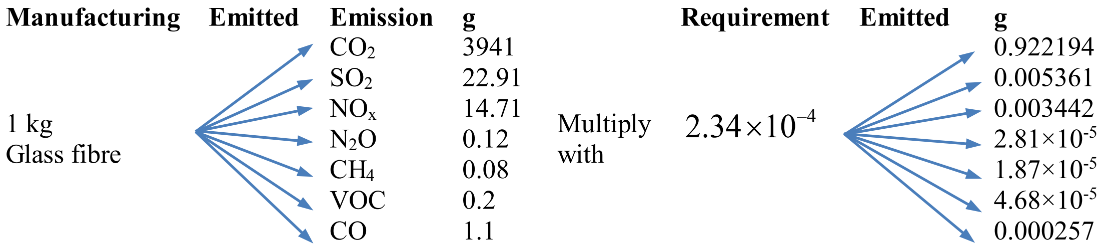

Figure 4.13: The method for calculation of emissions released, corresponding to functional unit.

Conversing the data from Figure 4.13 to a vector, and multiplying this vector by s_1, gives

$$\mathbf{g}_1 = \mathbf{B}_1 s_1 = \begin{pmatrix} CO_2 \\ SO_2 \\ NO_x \\ N_2O \\ CH_4 \\ VOC \\ CO \end{pmatrix} \times s_1 = \begin{pmatrix} 3941 \\ 22.91 \\ 14.71 \\ 0.12 \\ 0.08 \\ 0.2 \\ 1.1 \end{pmatrix} \times 2.34\times10^{-4} = \begin{bmatrix} 0.922194 \\ 0.005361 \\ 0.003442 \\ 2.81\times10^{-5} \\ 1.87\times10^{-5} \\ 4.68\times10^{-5} \\ 0.000257 \end{bmatrix} \text{g/kWh} \tag{4.18}$$

This can be done in a similar manner with the other two materials. The results of the emissions are accounted by

$$\mathbf{g}_2 = \begin{pmatrix} CO_2 \\ SO_2 \\ NO_x \\ N_2O \\ CH_4 \\ VOC \\ CO \end{pmatrix} \times s_2 = \begin{pmatrix} 2306.5 \\ 14.5 \\ 9.5 \\ 0.05 \\ 0.04 \\ 0.16 \\ 0.93 \end{pmatrix} \times 2.34\times10^{-4} = \begin{bmatrix} 0.199469 \\ 0.001254 \\ 0.000822 \\ 4.33\times10^{-6} \\ 3.46\times10^{-6} \\ 1.38\times10^{-5} \\ 8.04\times10^{-5} \end{bmatrix} \text{g/kWh} \tag{4.19}$$

$$\mathbf{g}_3 = \begin{pmatrix} CO_2 \\ SO_2 \\ NO_x \\ N_2O \\ CH_4 \\ VOC \\ CO \end{pmatrix} \times s_3 = \begin{pmatrix} 3114.00 \\ 14.58 \\ 8.89 \\ 0.09 \\ 0.06 \\ 0.18 \\ 1.57 \end{pmatrix} \times 8.94 \times 10^{-6} = \begin{bmatrix} 0.278392 \\ 0.001303 \\ 0.000795 \\ 8.05 \times 10^{-6} \\ 5.36 \times 10^{-6} \\ 1.61 \times 10^{-5} \\ 0.00014 \end{bmatrix} \text{g/kWh} \qquad (4.20)$$

We can put all the vectors $\mathbf{B}_1$, $\mathbf{B}_2$, $\mathbf{B}_3$ into one matrix in order to make the calculation easier:

$$\mathbf{B} = \left[\mathbf{B}_1\ \mathbf{B}_2\ \mathbf{B}_3\right] = \begin{pmatrix} CO_2 \\ SO_2 \\ NO_x \\ N_2O \\ CH_4 \\ VOC \\ CO \end{pmatrix} = \begin{pmatrix} 3941 \\ 22.91 \\ 14.71 \\ 0.12 \\ 0.08 \\ 0.2 \\ 1.1 \end{pmatrix} \begin{pmatrix} 2306.5 \\ 14.5 \\ 9.5 \\ 0.05 \\ 0.04 \\ 0.16 \\ 0.93 \end{pmatrix} \begin{pmatrix} 3114 \\ 14.58 \\ 8.89 \\ 0.09 \\ 0.06 \\ 0.18 \\ 1.57 \end{pmatrix} \left[\frac{\text{g}}{\text{kg}}\right]; \qquad (4.21)$$

$$\mathbf{s} = (s_1, s_2, s_3) = (0.000234)(0.0000865)(0.0000894)\ \text{kWh}^{-1}$$

We call $\hat{\mathbf{s}}$ = diagonal matrix of (s_1, s_2, s_3) so that matrix $\hat{\mathbf{s}}$ can be shown in (4.22):

$$\hat{\mathbf{s}} = \begin{bmatrix} s_1 & 0 & 0 \\ 0 & s_2 & 0 \\ 0 & 0 & s_3 \end{bmatrix} \qquad (4.22)$$

And finally, the calculation of the vectors related to the environmental intervention, when converted to matrix calculation, are:

$$\mathbf{g} = \mathbf{B}\hat{\mathbf{s}} = \left[\mathbf{B}_1\ \mathbf{B}_2\ \mathbf{B}_3\right] \begin{bmatrix} s_1 & 0 & 0 \\ 0 & s_2 & 0 \\ 0 & 0 & s_3 \end{bmatrix} \frac{\text{g}}{\text{kWh}} \qquad (4.23)$$

The results are then determined from:

$$\mathbf{g}=\begin{pmatrix} 3941 & 2306.5 & 3114 \\ 22.91 & 14.5 & 14.58 \\ 14.71 & 9.5 & 8.89 \\ 0.12 & 0.05 & 0.09 \\ 0.08 & 0.04 & 0.06 \\ 0.2 & 0.16 & 0.18 \\ 1.1 & 0.93 & 1.57 \end{pmatrix}(\mathrm{g})\begin{bmatrix} 0.000234 & 0 & 0 \\ 0 & 0.0000865 & 0 \\ 0 & 0 & 0.0000894 \end{bmatrix}\left[\frac{1}{\mathrm{kWh}}\right]$$

$$=\begin{pmatrix} 0.922194 & 0.199469 & 0.278392 \\ 0.005361 & 0.001254 & 0.001303 \\ 0.003442 & 0.000822 & 0.000795 \\ 2.81\times10^{-5} & 4.3\times10^{-6} & 8.0\times510^{-6} \\ 1.87\times10^{-5} & 3.46\times10^{-6} & 5.36\times10^{-6} \\ 4.68\times10^{-5} & 1.38\times10^{-5} & 1.61\times10^{-5} \\ 0.000257 & 8.04\times10^{-5} & 0.00014 \end{pmatrix}\frac{\mathrm{g}}{\mathrm{kWh}} \tag{4.24}$$

The vector for the environmental intervention **g** is explained as follows. In the rotor manufacturing, the emission releases related to the glass fibre with a fU of 1 kWh, consists of 0.992g CO_2, 0.0053 g SO_2, 0.0034 g NO_x, 2.8×10^{-5} g N_2O, 1.87×10^{-5} g CH_4, 4.86×10^{-5} g VOC, and 2.57×10^{-5} g of CO. Again, similar gap emissions exist for chromium steel and cast iron.

Table 4.22: A part of inventory list after calculation (table of glass fibre presented only, the full inventory lists shown in Appendix E. 2.1).

Inventory list	Input		Scaling factor	Output	
Glass fibre	**Economic flows (matrix A)**	**Environmental flows (matrix B, g)**	**Vector s [kg/kW]**	**Economic flows (vector f)**	**Environmental flows (matrix g) material emissions [g/kW]**
	-45.7 MJ/kg	3941	2.34×10^{-5}	0	0.922194
	1 kg	22.91		2.34×10^{-5} kg	0.005361
		14.71			0.003442
		0.12			2.81×10^{-5}
		0.08			1.87×10^{-5}
		0.2			4.68×10^{-5}
		1.1			0.000257

The summing of the results from the economic flows and environmental flows, leads to the partial inventory list will be shown in Table 4.22.

(b) Transportation and installation calculation: as mentioned earlier in 4.3.3, there are only three types of transportation modes presented in this study. According to the suggestion in Eecoinvent 2004, if the distances of transportation for the main wind turbine components are in the interval 100 km to 1000 km, 16 t trucks can be used. In the case of distances more than 1000 km 40 t trucks are used (Ecoinvent 2004). Therefore, in the transportation modes in this study, for land transport, 16 t light vehicles and 40 to 48 t heavy trucks are used in addition to the sea transport which uses an international cargo ship. It can be noted that in all transportation modes in this research, diesel is the only fuel considered.

Although there are many measurement methodologies for component transport, the calculation of transportation is recommended to be in terms of the ton-kilometers (t.km) of freight transport services (Guezuraga, Zauner & Pölz 2010). For example, if a truck delivers 10 tons over a distance of 500 km, this is represented by a transport service of 5000 t.km.

Table 4.23: Final energy consumption for vehicle travel. The energy values are based on the lower heating values of diesel fuels (42.8 MJ/kg diesel).

Mode of transportation	Transportation services	Diesel [kg/t/km]	Final energy Consumption [MJ/t/km]	Description data	Sources
Road	16t Light Truck RER	0.089	3.81	EURO class 2 engine	(Spielmann & Scholz 2004)
	40t Heavy truck RER	0.036	1.54	EURO class 2 engine	(Ecoinvent 2004)
Barge RER	Transoceanic tanker US	0.0013	0.38	EURO class 2 engine	(Ecoinvent 2004)

In Spielmann 2004 (Spielmann & Scholz 2004), the load factors of the trucks have been determined as being in the interval 0.25 – 0.62. It is assumed that the transportation of the components from manufacturer to the project site with load, and return with no load, has a load factor of 0.5. Table 4.23 shows the consumption figures for diesel used and these are based on a German report (Spielmann & Scholz 2004) and the Ecoinvent database 2004, under the average load factors. This is because the Vietnamese standard emission releases are mainly based on the European emission standard which currently complies with Euro 2 (UNEP 2014). The emissions from automobiles in Europe can also be applied to the Vietnam automobile emissions standard.

Table 4.24 quotes the emission factors related to the different transportation modes and then emissions during transportations were calculated based on the distance travelled.

Table 4.24: Transportation embodied energy and emission inventory data.

Modes	**SO_2 [kg/MJ]**	**NO_x [kg/MJ]**	**CO_2 [kg/MJ]**	**N_2O [kg/MJ]**	**CH_4 [kg/MJ]**	**NMVOC [kg/MJ]**	**CO [kg/MJ]**	$\left[\frac{\text{MJ}}{\text{t.km}}\right]$	**Ref.**
16 t Light Truck RER	4.0×10^{-5}	8.2×10^{-4}	0.35	2.8×10^{-5}	8.9×10^{-6}	3.5×10^{-4}	6.4×10^{-4}	3.81	(H. Mahmudi, Flynn & Checkel 2005. Life cycle analysis of biomass transportation: trains vs. trucks)
40t Heavy truck RER	2.7×10^{-5}	1.6×10^{-3}	7.6×10^{-2}	2.9×10^{-5}	4.5×10^{-5}	3.3×10^{-4}	7.5×10^{-4}	1.54	(H. Mahmudi, Flynn & Checkel 2005. Life cycle analysis of biomass transportation: trains vs. trucks)
Barge US	NA	NA	6.9×10^{-2}	0.18×10^{-5}	0.584×10^{-3}	NA	NA	0.38	(Ecoinvent 2004) (United States Energy Information Administration (EIA) 2011)

Table 4.13 illustrates the distance travelled for the rotor and nacelle. In this process, heavy trucks need to be employed to transport them. The calculation is carried out

for one turbine and then it is scaled up to twenty turbines later. It is important to note that the calculations do not mention the return journey.

Table 4.25: **Resulting data for rotor and nacelle transportation.**

Rotor and nacelle	Departure	Destination	Numbers				Fuel	Distance travelled [km]	Total distances travelled [t.km]	
90 tons	Fuhrländer, Germany	Port of Rotterdam, NE	Heavy truck	2	Light truck	1	Diesel	377	60,320	3,770
	Port of Rotterdam, NE	Nhatrang harbour, VN	Cargo ship	1			Diesel	17422	1,567,980	
	Nhatrang port, VN	Project site, VN	Heavy truck	2	Light truck	1	Diesel	243	19,440	2430

The total weight of the rotor and turbine for one wind turbine is approximately ninety tons (see Table 4.5). Therefore two heavy and one light trucks were required. It was assumed that the two heavy trucks carry 80 t and the small truck transports 10 t. The results in Table after calculations.

Finally, a formulation is to set up to in order to make the calculation easier. Table 4.26 describes the principle calculations for the total amounts of diesel and energy consumed.

Table 4.26: Results of rotor and nacelle transportations.

Modes	Formulation	Diesel [kg]	Final energy consumption [MJ]	
16 t Truck RER	$0.089\left[\frac{\text{kg}}{\text{t.km}}\right]\times(3770\ +2430)[\text{t.km}]=$	551.80	$3.81\left[\frac{\text{MJ}}{\text{t.km}}\right]\times(3770\ +2430)[\text{t.km}]=$	23622
40 t truck RER	$0.036\left[\frac{\text{kg}}{\text{t.km}}\right]\times(60{,}320+19{,}440)[\text{t.km}]=$	2775.65	$1.54\left[\frac{\text{MJ}}{\text{t.km}}\right]\times(60{,}320+19{,}440)[\text{t.km}]=$	122830
Barge RER	$0.0013\left[\frac{\text{kg}}{\text{t.km}}\right]\times1{,}567{,}980[\text{t.km}]=$	2038.374	$0.38\left[\frac{\text{MJ}}{\text{t.km}}\right]\times1{,}567{,}980[\text{t.km}]=$	59650

The same matrix calculation for the environmental assessments is performed and later it will be down scaled to represent the functional unit requirements of the wind farm. The matrix **B***'* is an environmental interaction integration of **B**₁', **B**₂', and **B**₃' which are related to the light truck, heavy truck and barge tanker in the transportation stages. The scaling vector **s***'* is the scaling vector for all transportation. Hence:

$$\mathbf{s'} = (s_1', s_2', s_3') = \left(\frac{23{,}622[\mathrm{MJ}]}{81468000[\mathrm{kWh}]}\right)\left(\frac{122{,}830[\mathrm{MJ}]}{81468000[\mathrm{kWh}]}\right)\left(\frac{59{,}650[\mathrm{MJ}]}{81468000[\mathrm{kWh}]}\right)$$

$$= \left(0.00029\frac{[\mathrm{MJ}]}{[\mathrm{kWh}]}\right)\left(0.000937\frac{[\mathrm{MJ}]}{[\mathrm{kWh}]}\right)\left(0.000732\frac{[\mathrm{MJ}]}{[\mathrm{kWh}]}\right)$$

$$\mathbf{B'} = \left[\mathbf{B}_1^{/}\ \mathbf{B}_2^{/}\ \mathbf{B}_3^{/}\right] = \begin{pmatrix} CO_2 \\ SO_2 \\ NO_x \\ N_2O \\ CH_4 \\ VOC \\ CO \end{pmatrix} = \begin{pmatrix} 3.50\times10^{-1} \\ 4.00\times10^{-5} \\ 8.20\times10^{-4} \\ 2.80\times10^{-5} \\ 8.90\times10^{-6} \\ 3.50\times10^{-4} \\ 6.40\times10^{-4} \end{pmatrix}\begin{pmatrix} 7.60\times10^{-2} \\ 2.70\times10^{-5} \\ 1.60\times10^{-3} \\ 2.90\times10^{-5} \\ 4.50\times10^{-5} \\ 3.30\times10^{-4} \\ 7.50\times10^{-4} \end{pmatrix}\begin{pmatrix} 6.90\times10^{-2} \\ 0 \\ 0 \\ 1.87\times10^{-6} \\ 5.84\times10^{-4} \\ 0 \\ 0 \end{pmatrix}$$

The vector **g**' can be calculated using (4.15); the results of **g**' are shown in Table 4.26. The matrix calculation for **g**' is

$$\mathbf{g'} = \mathbf{B'}\mathbf{\hat{s}'} =$$

$$\begin{bmatrix} 3.50\times10^{-1} & 7.60\times10^{-2} & 6.90\times10^{-2} \\ 4.00\times10^{-5} & 2.70\times10^{-5} & 0 \\ 8.20\times10^{-4} & 1.60\times10^{-3} & 0 \\ 2.80\times10^{-5} & 2.90\times10^{-5} & 1.87\times10^{-6} \\ 8.90\times10^{-6} & 4.50\times10^{-5} & 5.84\times10^{-4} \\ 3.50\times10^{-4} & 3.30\times10^{-4} & 0 \\ 6.40\times10^{-4} & 7.50\times10^{-4} & 0 \end{bmatrix} \left[\frac{\text{kg}}{\text{MJ}}\right] \tag{4.25}$$

$$\begin{bmatrix} 0.00029\left[\frac{\text{MJ}}{\text{kWh}}\right] & 0 & 0 \\ 0 & 0.000937\left[\frac{\text{MJ}}{\text{kWh}}\right] & 0 \\ 0 & 0 & 0.000732\left[\frac{\text{MJ}}{\text{kWh}}\right] \end{bmatrix}$$

Table 4.27: The value environmental intervention of vector.

kg/kWh	**16 t Truck**	**40 t Truck**	**Barge**
CO_2	0.101484	7.12×10^{-5}	0.050521
SO_2	1.16×10^{-5}	2.53×10^{-8}	0
NO_x	0.000238	1.50×10^{-6}	0
N_2O	8.12×10^{-6}	2.72×10^{-8}	1.37×10^{-6}
CH_4	2.58×10^{-6}	4.22×10^{-8}	0.000428
VOC	0.000101	3.09×10^{-7}	0
CO	0.000186	7.03×10^{-7}	0

Table 4.28: A part of inventory list after calculation during transportation stages (light vehicle only presented, the full inventory lists shown in Appendix E).

Inventory list	Input		Scaling factor	Output
Glass fibre	Environmental flows (matrix B’, kg/MJ)		Vector [MJ/kWh]	Environmental flows(matrix g) material emissions [g/kW]
	CO_2	3.50×10^{-1}	$\left(0.00029\left[\frac{\text{MJ}}{\text{kWh}}\right]\right)$	0.101
	SO_2	4.00×10^{-5}		1.16×10^{-5}
	NO_x	8.20×10^{-4}		2.38×10^{-4}
	N_2O	2.80×10^{-5}		8.12×10^{-6}
	CH_4	8.90×10^{-6}		2.58×10^{-6}
	VOC	3.50×10^{-4}		0.1×10^{-3}
	CO	6.40×10^{-4}		0.186×10^{-3}

(c) The installation, operation and maintenance, and disposals stages of the full life cycle are calculated using similar formulations but adjusted for the data required. The total detailed inventory list is shown in Appendix E.

Chapter 5

Environmental Impact Assessment Methodology

5.1 Supporting software

In performing the LCA in this study, the required models were developed and compiled in an Excel database. The emission and energy intensities were calculated for the complete system. The database was written in order to read the tabulated data, which is considered as the data input, into the analysis software “R” (first developed by Gentleman and Ihaka in 1997, also known as "R & R" (Robert Gentleman & Ross Ihaka 2014). R is a language and environment for statistical computing and graphics. This software is also a graphical user interface that performs Life Cycle Impact Assessment (LCIA) calculations including matrix analysis. This software was preferred as it is free, easy to use, and typical data can be imported in simple way from sources such as Excel, SPSS, STATA, and even a website dataset.

5.2 Environmental Impact Assessment

As stated in Chapter 3, the Impact Assessment should track all impacts related to and from the environment. However, due to the lack of data available in the modeling case studies and the restrictions in time for research, only one LCA (Life Cycle Assessment) can be conducted with five to eight impact categories as illustrated in Table 5.1. This is a summary of the common impacts on the environment. Furthermore, currently, there are many impact assessment methods available for none commercial purposes and these can easily be imported into a Life Cycle Analysis. However, which impact categories should be chosen in order to match the requirements of study and which category indicators provide an emission relevant to the LCA case (Simonen 2014b), does raise issues; i.e., which one satisfies to all demands. Referring to Hauschild 2012, the best approach for characterizing potential impact assessments is still being developed (Hauschild et al. 2012).

Fortunately, according to *open-LCA* 2014 of Rodríguez, who is the leader of the Green Delta team, it is possible to create new impacts assessment methods by modifying the existing impact assessment methodology in your own LCA. Moreover, in most cases, LCA practitioners prefer to choose the existing impact assessments that have already been published rather than develop their own impact assessment (Goedkoop et al. 2010a). The way to carry out the modification of a published Impact Assessment is in the impact flow categories, which can be adjusted by adding or deleting, and then the equivalence factors can be changed (Rodríguez 2014a). Compared with the way an Inventory Analysis is carried out, the Impact Assessment is more straightforward (Heijungs & Suh 2010b).

Table 5.1: Environmental impacts temporally estimated by Life Cycle Assessment.

Environmental problem field	**Units**
Acidification	kg SO_2 - equivalent
Climate change	kg CO_2 – equivalent
Eutrophication	Kg N- equivalent
Ozone depletion	kg CFC – 11equivalent
Human health	Varies
Depletion of abiotic resources (elements)	Kg Sg –equivalent
Smog	Kg Ethane

In addition, the inventory of an LCA usually contains hundreds of different results for emissions and resource extraction parameters. The data collected is available for calculation of many Impact Categories such as ecotoxicity, eutrophication, and human toxicity, however, in this study, there are three main environmental impact categories (stressors): acidification; climate change; and ozone depletion near ground level (called photochemical smog or photo-oxidant). These are considered with seven common emission gauges and energy calculations. In the characterization method, there is still controversy as to whether the mid-point or end-point indicators perform better in the Life Cycle Impact Assessment (Hertwich & Hammitt 2001). However, in this study, in order to maintain the Goal and Scope definition, the mid-point indicators were chosen for the seven emissions; these include SO_2, NO_x, N_2O, CO_2, CH_4, NMVOC, and CO. These emissions should be assigned to the three impact categories (acidification, climate change and photo-oxidant). As mentioned in 3.3.1.3, it is possible to assign emissions to more than one impact category and if one emission affects more than one category, it is calculated to affect each category with the same weight. The emissions contribute to a certain concentration and this is based on the chemical allocation.

5.3 Midpoint of Environmental Impact Categories

5.3.1 *Acidification*

The acidification impact is a typical midpoint of the LCIA (Life Cycle Impact Assessment). This is characterized by the change in pH balance in the local water and soil productivity. This has an impact on animals and vegetation. Obviously, plants and animals have optimum environmental pH levels, and can be live within a range of pH levels, but if the level is outside an appropriate value then this can have an adverse effect. The research conducted by Doney 2009 found that some aquatic species, such as oysters and sea urchins, have significant sensitivity to the changes of acid balance (Doney et al. 2009). The chemicals that contribute to acidification are sulfur oxides, ammonia and nitrous oxides.

5.3.1.1 Identified Impact Indicator

Impact indicator was selected using IS 14044 (Figure 3.4) for guidance. A standard approach in determining this follows the steps below:

- Obtain the LCI (Life Cycle Inventory) results; in this case, it is SO_2-equivalent.
- The LCI results are then assigned to an impact category (classification); hence, NO_x and SO_2 are assigned to the acidification impact category.
- For this category indicator or characterization mode, the assessment method determines the release of protons (H^+-equivalent); this leads to the calculation of the *AP* (Acidification Potential) equivalent (which is mostly SO_2-equivalent).

5.3.1.2 Characterization factor

The characterization factor is calculated based on chemical reactions although these are not presented in this case study. The impact category is converted into an AP using Table 5.2 which equates to the SO_2-equivalent factors. The formulation is given

$$AP = \sum_i (m_i AP_i) \text{ kg SO}_2\text{- equivalent} \tag{5.1}$$

Where m_i is the load factor for the component i which contributes to the acidification per fU (fundamental unit).

Table 5.2: Acidification Potential (*AP*) of some gas emissions.

Sources from (Heijungs et al. 1992), (Klopffer July 1995), (Hauschild & Wenzel 1998) , (Norris 2001).

Emission gas	Formula	Characterization factor *AP* (kg SO_2 – equivalent)
Carbon dioxide	CO_2	0
Sulphur dioxide	SO_2	1
Nitrogen dioxide	NO_x	0.7
Nitrogen Oxide	N_2O	0.7
Methane	CH_4	0
volatile organic compounds	VOC	0.8
Carbon oxide	CO	0

5.3.2 *Climate Change*

Climate change is defined as the raising average temperature of the Earth's surface, and leads to other significant changes to climate; for example, more extreme weather at unusual times. Climate change is caused by various factors such as biotic processes, variations in solar radiation received by the Earth, plate tectonics, and volcanic eruptions. Certain human activities have also been identified as significant reasons of recent climate change, often referred to as "global warming" (United States Environmental Protection Agency (EPA) 2014). Climate change can be explained in the following way. First, solar energy passes through the atmosphere which warms the Earth's surface. The earth absorbs solar heat and releases it as infrared radiation. Greenhouse gases caused by fossil combustion or other activities produces increased rates of infrared energy retention due to increased levels of greenhouse gases in the atmosphere. This increases the temperature of the Earth (Simonen 2014c).

5.3.2.1 Impact indicator

The Impact indicator is again selected using IS 14044 (shown in Figure 3.4). The standard approach is determining the Impact indicator follows the steps below:

- The LCI results: in this case, it is CO_2- equivalent.
- The LCI results are assigned to an impact category (classification), in this case CO_2, N_2O, and CH_4 are assigned to the climate change impact category.
- For the Category indicator or characterization mode, the method in determining this is to measure and calculate the GWP (global Warming Potential) equivalent (which is based on the CO_2 – equivalent).

5.3.2.2 Characterization factor

The Characterization factors are calculated by summing the CO_2-equivalent for the total GHGs. The way to do is to multiply the every component of the CO_2 emission in the inventory with the load index and then sum them to obtain the *GWP* index. The Global Warming Potentials over 100 years for some gases are in presented in Table 5.3. The formulation is given by

$$GWP = \sum_i (m_i GWP_i) \text{ kg } CO_2\text{- equivalent} \tag{5.2}$$

Where m_i is load of the respective substance i per fU.

Table 5.3: Some greenhouse gases with Global Warming Potential (GWP_{100}) or characterization factors.

Substance	**Formula**	**Characterization factor, GWP_{100} kg CO_2-equivalent**
Carbon dioxide	CO_2	1
Sulphur dioxide	SO_2	0
Nitrogen dioxide	NO_x	0
Nitrogen Oxide	N_2O	298
Methane	CH_4	25.75
volatile organic compounds	VOC	0
Carbon oxide	CO	0

5.3.3 ***Photo oxidant formation***

While ozone in the upper stratosphere is beneficial for the absorption of infrared radiation, ozone at ground level and in the lower stratosphere forms smog and produces poor air quality which obviously directly threatens health and the environment. It causes irritation of the respiratory system and reduces lung function. It can also cause permanent lung damage and aggravation of asthma in severe situations (United States Environmental Protection Agency (EPA) 1999). In addition to toxic ozone, which is well known, there are also other eco-toxic substances produced by human activities which contribute to a group called photo-oxidants which form this impact category.

Since the impacts are caused by various pollutants and have different reaction mechanisms, in this limited study it is assumed that photo-oxidant formations are based on reactive nitrogen NO_x and the reactive volatile organic compounds VOC, HMVOC, and CO (Klöpffer & Grahl 2014c).

5.3.3.1 Impact indicator

The Impact indicator is again selected using IS 14044 (Figure 3.4) and this is determined using:

- The LCI results: in this case it is ethane C_2H_4 – equivalent.
- The LCI results are assigned to the climate change impact category (classification) for the gases CH_4, SO_2, CO, NHVOC, and NO_x
- For the Category indicator or characterization mode, the determination method is to measure and calculate the *POCP* (Photo-Oxidant) equivalent (which is related to the C_2H_4 – equivalent).

5.3.3.2 Characterization factor

In the context of the impact category for the formation of photo-oxidant, the qualification of the impact indicator is obtained from the *POCP* characterization factors and presented in Table 5.3. This is then obtained using the individual POCP and the load factors so that

$$POCP = \sum_i (m_i POCP_i) \text{ kg } C_2H_4 \text{- equivalent} \tag{5.3}$$

Where m_i is load of the respective component i which is involved in smog formation per fU.

Table 5.4: Photo-Oxidant Potential of some gases emission.

Substance	Formula	Characterization factor, POCP (kg C_2H_4 –equivalent =1)	Sources
Carbon dioxide	CO_2	0	
Sulphur dioxide	SO_2	0.048	(Derwenta et al. 1998)
Nitrogen dioxide	NO_x	0.028	(Derwenta et al. 1998)
Nitrogen Oxide	N_2O	0	
Methane	CH_4	0.006	(Guinée et al. 2002)
volatile organic compounds	VOC	0.416	(Guinée et al. 2002)
Carbon oxide	CO	0.020	(Derwenta et al. 1998)

5.4 Characterization

According to ISO 14042-2000 (ISO 14042 2000), characterization involves the conversion of the LCA results into common units and the aggregation of the converted results within the impact categories. Conversion is obtained by mean multiplication. A formula for characterization is presented in (5.1), (5.2), and (5.3) and integrated as illustrated by Hejiungs (Heijungs & Suh 2010a):

$$\mathbf{h}_i = \sum_{j=1}^{n} (\mathbf{q}_i)_j \, \mathbf{g}_j \tag{5.4}$$

Where:

$\mathbf{q}_i$ is the characterization factor or represents the characterization vector for impact category i;

$\mathbf{g}_j$ is an environmental intervention vector in the inventory, and the result from inventory calculation; and

$\mathbf{h}_i$ is referred to as an environmental impact vector or the value of emissions after conversion to an impact category.

In this case study, the vector **h** is determined by

$$\mathbf{h} = \begin{pmatrix} \text{kg SO}_2\text{- equivalent} \\ \text{kg CO}_2\text{- equivalent} \\ \text{kg C}_2\text{H}_4\text{- equivalent} \end{pmatrix} \tag{5.5}$$

The results in Tables 4.22 and 4.28 can be used to obtain the partial calculation of the output of the inventory; this is presented below.

Assessing of acidification impact category, the characterization factors are specified as data in Table 5.5, and transferred into impact indicator values:

$$\textbf{vector } \mathbf{q}_{\mathbf{AP}} = \begin{pmatrix} CO_2 \\ SO_2 \\ NO_x \\ N_2O \\ CH_4 \\ VOC \\ CO \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0.7 \\ 0.7 \\ 0 \\ 0.8 \\ 0 \end{pmatrix}$$

$$\textbf{matrix } \mathbf{g}_{\mathbf{AP}} = \begin{bmatrix} 0.922194 & 0.101 \\ 0.005361 & 1.16\times10^{-5} \\ 0.003442 & 2.38\times10^{-4} \\ 2.81\times10^{-5} & 8.12\times10^{-6} \\ 1.87\times10^{-5} & 2.58\times10^{-6} \\ 4.68\times10^{-5} & 0.1\times10^{-3} \\ 0.000257 & 0.186\times10^{-3} \end{bmatrix}$$

And then

$$\textbf{matrix } \mathbf{h}_{\mathbf{AP}} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.7 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0.922194 & 0.101 \\ 0.005361 & 1.16\times10^{-5} \\ 0.003442 & 2.38\times10^{-4} \\ 2.81\times10^{-5} & 8.12\times10^{-6} \\ 1.87\times10^{-5} & 2.58\times10^{-6} \\ 4.68\times10^{-5} & 0.1\times10^{-3} \\ 0.000257 & 0.186\times10^{-3} \end{bmatrix} \begin{pmatrix} \text{kg } SO_2\text{- equivalent} \\ \text{kg } SO_2\text{- equivalent} \\ \text{kg } SO_2\text{- equivalent} \\ \text{kg } SO_2\text{- equivalent} \\ \text{kg } SO_2\text{- equivalent} \\ \text{kg } SO_2\text{- equivalent} \\ \text{kg } SO_2\text{- equivalent} \end{pmatrix}$$

In the final stage, the results are obtained as a sum in each impact category, with reference to the fU of 1 kWh, which are calculated and tabulated in Tables 5.6 and 5.7.

Table 5.5: Selected inventory parameters (column for rotor and nacelle includes glass fibre only while transportation is the full calculation of rotor and nacelle distances).

Environmental flows (matrix *g*) material emissions [g/kWh]		
Rotor and nacelle	**Transportation**	**Units**
0.922194	0.101	CO_2
0.005361	1.16×10^{-5}	SO_2
0.003442	2.38×10^{-4}	NOx
2.81×10^{-5}	8.12×10^{-6}	N_2O
1.87×10^{-5}	2.58×10^{-6}	CH_4
4.68×10^{-5}	0.1×10^{-3}	VOC
0.000257	0.186×10^{-3}	CO

Table 5.6: Acidification potential (AP) for the manufacture of the Rotor and Nacelle in SO_2 equivalent/fU.

Acidification	Inventory result (g/kWh see Table 5.5)	Characterization factor (kg SO_2-equivalent)	Impact indicator value *AP* (g SO_2-equivalent/kWh)
CO_2	0.922194	0	0
SO_2	0.005361	1	0.005361
NOx	0.003442	0.7	0.002409
N_2O	2.81×10^{-5}	0.7	1.97×10^{-5}
CH_4	1.87×10^{-5}	0	0
VOC	4.68×10^{-5}	0.8	3.74×10^{-5}
CO	0.000257	0	0
Total			**0.007828**

Table 5.7: Acidification potential (AP) for transportation of the Rotor and Nacelle in SO_2 equivalent/fU.

Acidification	Inventory result (g/kWh see Table 5.5)	Characterization factor (SO_2-equivalent)	Impact indicator value AP (g SO_2-equivalent/kWh)
CO_2	0.101	0	0
SO_2	1.16×10^{-5}	1	0.0000116
NOx	2.38×10^{-4}	0.7	0.0001666
N_2O	8.12×10^{-6}	0.7	0.000005684
CH_4	2.58×10^{-6}	0	0
VOC	0.1×10^{-3}	0.8	0.00008
CO	0.186×10^{-3}	0	0
Total			**0.000263884**

To conclude, the contribution to the AP of the Rotor and Nacelle production is approximately 0.007828g SO_2equivalent when wind plant generated 1 kWh. The amount released during the transportation is around 2.63×10^{-4}g SO_2 equivalent. This is much smaller than the amount generated during the production stage (for full calculation of impact assessment, see Appendix F).

Chapter 6

Results and discussion

6.1 Life Cycle Impact of total wind farm assessment

This study has investigated the environmental impacts of a wind generation system taking three categories into account: acidification, climate change and Photo-oxidant chemical smog. Hence, the environmental impacts of a 30 MW wind farm were identified and calculated for these three impact categories. There were modelled in chapter 5. Table 6.1 shows the environmental performance of emission impacts categories caused by the onshore wind farm. See appendix F for the calculation of the results.

Table 6.1: The results of total emission categorized according to impact assessment.

	Acidification SO_2 -eq		Global Warming CO_2-eq		Photo-Oxidant Potential C_2H_4-eq	
	g/kWh	**Weighted**	**g/kWh**	**Weighted**	**g/kWh**	**weighted**
Manufacture stage	0.0757	82.58%	11.9053	107.55%	0.0037	60.44%
Transportation	0.0103	11.21%	1.12135	10.13%	0.0015	24.50%
Construction, operation &maintenance service stage	0.0036	3.94%	0.4558	4.12%	0.0004	5.76%
Recycling	0	0.00%	-3.62	-32.70%	0	0.00%
Landfill stage	0.0021	2.28%	1.207	10.90%	0.0006	9.29%
Sum	**0.0917**	**100%**	**11.0694**	**100%**	**0.0062**	**100%**

This table compares the contribution to the total impacts of different stages of the life cycle in functional Units per kWh generated to the national grid. To be more specific, to generate and transmit 1kWh electricity from the wind farm to the grid, 14.69 g CO_2-equivalent (without recycling process) is released to climate change, 0.092 g SO_2 to acidification, and 0.0062 g C_2H_4-eq kWhel to the photochemical smog. The results can be compared with the outcomes from Ardente (Fulvio Ardente 2008) with 18.5 g CO_2-eq/kWh electricity, Weintzettela, who found a contribution to climate change of 11.5 g CO_2-eq/kWh generated (Weinzettela et al. 2009), or Schleisner (Schleisner 2000) who calculated an emission of 16.5 g CO_2-eq/kWh electricity. However, these results are divergent from the report by Vestas (2004) (Vetas July, 2006) with 5.3g CO_2-eq/kWh of electricity. This is because the Vestas report did not discuss the transformer and cable, and assumed there was no emission in operation stage. Furthermore, the different transportation stages also caused discrepancies.

The results in Table 6.1 are presented graphically in Figure 6.1 in order to clearly illustrate the effects that various life cycle stages have within these impact categories. The chart also depicts that how much of an impact each lifecycle stage has. These stages include manufacturing, delivery, installation, operation and maintenance, and end of life. The last stage includes the two sub-processes of recycling and landfill which are calculated within different impact categories.

For example, with regards to three impact categories, the manufacturing stage contributes the most to the Global Warming Potential (GWP) and Acidification Potential (AP) with approximately 12 g CO_2-eq and 0.0756 g SO_2-eq respectively in one kWh of electricity produced. In fact, at least 82 % of the CO_2-eq and SO_2-eq comes from the manufacturing activities. Conversely, the construction phases are determined to be the smallest contributor with the emission weighting. This varies from 4 % to 6 % in the three impact categories (not including recycling phase due to the special value of that considered in the GWP).

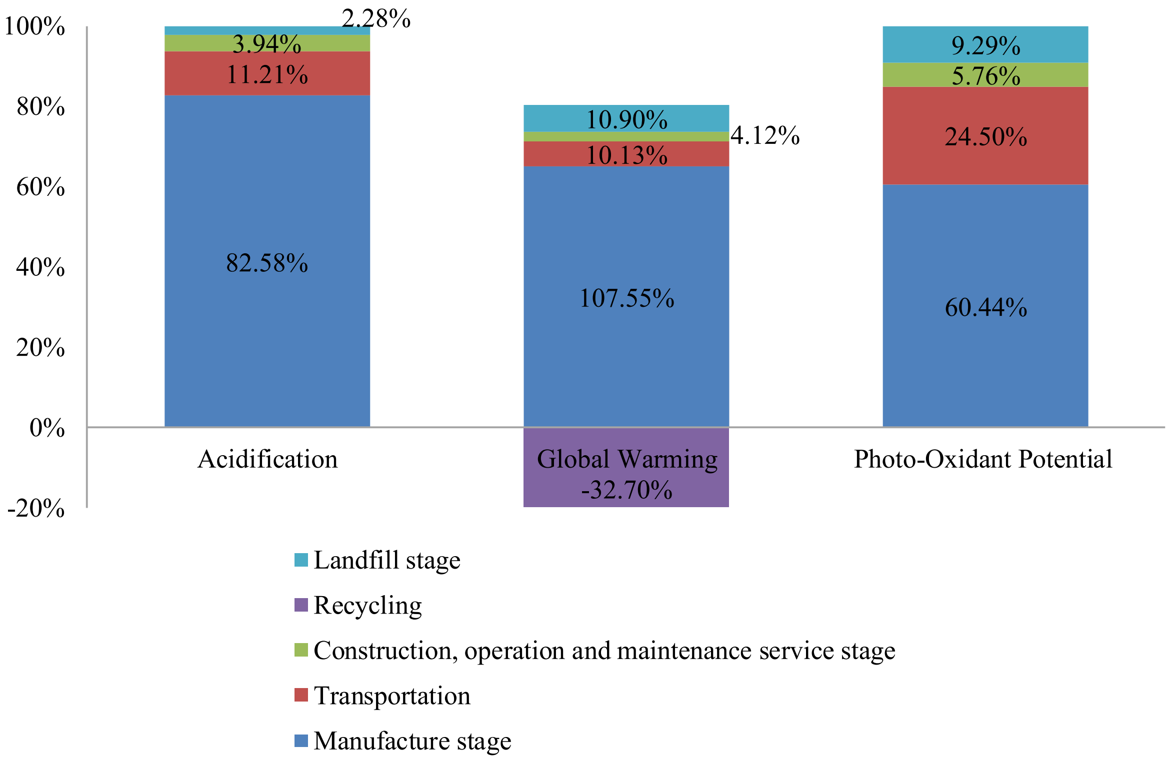

Figure 6.1: Environmental impacts of wind farm generation.

Noticeably, in GWP the column, there is a negative percentage value for recycling. This is due to the mass of recycled materials related to the recycling of steel and copper in the wind turbine components. These can be reused, and the environmental emission (CO_2-eq) in this case was a credit since it avoids the need to produce more steel and copper from raw steel and copper ores. In other words, if an amount of recycled material is used for another unit process, this means that there is no emission for manufacture of that product. The calculation for this case is computed in G.1 in Appendix G and the findings are put down as credits to the environment which counts towards the GWP climate change category.

To calculate the impact category via emission equivalent, the total credit emission above will be multiplied with the characterization matrix. In this work, there are three matrices: the AD, GWP and POCP matrices; the emission equivalent results are given in Table 6.1.

6.2 LCIA of different components contribute to impact categories

Table 6.2: The total Life Cycle Inventory results of various parts in wind turbine.

g/kWh	Low voltage transformer	Tower	Blade	Blade extender	Hub
CO_2	0.14258	3.68023	0.76635	0.199469	0.278392
SO_2	0.00063	0.023121	0.003393	0.001254	0.001303
NO_x	0.00038	0.015146	0.002223	0.000822	0.000795
N_2O	4.03×10^{-6}	0.000112	1.64×10^{-5}	4.33×10^{-6}	8.05×10^{-6}
CH_4	3.83×10^{-6}	6.39×10^{-5}	9.36×10^{-6}	3.46×10^{-6}	5.36×10^{-6}
VOC	7.33×10^{-5}	0.000255	3.74×10^{-5}	1.38×10^{-5}	1.61×10^{-5}
CO	0.000519	0.00148	0.000218	8.04×10^{-5}	0.00014

g/kWh	Generator	Gearbox	Main shaft	Basement
CO_2	0.169685	0.4061057	0.242575	5.616753
SO_2	0.001067	0.0021781	0.001525	0.008255
NO_x	0.000699	0.001378	0.000999	0.020485
N_2O	3.68×10^{-6}	1.05×10^{-5}	7.36×10^{-6}	3.08×10^{-5}
CH_4	2.94×10^{-6}	7.50×10^{-6}	4.21×10^{-6}	2.05×10^{-5}
VOC	1.18×10^{-5}	2.55×10^{-5}	1.68×10^{-5}	6.15×10^{-5}
CO	6.84×10^{-5}	0.0001877	9.78×10^{-5}	0.000537

Since the environmental impact assessment in Section 6.1 reveals that the majority of the environmental impacts were derived from the manufacturing stage (see Figure 6.1), then the environmental effects should be considered in this phase. There are nine components related to the disaggregated wind turbine assessment. The components in the component breakdown are the low voltage transformer (1.8 MVA), tower, blade, blade extender, hub, generator, gearbox, main shaft and basement foundation as illustrated in Table 6.2.

The results of the emission calculations in the LCI are presented in Table 6.2. Based on Chapter 5 (Sections 5.3.1, 5.3.2, and 5.3.3), the translation from the different emissions to one emission equivalent which matches one of the environmental impact categories, is simply done by multiplying the matrix characterization **q** and matrix **g** of the environmental intervention (by application of (5.2) in Chapter 5, and (G2), (G3), (G4) in Appendix G). The detailed results are shown in Appendix G.

Table 6.3 describes the amounts of the emission equivalent in Life Cycle Impact Assessment in terms of each component characterized in the three categories of AP, GWP and POCP. The emission values play a vital role in the interpretation.

Table 6.3: Environmental impacts of each component by functional unit.

$\frac{g}{kWh}$	**LV transformer**	**Tower**	**Blade**	**Blade extender**	**Hub**	**Generator**	**Gearbox**	**Main shaft**	**Basement**
SO_2-eq	0.000957	0.034016	0.004991	0.001843	0.001878	0.001568	0.00317	0.002243	0.022665
CO_2-eq	0.14388	3.716373	0.771478	0.200848	0.280929	0.170857	0.409428	0.244877	5.626459
C_2H_4-eq	8.18×10^{-5}	0.00167	0.000245	9.06×10^{-5}	9.43×10^{-5}	7.71×10^{-5}	0.000158	0.00011	0.001006

In Figure 6.2, the wind turbine is further split into different main parts. The pie charts show that both the tower and the basement occupy the largest areas in almost all of the three impact categories. In the acidification and photo-oxidant smog categories, the tower contributes approximately 47 % to each while the figures for the basement are about 39 % and 28 % respectively. In the climate change group, nearly half of the CO_2-eq emission is accounted for the basement, followed by the tower as the second largest contributor. This indicates that both the tower and the foundation are the two significant components contributing to the overall impacts of the wind farm; hence, the manufacturing stage plays a vital role in the total wind farm impact assessment. It is important to note that the total environmental impact on climate change for the wind farm is 14.69 g CO_2-eq/kWh_{el} while the foundations contribute 5.62 g CO_2-eq/kWh_{el}, which is 38 % of the total impact, and the tower contributes 3.7 g CO_2-eq/kWh_{el}, which corresponds to 25 % of the total impact.

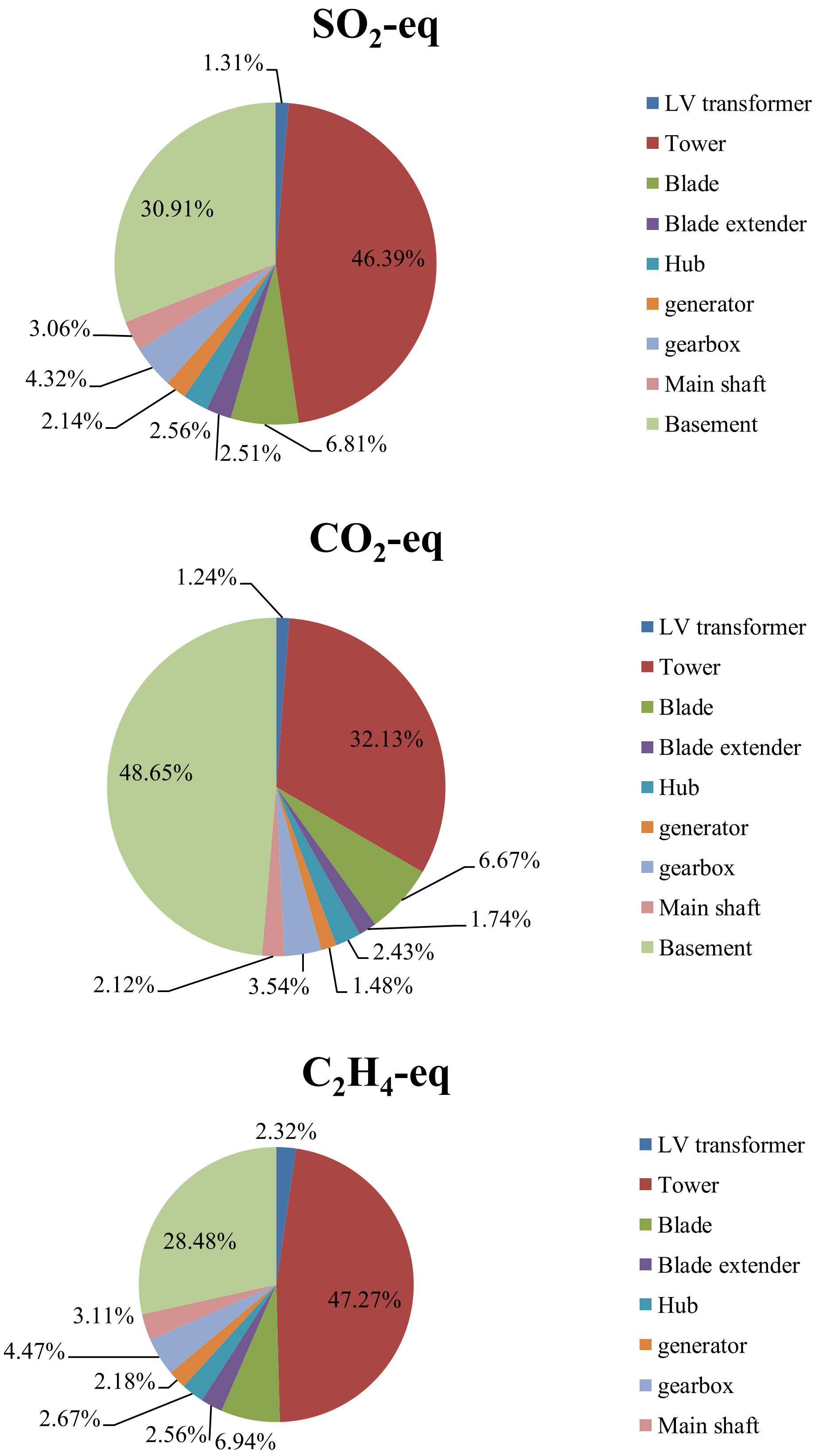

Figure 6.2: Environmental impact distributed on wind farm by unit process.

The blades contribute roughly 6% to the total impact, which is the third largest contributor in all the three categories. The other six constituents, namely blade extender, hub, generator, gearbox, main shaft and LV transformer, contribute almost equally from 1 % to 4 % in all three categories.

6.3 Energy payback time

The calculated capacity factor for the wind farm was previously determined to 0.31 and the working conditions established an average production of 2715.6 full-load hours annually. The total of output can be calculated 82.45 GWh per year or 1629.36 GWh during the life cycle.

Table 6.4 shows the primary energy required from fossil fuel sources to manufacture 1 kg of raw material. Based on the data for each material, the energy requirement during the manufacturing process is estimated and calculated.

Table 6.4: **Total primary energy consumption in mega-joules (MJ) for production of particular materials per kg (Schleisner 2000)**

Material(1 gk)	Coke (MJ/kg)	Coal (MJ/kg)	Oil (MJ/kg)	Natural gas (MJ/kg)	Total (MJ/kg)	adjusted	% Adjusted	Real value (MJ/kg)
Steel	1.6	17.4	6.55	0.1	25.65	22.87	17.7	21.11
Aluminum	0	27.3	9.7	2.15	39.15	35.7	8.80	35.7
Copper	3	45.1	13.6	16.5	78.2	75.6	3.30	75.62
Plastic (polyester/epoxy)	0	30.8	9.8	5.1	45.7	5.8	0.00	45.7
PVC	0	19	12.6	6.6	38.2	38.2	0.00	38.2
Rubber	0	19.8	20.5	0	40.3	40.3	0.00	40.3
Reinforced iron (rebars)	7.4	10.6	18.2	0.1	36.3	29.3	19.82	29.11
Concrete	0	3.45	0.23	0	3.68	3.64	0.00	3.68
Lead	0	20.3	9	6.3	35.6	35.6	0.00	35.6
Zinc	0	61.3	9.3	2.4	73	73	0.00	73
Float glass	0	1	0.8	7.5	9.3	9.4	0.00	9.3
Packing glass	0	2	0.8	5.3	8.1	8.1	1.00	8.02
Insulations, rock wool (/m3)	168	84	81	3	336	NA	0.00	336
Insulation, glass wool (/m3)	0	121	6	102	229	NA	0.00	229

Data sources are available for assessing the interaction between the manufacturing phases of a wind turbine and the depletion of energy natural resources such as coke, coal, oil and natural gas. In this work, this data is used to calculate the total energy requirement for the production of the main components of a wind turbine and then it is used to calculate the energy payback time for the total wind farm. Table 6.5 gives the data for fossil fuel use during the manufacturing.

Table 6.5: The total energy consumption during all manufacturing stage of wind turbine.

Materials of wind turbine	Kg/turbine	Kg of 20 turbines	Energy consumption factors (MJ/kg)	Total energy consumed for production (MJ)
Chromium steel	19071	381420	33.7	12853854
Glass fiber	22543	450860	45.7	20604302
Aluminum 0% recycle	560	11200	35.7	399840
Cast iron	16353	327060	29.11	9520717
Chromium steel	38631	772620	21.11	16310008
Copper	672	13440	75.67	1017005
Epoxy resin	648	12960	45.7	592272
Reinforcing steel	27848	556960	25.65	14286024
Rubber	280	5600	40.3	225680
Steel, low alloyed	28296	565920	22.87	12942590
Concrete	444.152	8883.04	3.68	32689.59
Total				**88784982**

The total primary energy requirement from fossil fuel sources is 88784.982 GJ (Table 6.5), or 24.662 GWh. The payback time of energy input can be defined as the ratio of total life-cycle energy input to the net electricity generated (Lee & Tzeng 2008a), and calculated as

$$\text{paypack time}=\frac{\text{energy input for manufacturing of components}}{\text{net annual electricity generated}}$$
$$=\frac{24.662\ \text{GWh}}{82.45\ \text{GWh/year}}=0.299=0.3\ \text{year}=3.6\ \text{months} \tag{6.1}$$

Therefore it can be stated that the energy payback time for the wind farm is 3.6 months, which is a good performance and correlates well to previous studies. The energy payback period is estimated between 3.1 months and 20 months by Khan 2005 (Khan, Hawboldt & Iqbal 2005), 0.39 years by Schleisner (2000) (Schleisner 2000), 0.62 years by Martinez (2009) (Martınez et al. 2008), and 1.7 years by Tremeac (2009) (Tremeac & Meunier 2009). Wind power systems in Vietnam appear to be performing relatively well. It is important to note that the total energy required for manufacturing the towers and foundations come from Vietnam; the total domestic energy input consumed is calculated for both as being 17859432 MJ. This is over 20 % of the total energy consumption of all manufacturing stages of the wind turbine. Therefore, the Vietnam energy payback time should be assessed more carefully.

To compare the energy payback time as a whole for the wind farm, all of the energy required for every stage must be considered. While the total energy requirement for all the wind farm stages is calculated as 1.29×10^8 MJ in Table 6.6, with the application of (6.1), the payback time for the whole process was found to be 0.434 years or 5.2 months. This takes into consideration all of the energy consumed. This table also describes the total energy requirements for every life cycle stage (which is detailed in Appendix H), and then compares with the total energy inputs.

Table 6.6: The comparison of different energy consumption stages with the total energy consumption and the annual power generated.

Stages	**Energy consumption (MJ)**	**compared to total energy consumption**	**Compared to an annual power generated**
Manufacture of wind turbine	88784982	0.69	0.299121
Manufacture of cables	21793035	0.17	0.073422
Manufacture of transformers	5186641	0.04	0.017474
Transportation	2184515	0.02	0.00736
Construction	2708471	0.02	0.009125
Operation and maintenance	24384	0.00	8.22×10^{-5}
Gearbox replacement	6153426	0.05	0.020731
Decommissioning	1775700	0.01	0.005982
Total energy consumption	1.29×10^{8}	1	0.434607

As can be seen from Figure 6.3, the manufacture of the turbine still dominates the energy investment. It is up to 70 % of the total energy input, followed then by the electrical cables at 17 %, which corresponds to 21793 GJ of the total. The decommissioning stage took the smallest percentage at 1 %; gearbox replacement during time cycle is five times of that of disposal stage. This means that the replacement will have a significant impact on the energy return.

To conclude based on the analysis of the wind farm in terms of its environmental impact and energy payback analysis, the most important aspect to consider is the manufacture of the wind turbine. Further, to assess the manufacturing stage, the two key parameters in this study are proposed CO_2-equivalent emission and energy payback time. Although they can vary and depend on the assumptions made, the most important component is still the manufacturing phase, which can be affected by the use of recycled materials. The analysis shows that most materials in the wind turbine can be recycled, and this can have large impact on emission credit.

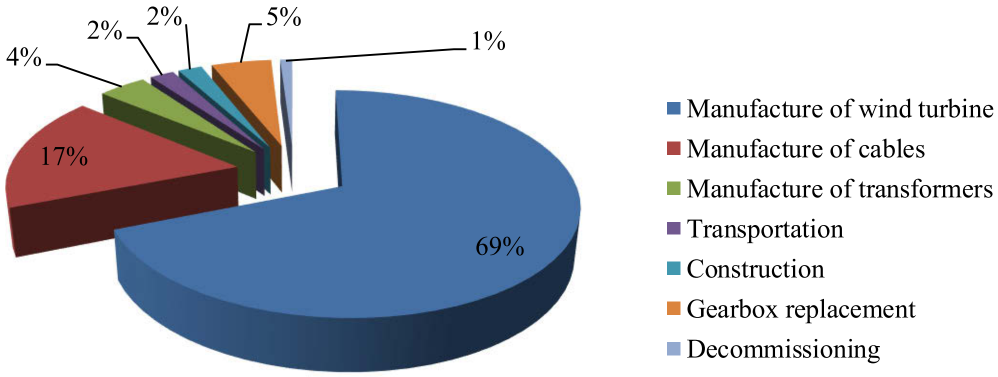

Figure 6.3: The comparison between the energy input of various stages and total energy consumption of wind farm.

The energy payback time for a hydro power plant is 16.2 months and for a coal fire power station it is 14.2 months; these are 3.16 and 2.72 times longer than those for wind power (Guezuraga, Zauner & Pölz 2010). Due to the rapid growth in the demand for energy experienced in the recent years, it is very important to invest in these technologies in order to achieve more sustainable development. According to research from Vietnam Coal, while power plants and combined heat power plants represent the largest CO_2 emission (228 g CO_2-eq/kWh and 1046 g CO_2-eq/kWh, respectively), the wind farm in this study has been calculated as having about 14 g CO_2-eq/kWh. This means that wind energy gradually becomes more attractive in terms of the power for future energy pathways in Vietnam. The results from this study should also be used as reliable data to promote more sustainable policies to support wind energy development. Visual and noise pollution are not considered in this analysis, but they should be carefully considered as they represent a barrier in the development process of this source of renewable energy.

6.4 Uncertainty Analysis

It is crucial to know that the uncertainty in a unit-process-based Life Cycle Assessment (PLCA) will occur in almost any LCA case. This is because they are based mainly on inventory data and that uncertainties will occur in the collection of data. For example, the manufacturing process for an on shore wind farm, such as in this study, is determined mostly by using other studies, so then data and information were derived from various sources. This leads to the high uncertainty since the data is not the primary data collected from the manufacture of the actual case under study.

It is possible to address the problems associated with the different data quality indicators in the inventory. One method was developed by Weidema 1996 (Weidema & Wesnæs 1996), which presented five data quality indicators: reliability, completeness, temporal correlation, geographical correlation, and technological correlation. It is assumed that the data sources in this study are reliable and complete (coming from industrial and academic sources, and academic literature), and within the scope boundary and definition of this study. Therefore the two rows for the reliability and completeness criteria of the inventory data have to correctly meet the requirements and eligibility. A data quality matrix is set up as shown in Table 6.7. A pedigree illustrates key aspects in a matrix:

- Columns represent pedigree criteria.
- Lines represent qualitative characterizations of each criteria by expressing different levels of data quality or uncertainty.
- Quantitative scores are assigned to each qualitative description.

Table 6.7: The matrix of uncertainty for the inventory.

Assumed uncertainty	Fully quantified or 5% or Less	Fully quantified or 5 - 10%	Fully quantified or 10 - 25%	Fully quantified or 25 - 50%	Fully quantified or unknown or larger than 50%
Temporal correlation U3	Less than 3 years of difference to year of study	Less than 6 years difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than 15 years of difference
Geographical correlation U4	Data from area under study (e.g. Alberta)	Data from larger area but including area under study (e.g. Canada)	Data from outside the specified location but with similar condition (e.g. USA/Denmark)	Data from outside the area but with slightly similar condition (e.g. Outside of North America and Europe)	Data from unknown area
Technological correlation U5	Data for similar process and materials from same producer and technology under study	Data for similar process or materials under study but from different producer	Data for similar processes or materials but from different technology	Data for related processes or materials but from same technology	Data for related processes or materials but from different technology

Source: modified from the table Pedigree matrix in open LCA (Rodríguez 2014b) and (Nico W. Van Den Berg et al. 2011)

When the data quality matrix has been formulated it can be used with all inventory data to quantify the associated uncertainty. The overall uncertainty for the input data was determined by taking the square root of the sum of squares of the three uncertainty factors determined from the matrix (Table 6.7). From these values, uncertainty for a unit process has been determined using the weighted average method. Based on the developed data quality matrix, uncertainties were found for the different unit processes; and these are presented in Table 6.8. It is important to note that the assumed uncertainties for the unit processes may be somewhat overestimated in few circumstances.

The uncertainties are helpful in detailing the LCA results by providing inputs from a probable range of values corresponding to different unit processes in a Monte Carlo simulation. This simulation tool takes random values from a specified range (in this case +/-uncertainty range) for different unit processes, runs repeated iterations, and provides an overall uncertainty in the final LCA results (Huijbregts 1998). This assumes a sufficiently large sample size of test runs. Thus, it helps in conveying more information to the decision maker rather providing a fixed value, which could be of limited use.

Table 6.8: Uncertainty for unit process of all wind farm configurations.

Unit processes	Indicators	Uncertainty factor	Standard deviation (SD %)	Weighted average SO_2-eq	Weighted average CO_2-eq	Weighted average C_2H_4-eq
Manufacture stage	U3	10 %	37.41	82.58 %	81.0 %	60.44 %
	U4	30 %				
	U5	20 %				
Turbine transportation and installation stage	U3	10 %	17.32	11.21 %	7.63 %	24.50 %
	U4	10 %				
	U5	30 %				
Power generation & maintenance stages	U3	5 %	22.91	3.94 %	3.10 %	5.76 %
	U4	20 %				
	U5	10 %				
Decommissioning	U3	10 %	36.7	2.28 %	8.21 %	9.29 %
	U4	25 %				
	U5	25 %				

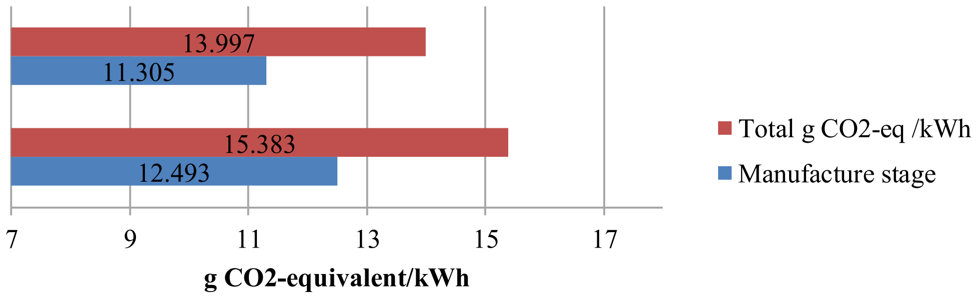

Figure 6.4: Comparison of Global Warming Potential impacts from configurations under 95 % confidence range uncertainties.

After calculation (see appendix I for more details), Figures 6.4, 6.5, and 6.6 illustrate the findings from the uncertainty analysis and compares them to the largest impact from the manufacture stage. It is apparent that for acidification, climate change and the photo oxidant smog, the impact of the configuration is comparable between the manufacturing stage and the total life cycle assessment phases. These results show that range of CO_2-eq could vary in the range from 14 to 15.3 g per 1 kWh generated of total wind farm while that of manufacture is from 11 g to around 12.5 g CO_2- eq

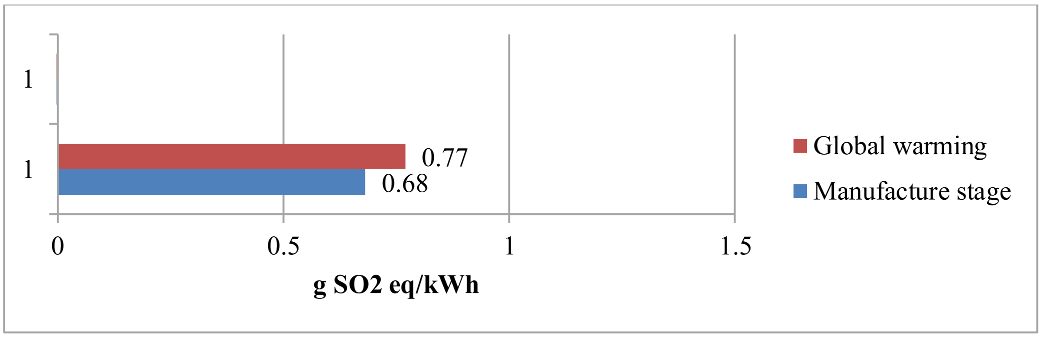

Figure 6.5: Comparison of Acidification potential impacts from configurations under 95 % confidence range uncertainties.

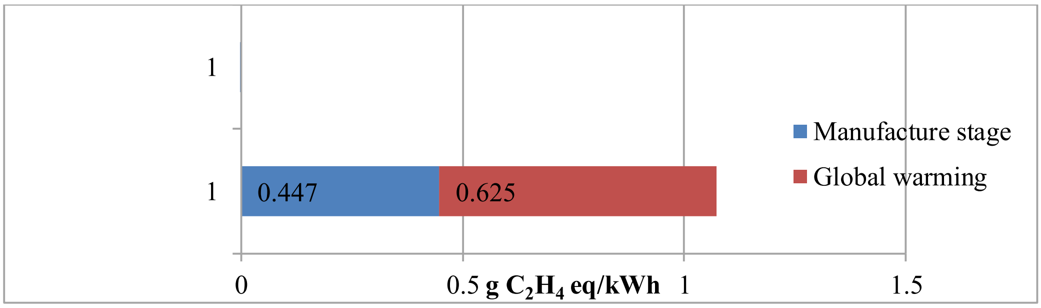

Figure 6.6: Comparison of photo-oxidant chemical potential impacts from configurations under 95 % confidence range uncertainties.

6.5 Conclusions and future work

6.5.1 Conclusion

In this thesis, a life cycle model was created in order to estimate and analyze the environmental impacts associated with integrating wind energy. It was observed that the manufacturing stage is the unit process that has the most impacts, which is associated with the materials used for wind turbines. To reduce these impacts, a solution would be to propose to use of raw materials which address energy saving and clean technology. However, it needs the support of the Vietnamese government, for example, changing policy to encourage companies to invest in wind technologies, with the expansion of manufacturing factories which implement clean energy policies, possibly with the use of subsidies. In addition, in the wind farm studied, each stage of the entire life cycle is compared for emissions from the energy requirement. This plant was determined to perform quite well across all the stages.

Furthermore, an impressive point is that in the recycling stage of the global impact category, more materials can be reused or recycled. If recycling is carried out then fewer emissions are emitted into atmosphere. This is especially true for the steel and iron, which have high energy requirements and can damage the environment through depletion of natural resources.

6.5.2 Future research

This study does not cover the issue of variation of wind electricity transmitted to the national grid in terms of it being an intermittent energy source. In addition, fossil fuel resources such as gas, oil and coal were not considered as complementary energy sources to wind energy. The unit process chain should be analyzed in depth and for many different scenarios, such as the integration of many regional areas within one functional unit, and comparison of different transportation approaches. Further research should examine the influence of the wind farm infrastructure configuration; also, the collection substation needs to be analyzed. The expansion of the impact categories, such as land use and fossil fuel energy resources demands, and the emission factors, should be pursued in further studies under Vietnamese scenarios. Under such circumstances, how the life cycle research reported here changes would be interesting to analyze and is strongly recommended for future studies.

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Appendix A

Table A.1: Wind turbine main characteristics.

Parameters	**Specifications**	**Sources**
Rated power output/wind turbine	1.5 MW	(Khanh, 2012 [A6])
Number of wind turbines	20 Units	(Khanh, 2012 [A6])
Total installed capacity	30 MW	(Khanh, 2012 [A6])
Turbine manufacturer and models	Fuhrländer – Germany, FL MD - 77	(Khanh, 2012 [A6])
Location –town and state	Binh Thuan, Vietnam	(Khanh, 2012 [A6])
Wind farm owner	REVN	(Khanh, 2012 [A6])
Predicted life of nacelle (years)	20	(Khanh, 2012 [A6])
Capacity factor	0.31	Calculated
Full load hours	2,715.6 h	Calculated
Cut –in wind speed (m/s)	4 m/s	(TrueWind Solutions LLC, 2001 [A10])
Cut-out wind speed (m/s)	25 m/s	(TrueWind Solutions LLC, 2001 [A10])
Average wind speed of specific site (m/s)	7.2 m/s	(TrueWind Solutions LLC, 2001 [A10])
Hub height	60 m	(Khanh, 2012 [A6])
Blade length diameter	77 m	(Khanh, 2012 [A6])
Losses in Transmission	0.03	(ICONTEC, 2012 [A5])
Lifetime of transformer	35 years	ABB 2003
Capacity of transformer	1x 45 MVA, 20x1.8MVA	(Khanh, 2012 [A6])
Annual production (excl. losses)	85 GWh	(Khanh, 2012 [A6])
Annual production (incl. losses)	82.45 GWh	Calculated
Production over the life time (incl. losses)	1,292.58 GWh	Calculated
Length of transmission line 110 kV	1,500 m	(Khanh, 2012 [A6])

Appendix B

Table B.1: Material distribution in wind turbine.

Material	Rotor mass [ton]		Nacelle [ton]		Tower [ton]		Basement [ton]	
	One unit	20 Units	One unit	20 units	One unit	20 units	One unit	20 units
Glass fiber reinforced plastics	19.071	381.420	3.472	69.440				
Chromium steel	7.047	140.940	31.620					
Cast iron	7.281	145.620	9.072					
Steel, low alloyed			10.192	203.840	128.922	2578.440		
Rubber			0.280	5.600				
Aluminum 0% recycle			0.560	11.200				
Copper			0.672	13.440				
Lubricant			0.168	3.360				
Epoxy resin					0.648	12.960		
Concrete							444.152	8883.040
Reinforced steel							27.848	556.960

Appendix C

Table C.1: Material type and disposal method considered.

Material type	Removal Scenario	Reference
Iron	90% Recovery 10% losses in landfill	(Vetas, July, 2006 [A11])
Cast iron	90% Recovery 10% losses in landfill	(Vetas, July, 2006 [A11])
Steel	90% Recovery 10% losses in landfill	(Vetas, July, 2006 [A11])
Stainless steel	90% Recovery 10% losses in landfill	(Vetas, July, 2006 [A11])
High-strength steel	90% Recovery 10% losses in landfill	(Vetas, July, 2006 [A11])
Lead	90% Recovery 10% losses in landfill	(Vetas, July, 2006 [A11])
Aluminum	90% Recovery 10% losses in landfill	(Vetas, July, 2006 [A11])
Copper	95 % recovery 5% losses in landfill	(Martınez et al, 2008 [A7])
Epoxy	Landfill 100%	(Martınez et al., 2008 [A7])
Concrete	Landfill 100%	(Martınez et al., 2008 [A7])
Plastic PVC	Landfill 100%	(Vetas, July, 2006 [A11])
Other plastics	Combusted 100%	(Vetas, July, 2006 [A11])
Rubber	Combusted 100%	(Vetas, July, 2006 [A11])
Fibre glass	Landfill 100%	(Vetas, July, 2006 [A11])
Oil	Combusted 100%	(Vetas, July, 2006 [A11])

Appendix D

Table D.1: Emission/kg material produced and energy embodied in unit processes.

Material [1kg]	CO_2 [g]	SO_2 [g]	NO_x [g]	N_2O [g]	CH_4 [g]	NMVOC [g]	CO [g]	MJ/kg (calc.)	Sources
Manufacture									
Steel carbon/low alloyed	2,306.50	14.50	9.50	0.070	0.040	0.160	0.930	34.000	(White et al, 2000 [A12])
Steel stainless	3,275.00	14.50	9.50	0.070	0.040	0.160	0.930	53.000	(White et al 2000 [A12])
Rebar steel	2,163.83	6.62	2.88	0.070	0.100	3.740	26.53	34.260	(Schleisner, 2000 [A9])
Aluminum	3,433.50	21	13.00	0.105	0.065	0.145	0.745	39.150	(Schleisner, 2000 [A9])
Copper	6,536.00	35.61	23.19	0.190	0.160	0.250	1.570	78.200	(Schleisner, 2000 [A9])
Plastic, polyester/epoxy	3,941.00	22.91	14.71	0.120	0.080	0.200	1.100	45.700	(Schleisner, 2000 [A9])
PVC	3,113.00	14.75	10.49	0.090	0.080	0.200	1.040	76.400	(Schleisner, 2000 [A9])
Rubber	3,398.00	16.06	10.61	0.100	0.060	0.180	1.060	79.600	(Schleisner, 2000 [A9])
Reinforced iron (rebars)	3,114.00	14.58	8.89	0.090	0.060	0.180	1.570	29.300	(Schleisner, 2000 [A9])
Cast iron	3,114.00	14.58	8.89	0.090	0.060	0.180	1.570	29.300	(Schleisner, 2000 [A9])
Concrete (construction)	703.00	0.01	2.50	0.000	0.000	0.000	0.000	3.680	(Schleisner, 2000 [A9])
Lead	2,953.00	18.19	19.82	0.110	0.070	0.550	2.030	35.600	(Schleisner, 2000 [A9])
Zinc	6,648.00	47.49	35.66	0.230	0.120	0.600	2.390	73.000	(Schleisner, 2000 [A9])
Float glass	581.00	0.87	2.41	0.010	0.040	0.150	0.660	9.400	(Schleisner, 2000 [A9])
Packing glass	551.00	1.58	2.48	0.010	0.030	0.140	0.640	8.100	(Schleisner, 2000 [A9])
Insulations, rock wool (/m^3)	1,042.00	6.08	2.82	0.030	0.020	0.060	0.820	336.000	(Schleisner, 2000 [A9])
Insulation, glass wool (/m^3)	1,008.00	4.98	3.96	0.030	0.030	0.080	0.360	229.000	(Schleisner, 2000 [A9])
Concrete (foundation)	835.00	0.60	3.20	0.000	0.000	0.000	0.000	0.810	(Schleisner, 2000 [A9])
Recycle	**CO_2 –e**								
Steel	1819							9.7	(Martınez et al., 2008 [A7])
Aluminum	738							16.8	(Martınez et al., 2008 [A7])
Copper	3431							9.4	(Martınez et al., 2008 [A7])
Emission per kg material disposal									
Plastic (polyester/epoxy)	4680	3.6	6	0.16	0.24	0.36	87.52	0.04 (GHK, 2006)	(Schleisner, 2000 [A9])
PVC	4680	3.6	6	0.16	0.24	0.36	87.52		(Schleisner, 2000 [A9])
Rubber	3510	2.7	4.5	0.12	0.18	0.27	65.66		(Schleisner, 2000 [A9])

Appendix E

E.1 Formulation Calculation of Inventory.

The inventory analysis formulation is developed in five steps. First, the process is modelled as a column vector, for example, the electricity production which required 3 litres of fuel input to produce 12 kWh of electricity as an output, and releases 1.2 kg of Carbon dioxide (CO_2) and 0.3 of sulphur dioxide (SO_2) as shown in Figure E.1.

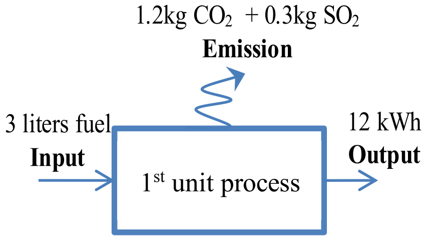


Figure E.1: The production of electricity, the 1st modelled unit process.

Since a linear space is an abstract concept which allows to unique representation of a multidimensional data point as a simple vector then the unit process can be performed using a linear space for a process vector **P** (E1). See Apostol 1969 [A1] for more information.

$$\mathbf{P} = \begin{bmatrix} -3 \\ 12 \\ 1.2 \\ 0.3 \end{bmatrix} = \begin{pmatrix} \text{litre of fuel} \\ \text{kWh of electricity} \\ \text{kg } CO_2 \\ \text{kg } SO_2 \end{pmatrix} \tag{E.1}$$

The minus sign is a convention indicator for the data input. It is indicates the positive flow direction only. The second step is to present the system of unit process. It is supposed that 100 litres of fuel needs 50 litre of crude oil, and that 10 kg CO_2 and 2kg SO_2 ere emitted to environment. Figure E.2 shows the second unit process chart.

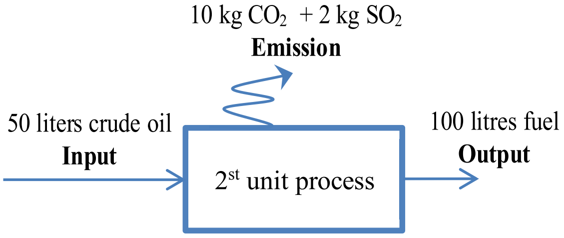


Figure E.2: The production of fuel, the 2st modelled unit process.

Similarly, the vector in the 2st modelled unit process is that based on the first model, the fifth parameter in **P2** added the crude oil consumption so that:

$$\mathbf{P}_2 = \begin{bmatrix} 100 \\ 0 \\ 10 \\ 2 \\ -50 \end{bmatrix} = \begin{pmatrix} \text{litre of fuel} \\ \text{kWh of electricity} \\ \text{kg CO}_2 \\ \text{kg SO}_2 \\ \text{litre of crude oil} \end{pmatrix} \tag{E.2}$$

Before integration of two unit process displayed in Figure E3, the first unit process must be modified and the fifth parameter added to match the second process where:

$$\mathbf{P}_1 = \begin{bmatrix} -3 \\ 12 \\ 1.2 \\ 0.3 \\ 0 \end{bmatrix} = \begin{pmatrix} \text{litre of fuel} \\ \text{kWh of electricity} \\ \text{kg CO}_2 \\ \text{kg SO}_2 \\ \text{litre of crude oil} \end{pmatrix} \tag{E.3}$$

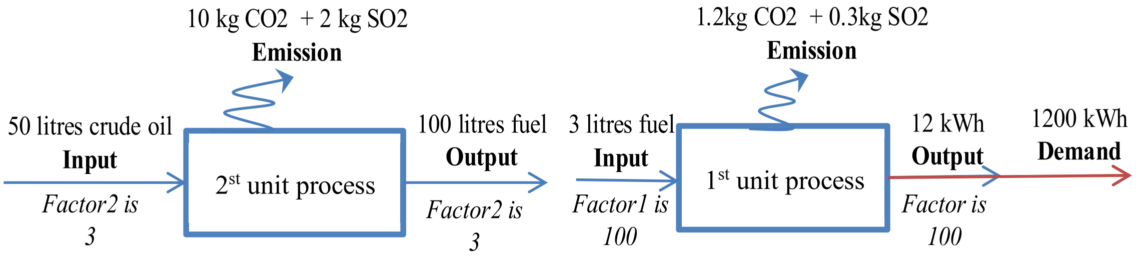


Figure E.3: Incorporation of two unit process.

The combination of both unit processes is

$$\mathbf{P} = \left[\mathbf{P}_1 \mid \mathbf{P}_2\right] = \left[\begin{bmatrix} -3 \\ 12 \\ 1.2 \\ 0.3 \\ 0 \end{bmatrix} \begin{bmatrix} 100 \\ 0 \\ 10 \\ 2 \\ -50 \end{bmatrix} \right] \tag{E.4}$$

P is preferred as the process matrix; the new convention is that the first column represents the unit process of electricity generation; the second is the unit process of fuel production. For expansion, assume that every column vector is an individual unit process. A matrix process is defined as $[P_{ij}]$ with i denotes the row index and j the index of column.

The next step is to divide the matrix into two parts. The first one presents the flows related to system economics, referred to as the economic flows. The second is are the environmental flows. In this case the two first rows are the economic flows and the remaining are the environmental flows. The matrix **P** can then be split as two partitions:

$$\mathbf{P} = \left[\begin{array}{cc} -3 & 100 \\ 12 & 0 \\ \hline 1.2 & 10 \\ 0.3 & 2 \\ 0 & -50 \end{array}\right] = \left[\begin{array}{c} \mathbf{A} \\ \hline \mathbf{B} \end{array}\right] \qquad \text{(E.5)}$$

where,

A is presented as technology matrix

B is environmental matrix

Note that the number columns of matrix **A, B, P** are similar.

In the fourth step, which involves in the Goal and Scope of definition, a reference flow is identified as the required performance ϕ of the system. For easier understanding, a reference flow in this example could be set as 1200 kWh of power generation. The vector for thr requirement is

$$\mathbf{f} = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 1200 \end{bmatrix} \qquad \text{(E.6)}$$

Where the vector **f** will be referred to as the final (external) demand vector, because it is an exogenously define set of economic flows.

Finally, a set of environmental flows related to reference flows is set up to define a vector for the environmental intervention; this is the inventory vector **g**:

$$\mathbf{g} = \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} \qquad \text{(E.7)}$$

where

g_1 denotes that the number of kg of CO_2 released by the total system

g_2 denotes that the number of kg of SO_2 released by the total system

g_3 denotes that the amounts of crude oil litres, required by the total system

The final demand vector and the inventory vector is **q**

$$\mathbf{q} = \left[\begin{array}{c} \mathbf{f} \\ \hline \mathbf{g} \end{array}\right] = \left[\begin{array}{c} 0 \\ 1200 \\ \hline g_1 \\ g_2 \\ g_3 \end{array}\right] \qquad \text{(E.8)}$$

It is simple to see that the reference flows and the unit processes differ. The unit processes 1 and 2 generate 12 and 0 kWh while the final demand needs 1200 kWh. Obviously, unit process 1 is required to be scale up by a factor of 100 times to meet the energy requirement. This leads to the input requirement of unit process 1 also being multiplied by 100 to meet the scale (Figure E3). Similarly in order to meet the requirement for the fuel input for unit process 1, a factor of 3 is determined as the scaling factor in order to meet the final demand. This is the effects on economic flows.

In the same way, the environmental flows are also affected by the same scale. Considering to the both of unit process, the amount of CO_2 will increase up to 120 kg and 30 kg, while there is a scaling of 30 kg and 6 kg for SO_2 for first unit and the second unit processes respectively. The amount of crude oil input in unit process 2 is 150 litres. To sum up, for the final demand, the factors for each unit process can be determined; for this example, the inventory vector **g** is

$$\mathbf{g} = \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} = \begin{bmatrix} 120+30 \\ 30+6 \\ 150 \end{bmatrix} = \begin{pmatrix} 150 \text{ kg CO}_2 \\ 36 \text{ kg SO}_2 \\ 150 \text{ litres crude oil} \end{pmatrix} \qquad \text{(E.9)}$$

The scaling factors are represented by the vector by **s** and written as

$$\mathbf{s} = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix}$$

and

$$\text{matrix } \mathbf{A} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix};\ \mathbf{s} = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix};\ \mathbf{f} = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix};\ \text{matrix } \mathbf{B} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \\ b_{31} & b_{32} \end{bmatrix};\ \mathbf{g} = \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} \qquad \text{(E.10)}$$

For the first economic flow, in the first row, a balance equation can be set up for fuel where:

$$a_{11} \times s_1 + a_{12} \times s_2 = f_1 \tag{E.11}$$

For the second economic flow, in the second row, the balance equation is

$$a_{21} \times s_1 + a_{22} \times s_2 = f_2 \tag{E.12}$$

Generally, for put both (E11) and (E12), the total system equation is:

$$\begin{cases} a_{11} \times s_1 + a_{12} \times s_2 = f_1 \\ a_{21} \times s_1 + a_{22} \times s_2 = f_2 \end{cases}$$

which can be written as a matrix calculation

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} \longrightarrow \mathbf{As} = \mathbf{f} \longrightarrow \mathbf{s} = \mathbf{A}^{-1}\mathbf{f} \tag{E.13}$$

This is a method for calculating the scaling vectors **s** for a unit process based on the economic flows. With knowledge of the final demand $\mathbf{A}^{-1}\mathbf{f}$ it can be calculated. $\mathbf{A}^{-1}$ is the inverse matrix of matrix technology **A** (**A** must be square and invertible).

To solve the inventory problem, the environmental flows must be obtained on a system-wide aggregated manner. Based on the scaling factors that are already known, the environmental flows can be accounted for in the follow way.

For the first environmental flow, CO_2:

$$g_1 = b_{11} \times s_1 + b_{12} \times s_2$$

For the second flows, SO_2:

$$g_2 = b_{21} \times s_1 + b_{22} \times s_2$$

For the final flow, in litres:

$$g_3 = b_{31} \times s_1 + b_{32} \times s_2$$

So gathering the three Equations together

$$\begin{cases} g_1 = b_{11} \times s_1 + b_{12} \times s_2 \\ g_2 = b_{21} \times s_1 + b_{22} \times s_2 \\ g_3 = b_{31} \times s_1 + b_{32} \times s_2 \end{cases}$$

This can be written as matrix calculation:

$$\begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \\ b_{31} & b_{32} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} \longrightarrow \mathbf{g} = \mathbf{Bs} \tag{E.14}$$

The expansion of this, for *n* economic flows and *m* environmental flows, gives:

$$\begin{cases} a_{11}s_1 + \cdots + a_{1i}s_i + \cdots + a_{1n}s_n = f_1 \\ \vdots \\ a_{i1}s_1 + \cdots + a_{ii}s_i + \cdots + a_{in}s_n = f_i \\ \vdots \\ a_{n1}s_1 + \cdots + a_{ni}s_i + \cdots + a_{nn}s_n = f_n \end{cases} \qquad \mathbf{A} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}; \ \mathbf{s} = \begin{bmatrix} s_1 \\ M \\ s_n \end{bmatrix}; \ \mathbf{f} = \begin{bmatrix} f_1 \\ M \\ f_n \end{bmatrix} \tag{E.15}$$

E.2 Detailed Inventory calculation.

Table E.1: Inventory list after calculation of rotor manufacture.

Inventory list	Rotor			
	Input		**Scaling factor Vector s [kg/kWh]**	**Output**
	Environmental flows (matrix B, g)			**Environmental flows (matrix g) material emissions [g/kWh]**
Glass fibre	CO_2	3941	0.000234	0.922194
	SO_2	22.91		0.005361
	NO_x	14.71		0.003442
	N_2O	0.12		2.81×10^{-5}
	CH_4	0.08		1.87×10^{-5}
	VOC	0.2		4.68×10^{-5}
	CO	1.1		0.000257
Chromium steel	CO_2	2306	0.0000865	0.199469
	SO_2	14.5		0.001254
	NO_x	9.5		0.000822
	N_2O	0.05		4.33×10^{-6}
	CH_4	0.04		3.46×10^{-6}
	VOC	0.16		1.38×10^{-5}
	CO	0.93		8.04×10^{-5}
Cast iron	CO_2	3114.00	0.0000894	0.278392
	SO_2	14.58		0.001303
	NO_x	8.89		0.000795
	N_2O	0.09		8.05×10^{-6}
	CH_4	0.06		5.36×10^{-6}
	VOC	0.18		1.61×10^{-5}
	CO	1.57		0.00014

$$\mathbf{g} = \mathbf{B}\hat{\mathbf{s}} = \begin{bmatrix} 3275 & 2306.5 & 3114 \\ 14.5 & 14.5 & 14.58 \\ 9.5 & 9.5 & 8.89 \\ 0.05 & 0.05 & 0.09 \\ 0.04 & 0.04 & 0.06 \\ 0.16 & 0.16 & 0.18 \\ 0.93 & 0.93 & 1.57 \end{bmatrix} \left(\frac{\text{g}}{\text{kg}} \right) \begin{bmatrix} 2.34 \times 10^{-4} & 0 & 0 \\ 0 & 8.65 \times 10^{-5} & 0 \\ 0 & 0 & 8.94 \times 10^{-5} \end{bmatrix} \left(\frac{\text{kg}}{\text{kWh}} \right)$$

$$= \begin{bmatrix} 0.76635 & 0.199469 & 0.278392 \\ 0.003393 & 0.001254 & 0.001303 \\ 0.002223 & 0.000822 & 0.000795 \\ 1.64 \times 10^{-5} & 4.33 \times 10^{-6} & 8.05 \times 10^{-6} \\ 9.36 \times 10^{-6} & 3.46 \times 10^{-6} & 5.36 \times 10^{-6} \\ 3.74 \times 10^{-5} & 1.38 \times 10^{-5} & 1.61 \times 10^{-5} \\ 0.000218 & 8.04 \times 10^{-5} & 0.00014 \end{bmatrix} \left(\frac{\text{g}}{\text{kWh}} \right)$$

E.3 Manufacture of nacelle

Table E.2: Inventory list after calculation of nacelle manufacture.

Inventory list	**Nacelle**			
	Input		**Scaling factor Vector s [kg/kWh]**	**Output**
	Environmental flows (matrix B, g)			**Environmental flows (matrix *g*) material emissions [g/kWh]**
Glass fibre	CO_2	3275	4.26×10^{-5}	0.14
	SO_2	14.5		6.18×10^{-4}
	NO_x	9.5		4.05×10^{-4}
	N_2O	0.07		2.98×10^{-6}
	CH_4	0.04		1.7×10^{-6}
	VOC	0.16		6.82×10^{-6}
	CO	0.93		3.96×10^{-5}
Steel, low alloyed	CO_2	2306.50	1.25×10^{-4}	0.000289
	SO_2	14.5		1.81×10^{-3}
	NO_x	9.5		1.19×10^{-3}
	N_2O	0.07		8.76×10^{-6}
	CH_4	0.04		5×10^{-6}
	VOC	0.16		2×10^{-5}
	CO	0.93		1.16×10^{-4}
Rubber	CO_2	3398.00	3.44×10^{-6}	1.17×10^{-5}
	SO_2	16.06		5.52×10^{-5}
	NO_x	10.61		3.65×10^{-5}
	N_2O	0.1		3.44×10^{-7}
	CH_4	0.06		2.06×10^{-7}
	VOC	0.18		6.19×10^{-7}
	CO	1.06		3.64×10^{-6}
Aluminum	CO_2	3433.50	6.87×10^{-6}	2.36×10^{-2}

0% recycle	SO_2	21		1.44×10^{-4}
	NO_x	13		8.94×10^{-5}
	N_2O	0.105		7.22×10^{-7}
	CH_4	0.065		4.47×10^{-7}
	VOC	0.145		9.97×10^{-7}
	CO	0.745		5.12×10^{-6}
Copper	CO_2	6536.00	8.25×10^{-6}	5.39×10^{-2}
	SO_2	35.61		2.94×10^{-4}
	NO_x	23.19		1.91×10^{-4}
	N_2O	0.19		1.57×10^{-6}
	CH_4	0.16		1.32×10^{-6}
	VOC	0.25		2.06×10^{-6}
	CO	1.57		1.3×10^{-5}
Chromium steel	CO_2	2306	0.0003881279	0.895023
	SO_2	14.5		0.005628
	NO_x	9.5		0.003687
	N_2O	0.05		1.94×10^{-5}
	CH_4	0.04		1.55×10^{-5}
	VOC	0.16		6.21×10^{-5}
	CO	0.93		0.000361
Cast iron	CO_2	3114.00	0.0001113566	0.346764
	SO_2	14.58		0.001624
	NO_x	8.89		0.00099
	N_2O	0.09		1×10^{-5}
	CH_4	0.06		6.68×10^{-6}
	VOC	0.18		2×10^{-5}
	CO	1.57		0.000175
Lubricant	CO_2	0	2.06×10^{-6}	0
	SO_2	0		0
	NO_x	0		0
	N_2O	0		0
	CH_4	0		0
	VOC	0		0
	CO	0		0

$$\mathbf{g}=\mathbf{B\hat{s}}=\begin{bmatrix} 3275 & 2{,}306.50 & 3{,}398.00 & 3433.5 & 6536 & 2306 & 3114 \\ 14.5 & 14.5 & 16.06 & 21 & 35.61 & 14.5 & 14.58 \\ 9.5 & 9.5 & 10.61 & 13 & 23.19 & 9.5 & 8.89 \\ 0.07 & 0.07 & 0.1 & 0.105 & 0.19 & 0.05 & 0.09 \\ 0.04 & 0.04 & 0.06 & 0.065 & 0.16 & 0.04 & 0.06 \\ 0.16 & 0.16 & 0.18 & 0.145 & 0.25 & 0.16 & 0.18 \\ 0.93 & 0.93 & 1.06 & 0.745 & 1.57 & 0.93 & 1.57 \end{bmatrix}\left(\frac{\text{g}}{\text{kg}}\right)$$

$$\begin{bmatrix} 0 & 1.25\times10^{-4} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3.44\times10^{-6} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 6.87\times10^{-6} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 8.25\times10^{-6} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.00039 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.00011 \end{bmatrix}\left(\frac{\text{kg}}{\text{kWh}}\right)$$

E.4 Manufacture of tower.

Table E.3: Inventory list after calculation of tower manufacture.

Inventory list	**Tower**			
	Input		**Scaling factor Vector s [kg/kWh]**	**Output**
	Environmental flows (matrix B, g)			**Environmental flows (matrix g) material emissions [g/kWh]**
Steel, low alloyed	CO_2	2306.50	0.001582	3.650005
	SO_2	14.5		0.022946
	NO_x	9.5		0.015034
	N_2O	0.07		0.000111
	CH_4	0.04		6.33×10^{-5}
	VOC	0.16		0.000253
	CO	0.93		0.001472
Epoxy resin	CO_2	3941.00	7.95×10^{-6}	0.031347
	SO_2	22.91		0.000182
	NO_x	14.71		0.000117
	N_2O	0.12		9.54×10^{-7}
	CH_4	0.08		6.36×10^{-7}
	VOC	0.2		1.59×10^{-6}
	CO	1.1		8.75×10^{-6}

$$\mathbf{g}=\mathbf{B\hat{s}}=\begin{bmatrix} 3.650005 & 0.031347 \\ 0.022946 & 0.000182 \\ 0.015034 & 0.000117 \\ 0.000111 & 9.54\times10^{-7} \\ 6.33\times10^{-5} & 6.36\times10^{-7} \\ 0.000253 & 1.59\times10^{-6} \\ 0.001472 & 8.75\times10^{-6} \end{bmatrix}\left(\frac{\text{g}}{\text{kg}}\right)\begin{bmatrix} 0.001582 & 0 \\ 0 & 7.95\times10^{-6} \end{bmatrix}\left(\frac{\text{kg}}{\text{kWh}}\right)$$

E.5 Manufacture of basement.

Table E.4: Inventory list after calculation of basement manufacture.

Inventory list	Basement			
	Input		Scaling factor Vector s [kg/kWh]	Output
	Environmental flows (matrix B, g)			Environmental flows (matrix g) material emissions [g/kWh]
Concrete	CO_2	835	0.005452	4.552302
	SO_2	0.6		0.003271
	NO_x	3.2		0.017446
	N_2O	0		0
	CH_4	0		0
	VOC	0		0
	CO	0		0
Reinforced steel	CO_2	3114.00	0.000342	1.064451
	SO_2	14.58		0.004984
	NO_x	8.89		0.003039
	N_2O	0.09		3.08×10^{-5}
	CH_4	0.06		2.05×10^{-5}
	VOC	0.18		6.15×10^{-5}
	CO	1.57		0.000537

$$\mathbf{g} = \mathbf{B}\hat{\mathbf{s}} = \begin{bmatrix} 4.552302 & 1.064451 \\ 0.003271 & 0.004984 \\ 0.017446 & 0.003039 \\ 0 & 3.08\times10^{-5} \\ 0 & 2.05\times10^{-5} \\ 0 & 6.15\times10^{-5} \\ 0 & 0.000537 \end{bmatrix} \left(\frac{\text{g}}{\text{kg}}\right) \begin{bmatrix} 0.005452 & 0 \\ 0 & 0.000342 \end{bmatrix} \left(\frac{\text{kg}}{\text{kWh}}\right)$$

E.6 Manufacture of transformers

The 1.5 MVA in the 45 MVA transformer must correspond to the generation 1 kWh in the function Unit. This accounts for a power factor. So that the scale factors chosen as 1.5 MVA/kWh. This is illustrated in Figure E.4. The inventory is given in Table E.5.

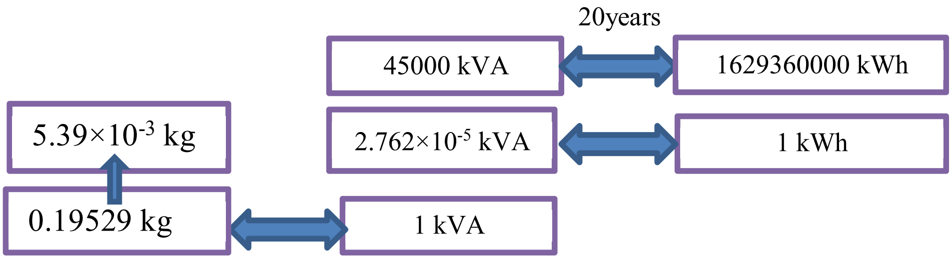


Figure E.4: The explanation of how to select the scale factor in entire wind farm life.

Table E.5: Inventory list after calculation of 45 MVA transformer manufacture.

Inventory	**Input Environmental flows (matrix B, g/kg unit)**		**Scaling factor Vector s [kg/kWh]**	**Output Environmental flows (matrix g) material emissions [g/kWh]**
Copper	CO_2	6536.00	0.00000539	0.035229
	SO_2	35.61		0.000192
	NO_x	23.19		0.000125
	N_2O	0.19		1.02×10^{-6}
	CH_4	0.16		8.62×10^{-7}
	VOC	0.25		1.35×10^{-6}
	CO	1.57		8.46×10^{-6}
Electrical steel	CO_2	2,163.83	0.00001231	0.026637
	SO_2	6.62		8.15×10^{-5}
	NO_x	2.88		3.55×10^{-5}
	N_2O	0.07		8.62×10^{-7}
	CH_4	0.1		1.23×10^{-6}
	VOC	3.74		4.6×10^{-5}
	CO	26.53		0.000327
Steel sheet	CO_2	3,275.00	0.00000509	0.01667
	SO_2	14.5		7.38×10^{-5}
	NO_x	9.5		4.84×10^{-5}
	N_2O	0.07		3.56×10^{-7}
	CH_4	0.04		2.04×10^{-7}
	VOC	0.16		8.14×10^{-7}
	CO	0.93		4.73×10^{-6}
Steel profile	CO_2	3114.00	0.00000466	0.01667
	SO_2	14.58		7.38×10^{-5}
	NO_x	8.89		4.84×10^{-5}
	N_2O	0.09		3.56×10^{-7}
	CH_4	0.06		2.04×10^{-7}
	VOC	0.18		8.14×10^{-7}
	CO	1.57		4.73×10^{-6}

$$\mathbf{g}=\begin{bmatrix}35.22904 & 26.63675 & 16.66975 & 14.51124\\ 0.191938 & 0.081492 & 0.073805 & 0.067943\\ 0.124994 & 0.035453 & 0.048355 & 0.041427\\ 0.001024 & 0.000862 & 0.000356 & 0.000419\\ 0.000862 & 0.001231 & 0.000204 & 0.00028\\ 0.001348 & 0.046039 & 0.000814 & 0.000839\\ 0.008462 & 0.326584 & 0.004734 & 0.007316\end{bmatrix}\left(\frac{\mathrm{g}}{\mathrm{kg}}\right)$$

$$\begin{bmatrix}0.00539 & 0 & 0 & 0\\ 0 & 0.01231 & 0 & 0\\ 0 & 0 & 0.00509 & 0\\ 0 & 0 & 0 & 0.00466\end{bmatrix}\left(\frac{\mathrm{kg}}{\mathrm{kWh}}\right)$$

Table E.6: The information for the 45 MVA transformer, the third column per the conversion to function Unit of 1kWh.

Materials	Kg/transformer	kg/MVA (calc.)	kg/kWh (calc.)	% mass (calc.)
Copper profile	8,788	195.29	0.00000539	0.146
Electrical steel	20,050	445.56	0.00001231	0.333
Steel sheet	8,258	184.11	0.00000509	0.137
Steel profile	7,600	168.89	0.00000466	0.126
Transformer oil	15,500	344.44	0.00000951	0.257

For the 1.8 MVA transformer, a similar inventory can be formulated as given in Table E.7.

Table E.7: Inventory list after calculation of 1.8 MVA transformer manufacture, with respect to functional unit (1kWh).

Inventory list	**1.8 MVA transformer**			
	Input		**Scaling factor Vector s [kg/kWh]**	**Output**
	Environmental flows (matrix B, g/kg unit)			**Environmental flows (matrix g) material emissions [g/kWh]**
Copper	CO_2	6536.00	0.000006926	0.045268
	SO_2	35.61		0.000247
	NO_x	23.19		0.000161
	N_2O	0.19		1.32×10^{-6}
	CH_4	0.16		1.11×10^{-6}
	VOC	0.25		1.73×10^{-6}
	CO	1.57		1.09×10^{-5}
Electrical steel	CO_2	2,163.83	0.000018305	0.039609
	SO_2	6.62		0.000121
	NO_x	2.88		5.27×10^{-5}
	N_2O	0.07		1.28×10^{-6}
	CH_4	0.1		1.83×10^{-6}
	VOC	3.74		6.85×10^{-5}
	CO	26.53		0.000486
Steel sheet	CO_2	3,275.00	0.000009675	0.031686
	SO_2	14.5		0.00014
	NO_x	9.5		9.19×10^{-5}
	N_2O	0.07		6.77×10^{-7}
	CH_4	0.04		3.87×10^{-7}
	VOC	0.16		1.55×10^{-6}
	CO	0.93		9×10^{-6}
Steel profile	CO_2	3114.00	0.000008355	0.026017
	SO_2	14.58		0.000122
	NO_x	8.89		7.43×10^{-5}
	N_2O	0.09		7.52×10^{-7}
	CH_4	0.06		5.01×10^{-7}
	VOC	0.18		1.5×10^{-6}
	CO	1.57		1.31×10^{-5}

For the 1.8 MVA transformers, the scale factor is estimated as follows. It accounts for one 1.5 MW turbine which generates approximately 81468000 kWh of energy which corresponds to one 1.8 MVA transformer. The scaling factor is then 1800 kVA/ 81468000 kW = 2.2×10^{-5}.

Table E.8 List main materials required in manufacture phase of transformer 1.8 MVA.

Materials	kg/transformer	kg/MVA (calc.)	kg/kWh (calc.)	% mass (calc.)
Copper profile	566.685	314.825	0.000006926	0.126
Electrical steel	1,497.668	832.038	0.000018305	0.333
Steel sheet	791.560	439.756	0.000009675	0.176
Steel profile	683.620	379.789	0.000008355	0.152
Transformer oil	960.000	314.825	0.006000926	0.213
Total weight	4,497.500	2,498.611	0.000054969	100 %

$$\mathbf{g} = \begin{bmatrix} 45.26834 & 39.60891 & 31.68563 & 26.01747 \\ 0.246635 & 0.121179 & 0.140288 & 0.121816 \\ 0.160614 & 0.052718 & 0.091913 & 0.074276 \\ 0.001316 & 0.001281 & 0.000677 & 0.000752 \\ 0.001108 & 0.001831 & 0.000387 & 0.000501 \\ 0.001732 & 0.068461 & 0.001548 & 0.001504 \\ 0.010874 & 0.485632 & 0.008998 & 0.013117 \end{bmatrix} \left(\frac{\mathrm{g}}{\mathrm{kg}}\right)$$

$$\begin{bmatrix} 0.006926 & 0 & 0 & 0 \\ 0 & 0.018305 & 0 & 0 \\ 0 & 0 & 0.009675 & 0 \\ 0 & 0 & 0 & 0.008355 \end{bmatrix} \left(\frac{\mathrm{kg}}{\mathrm{kWh}}\right)$$

E.7 Manufacture of electrical cables

The 22 kV cable measured 10.5 km and would be used for 20 years of the wind farm life, the scale factor is calculated as 10500 m /1629360000 kWh = 6.44×10^{-6} m/kWh. Tables E.9 and E.10 give the data details.

Table E.9: Cabling materials of 22 kV per metre.

Material	**Copper**	**XLPE**	**Polypropylene**	**Steel pipe**	**Lead**
Weight (kg/km)	16.88 kg/m	1kg/m	1kg/m	2.2 kg/m	4.52 kg/m
Scale factors 6.44×10^{-6} m/kWh	0.000109 kg/kWh	6.44×10^{-6} kg/kWh	6.44×10^{-6} kg/kWh	1.42×10^{-5} kg/kWh	2.91×10^{-5} kg/kWh

Table E.10: Inventory list after calculation of 22 kV cable in production process, with respect to functional unit (1 kW).

Inventory list	**22 kV**			
	Input		**Scaling factor Vector *s* (kg/kWh)**	**Output**
	Environmental flows (matrix B, g/kg unit)			**Environmental flows (matrix *g*) material emissions (g/kWh)**
Copper	CO_2	6536.00	0.000109	0.712424
	SO_2	35.61		0.003881
	NO_x	23.19		0.002528
	N_2O	0.19		2.07×10^{-5}
	CH_4	0.16		1.74×10^{-5}
	VOC	0.25		2.73×10^{-5}
	CO	1.57		0.000171
XLPE	CO_2	3,941.00	6.44×10^{-6}	0.02538
	SO_2	22.91		0.000148
	NO_x	14.71		9.47×10^{-5}
	N_2O	0.12		7.73×10^{-7}
	CH_4	0.08		5.15×10^{-7}
	VOC	0.2		1.29×10^{-6}
	CO	1.1		7.08×10^{-6}
Steel pipe	CO_2	2,163.83	1.42×10^{-5}	0.030726
	SO_2	6.62		9.4×10^{-5}
	NO_x	2.88		4.09×10^{-5}
	N_2O	0.07		9.94×10^{-7}
	CH_4	0.1		1.42×10^{-6}
	VOC	3.74		5.31×10^{-5}
	CO	26.53		0.000377
Lead	CO_2	2,953.00	2.91×10^{-5}	0.085932
	SO_2	18.19		0.000529
	NO_x	19.82		0.000577
	N_2O	0.11		3.2×10^{-6}
	CH_4	0.07		2.04×10^{-6}
	VOC	0.55		1.6×10^{-5}
	CO	2.030		5.91×10^{-5}

$$\mathbf{g} = \begin{bmatrix} 0.712424 & 0.02538 & 0.030726 & 0.085932 \\ 0.003881 & 0.000148 & 9.4\times10^{-5} & 0.000529 \\ 0.002528 & 9.47\times10^{-5} & 4.09\times10^{-5} & 0.000577 \\ 2.07\times10^{-5} & 7.73\times10^{-7} & 9.94\times10^{-7} & 3.2\times10^{-6} \\ 1.74\times10^{-5} & 5.15\times10^{-7} & 1.42\times10^{-6} & 2.04\times10^{-6} \\ 2.73\times10^{-5} & 1.29\times10^{-6} & 5.31\times10^{-5} & 1.6\times10^{-5} \\ 0.000171 & 7.08\times10^{-6} & 0.000377 & 5.91\times10^{-5} \end{bmatrix} \left(\frac{\text{g}}{\text{kg}}\right)$$

$$\begin{bmatrix} 0.000109 & 0 & 0 & 0 \\ 0 & 6.44\times10^{-6} & 0 & 0 \\ 0 & 0 & 1.42\times10^{-5} & 0 \\ 0 & 0 & 0 & 2.91\times10^{-5} \end{bmatrix} \left(\frac{\text{kg}}{\text{kWh}}\right)$$

The 110 kV cable measured 1500 m in length and would be used for the 20 years of the wind farm life. The scaling factor is calculated as 1500 m/1629360000 kWh = 9.206069×10^{-7} m/kWh.

Table E.11: Life cycle inventory of 110 kV cable.

Material	Copper	XLPE	Polypropylene	Steel pipe	Lead
Weight [kg/km]	16.88 kg/m	9.06 kg/m	4.53 kg/m	16.88 kg/m	13.354kg/m
Scale factors 9.2×10^{-7} m/kWh	1.552×10^{-5}	8.34×10^{-6}	4.17×10^{-6}	1.55×10^{-5}	1.23×10^{-5}
	kg/kWh	kg/kWh	kg/kWh	kg/kWh	kg/kWh

Table E.12: Inventory list after calculation of 110kV cable in production process, with respect to functional unit (1kW).

Inventory list	110 kV			
	Input		Scaling factor Vector s [kg/kWh]	Output
	Environmental flows (matrix B, g/kg unit)			Environmental flows (matrix g) material emissions [g/kWh]
Copper	CO_2	6536.00	1.552×10^{-5}	0.101439
	SO_2	35.61		0.000553
	NO_x	23.19		0.00036
	N_2O	0.19		2.95×10^{-6}
	CH_4	0.16		2.48×10^{-6}
	VOC	0.25		3.88×10^{-6}
	CO	1.57		2.44×10^{-5}
XLPE	CO_2	3,941.00	8.34×10^{-6}	0.032868
	SO_2	22.91		0.000191
	NO_x	14.71		0.000123
	N_2O	0.12		1×10^{-6}
	CH_4	0.08		6.67×10^{-7}
	VOC	0.2		1.67×10^{-6}

	CO	1.1		9.17×10^{-6}
Steel pipe	CO_2	2,163.83	1.55×10^{-5}	0.033539
	SO_2	6.62		0.000103
	NO_x	2.88		4.46×10^{-5}
	N_2O	0.07		1.09×10^{-6}
	CH_4	0.1		1.55×10^{-6}
	VOC	3.74		5.8×10^{-5}
	CO	26.53		0.000411
Lead	CO_2	2,953.00	1.23×10^{-5}	0.036322
	SO_2	18.19		0.000224
	NO_x	19.82		0.000244
	N_2O	0.11		1.35×10^{-6}
	CH_4	0.07		8.61×10^{-7}
	VOC	0.55		6.77×10^{-6}
	CO	2.030		2.5×10^{-5}

$$\mathbf{g}=\begin{bmatrix} 0.101439 & 0.032868 & 0.033539 & 0.036322 \\ 0.000553 & 0.000191 & 0.000103 & 0.000224 \\ 0.00036 & 0.000123 & 4.46\times10^{-5} & 0.000244 \\ 2.95\times10^{-6} & 1\times10^{-6} & 1.09\times10^{-6} & 1.35\times10^{-6} \\ 2.48\times10^{-6} & 6.67\times10^{-7} & 1.55\times10^{-6} & 8.61\times10^{-7} \\ 3.88\times10^{-6} & 1.67\times10^{-6} & 5.8\times10^{-5} & 6.77\times10^{-6} \\ 2.44\times10^{-5} & 9.17\times10^{-6} & 0.000411 & 2.5\times10^{-5} \end{bmatrix}\left(\frac{\mathrm{g}}{\mathrm{kg}}\right)$$

$$\begin{bmatrix} 1.55\times10^{-5} & 0 & 0 & 0 \\ 0 & 8.34\times10^{-6} & 0 & 0 \\ 0 & 0 & 1.55\times10^{-5} & 0 \\ 0 & 0 & 0 & 1.23\times10^{-5} \end{bmatrix}\left(\frac{\mathrm{kg}}{\mathrm{kWh}}\right)$$

E.8 Transportation of rotor and nacelle

Table E.13: Transportation embodied energy and emission inventory data.

Modes	CO_2 [kg/MJ]	SO_2 [kg/MJ]	NO_x [kg/MJ]	N_2O [kg/MJ]	CH_4 [kg/MJ]	NMVOC [kg/MJ]	CO [kg/MJ]	$\frac{MJ}{t.km}$
Light Truck 16t RER	3.5×10^{-1}	4.0×10^{-5}	8.2×10^{-4}	2.8×10^{-5}	8.9×10^{-6}	3.5×10^{-4}	6.4×10^{-4}	3.81
Heavy truck 40t RER	7.6×10^{-2}	2.7×10^{-5}	1.6×10^{-3}	2.9×10^{-5}	4.5×10^{-5}	3.3×10^{-4}	7.5×10^{-4}	1.54
Barge US	6.9×10^{-2}	NA	NA	0.187×10^{-5}	0.584×10^{-3}	NA	NA	0.38

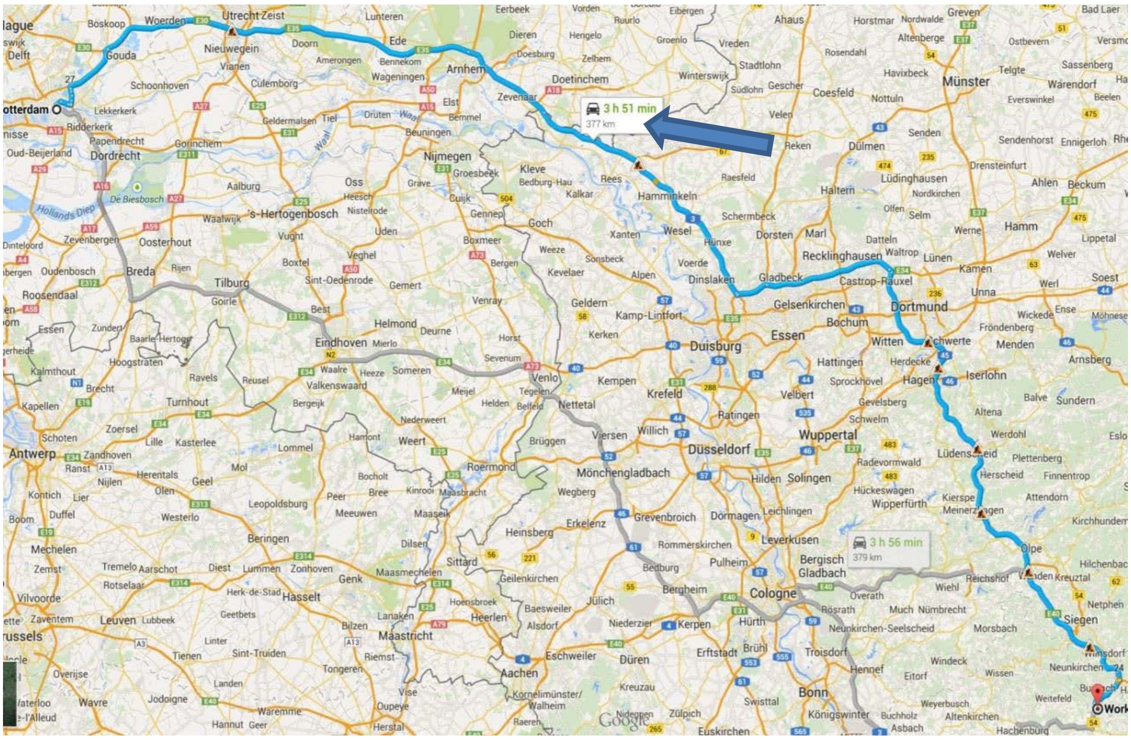
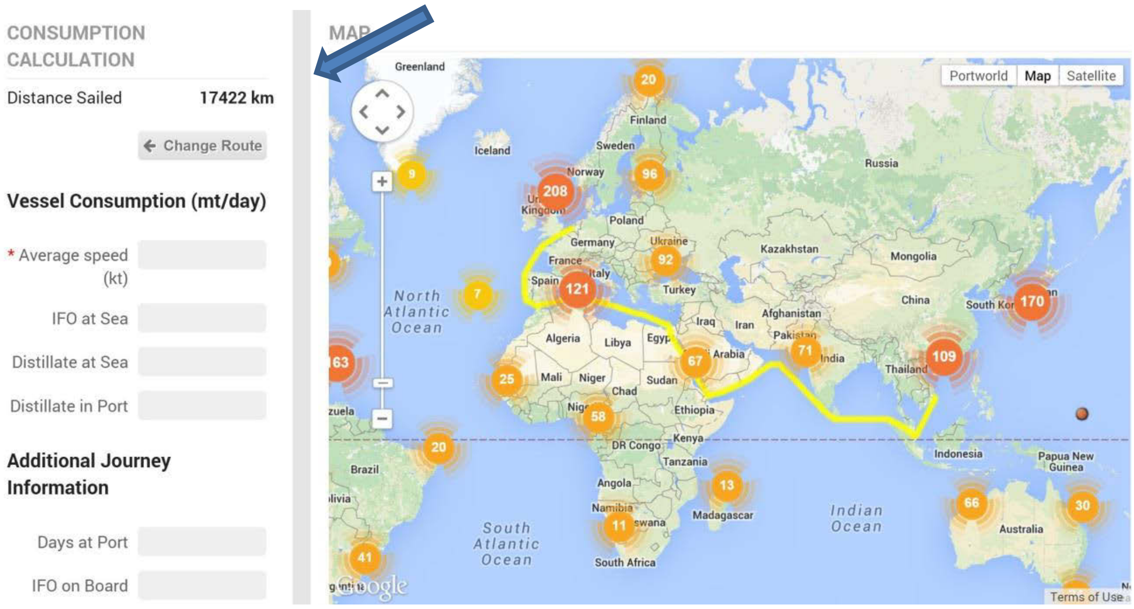


Figure E.5: The route of rotor and nacelle from Fuhrländer AG, GER to Port of Rotterdam NE Fuhrländer AG, GER to Port of Rotterdam, NE (Google Map, 2014).



CONSUMPTION CALCULATION

Distance Sailed 17422 km

Change Route

Vessel Consumption (mt/day)

* Average speed (kt)

IFO at Sea

Distillate at Sea

Distillate in Port

Additional Journey Information

Days at Port

IFO on Board

Figure E.6: The route from Port of Rotterdam NE to Nhatrang port (Petromedia Ltd, 2014).

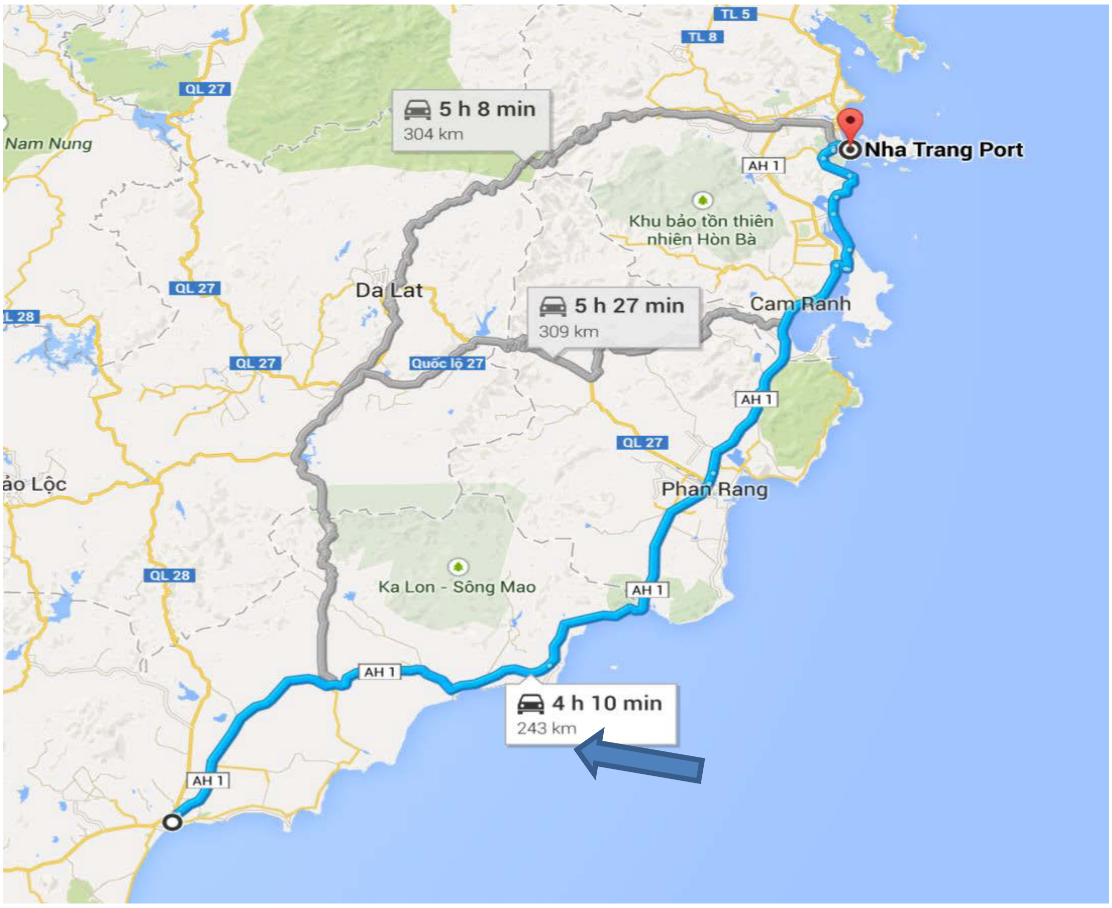


Figure E.7: The route from Nhatrang port to project site (Google Map, 2014).

Table E.14: Distance travelled of rotor and nacelle.

Main components	Departure	Destination	Mode of transport	Fuel	Distance travelled (km)	References
Rotor and nacelle	Fuhrländer AG, GER	Port of Rotterdam, NE	Truck	Diesel	377	(Google Map, 2014)
	Port of Rotterdam, NE	Nhatrang harbour, VN	Cargo ship	Diesel	17422	(Petromedia Ltd, 2014)
	Nhatrang port, VN	Project site, VN	Truck	Diesel	243	(Google Map, 2014)

For rotor and nacelle delivery, it is assumed that to transport all of these components of one turbine from Fuhrländer AG to the Port of Rotterdam, and from the Port of Nhatrang to Binh Thuan wind farm requires two heavy 40 t trucks and one light 10 t truck, while the travel of them through the sea, one standard barge is used to ship.

Table E.15: Resulting of rotor and nacelle transportations.

Modes	Formulation	Diesel [kg]	Final energy consumption [GJ]	
16 t Truck RER	$0.089\left(\frac{\text{kg}}{\text{tkm}}\right)\times (3770\ +2430)(\text{tkm})$	551.80	$3.81\left(\frac{\text{MJ}}{\text{tkm}}\right)\times (3770\ +2430)(\text{tkm})$	23.622
40 t truck RER	$0.036\left(\frac{\text{kg}}{\text{tkm}}\right)\times (30{,}160+19{,}440)(\text{tkm})$	1785.6	$1.54\left(\frac{\text{MJ}}{\text{tkm}}\right)\times (30{,}160+19{,}440)(\text{tkm})$	76,344
Barge RER	$0.0013\left(\frac{\text{kg}}{\text{tkm}}\right)\times 1{,}567{,}980(\text{tkm})$	2038.374	$0.38\left(\frac{\text{MJ}}{\text{tkm}}\right)\times 1{,}567{,}980(\text{tkm})$	59.650

The same matrix calculation for the environmental assessment can be used and later it will be down scaled to meet the functional unit requirement of the wind farm. Matrix **B’** is an environmental interaction integration of $\mathbf{B}_1$’ $\mathbf{B}_2$’ $\mathbf{B}_3$’ related to the light truck, heavy truck and barge tanker. The scaling vectors **s’** of matrix **A** is a scaling vector for all transportation.

Table E.16: Inventory list after calculation during transportation stages of rotor and nacelle.

Inventory list	Transportation stages of rotor and nacelle			
	Input		Scaling factor Vector s [MJ/kWh]	Output
	Environmental flows (matrix B, kg/MJ unit)			Environmental flows (matrix g) material emissions [kg/kWh]
Truck 16t RER	CO_2	3.50×10^{-1}	0.00029	0.101484
	SO_2	4.00×10^{-5}		1.16×10^{-5}
	NO_x	8.20×10^{-4}		0.000238
	N_2O	2.80×10^{-5}		8.12×10^{-6}
	CH_4	8.90×10^{-6}		2.58×10^{-6}
	VOC	3.50×10^{-4}		0.000101
	CO	6.40×10^{-4}		0.000186
truck 40t RER	CO_2	7.60×10^{-2}	0.000937	7.12×10^{-5}
	SO_2	2.70×10^{-5}		2.53×10^{-8}
	NO_x	1.60×10^{-3}		1.50×10^{-6}
	N_2O	2.90×10^{-5}		2.72×10^{-8}
	CH_4	4.50×10^{-5}		4.22×10^{-8}
	VOC	3.30×10^{-4}		3.09×10^{-7}
	CO	7.50×10^{-4}		7.03×10^{-7}
Barge RER	CO_2	6.90×10^{-2}	0.000732	0.050521
	SO_2	NA		0
	NO_x	NA		0
	N_2O	1.87×10^{-6}		1.37×10^{-6}
	CH_4	5.84×10^{-4}		0.000428
	VOC	NA		0
	CO	NA		0

$$\mathbf{s} = (s_1, s_2, s_3) = \left(\frac{23{,}622\ \text{MJ}}{81468000\ \text{kWh}}\right)\left(\frac{76{,}344\ \text{MJ}}{81468000\ \text{kWh}}\right)\left(\frac{59{,}650\ \text{MJ}}{81468000\ \text{kWh}}\right)$$

$$= \left(2.9\times10^{-4}\,\frac{\text{MJ}}{\text{kWh}}\right)\left(9.37\times10^{-4}\,\frac{\text{MJ}}{\text{kWh}}\right)\left(7.32\times10^{-4}\,\frac{\text{MJ}}{\text{kWh}}\right)$$

$\mathbf{g} =$

$$\begin{bmatrix} 3.50\times10^{-1} & 7.60\times10^{-2} & 6.90\times10^{-2} \\ 4.00\times10^{-5} & 2.70\times10^{-5} & 0 \\ 8.20\times10^{-4} & 1.60\times10^{-3} & 0 \\ 2.80\times10^{-5} & 2.90\times10^{-5} & 1.87\times10^{-6} \\ 8.90\times10^{-6} & 4.50\times10^{-5} & 5.84\times10^{-4} \\ 3.50\times10^{-4} & 3.30\times10^{-4} & 0 \\ 6.40\times10^{-4} & 7.50\times10^{-4} & 0 \end{bmatrix} \left(\frac{\text{kg}}{\text{MJ}}\right) \begin{bmatrix} 0.00029 & 0 & 0 \\ 0 & 0.000937 & 0 \\ 0 & 0 & 0.000732 \end{bmatrix} \left(\frac{\text{MJ}}{\text{kWh}}\right)$$

E.9 Transportation of tower and foundation

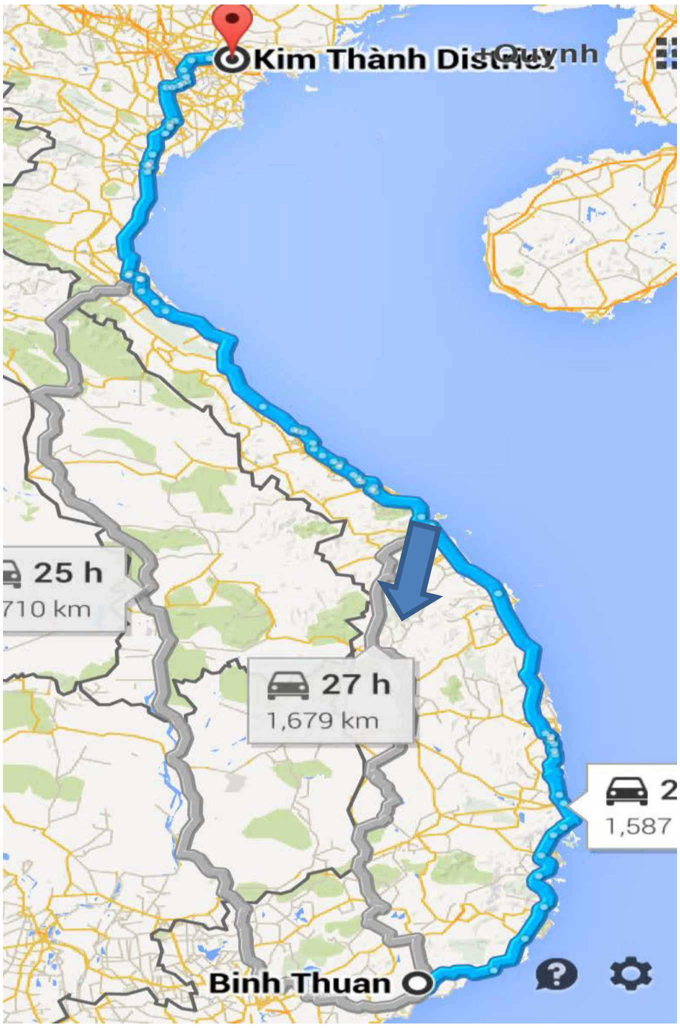


Figure E.8: Distance estimation for transportation of tower (Google Map, 2014).

Table E.17: Distance travelled of tower and foundation.

Main components	Departure	Destination	Mode of transport	Fuel	Distance travelled [km]	Weight [t]	References
Tower	Hai Duong province, VN	Project site	Truck	Diesel	1,587	129.57	(Google Map, 2014)
Foundation	Nhatrang, VN	Project site	Truck	Diesel	243	472	(Google Map, 2014)

For the tower, it is assumed that to transport it three heavy 40 t trucks and one light 10 t truck are required per tower. For foundation, it is assumed that up to ten heavy trucks needed to carry nearly 480 tons of foundation. Table E.18 presents the results after calculation.

Table E.18: Resulting of tower and foundation transportations.

Modes	Formulation	Diesel [kg]	Final energy consumption [MJ]	
16 t Truck RER	$0.089\left(\frac{\text{kg}}{\text{tkm}}\right)\times$ $\left(1\times10[\text{t}]\times1587[\text{km}]\right)$	1412.43	$3.81\left(\frac{\text{MJ}}{\text{tkm}}\right)\times$ $\left(1\times10\times1587\right)\left(\text{tkm}\right)$	60464.7
40 t Truck RER	$0.036\left(\frac{\text{kg}}{\text{tkm}}\right)\times$ $\left(3\times40[\text{t}]\times1587[\text{km}]\right)$ $0.036\left(\frac{\text{kg}}{\text{tkm}}\right)\times$ $\left(12\times39.4[\text{t}]\times243[\text{km}]\right)$	10991.89	$1.54\left(\frac{\text{MJ}}{\text{tkm}}\right)\times$ $\begin{pmatrix}3\times40\times1587\\+12\times39.4\times243\end{pmatrix}\left(\text{tkm}\right)$	470208.8

Table E.19: Inventory list after calculation during transportation stages of tower and foundation.

Inventory list	Basement			
	Input		Scaling factor Vector s [MJ/kWh]	Output
	Environmental flows (matrix B, kg/MJ unit)			Environmental flows (matrix g) material emissions [kg/kWh]
16 t Truck RER	CO_2	3.50×10^{-1}	0.000742	0.00026
	SO_2	4.00×10^{-5}		2.97×10^{-8}
	NO_x	8.20×10^{-4}		6.09×10^{-7}
	N_2O	2.80×10^{-5}		2.08×10^{-8}
	CH_4	8.90×10^{-6}		6.61×10^{-9}
	VOC	3.50×10^{-4}		2.6×10^{-7}
	CO	6.40×10^{-4}		4.75×10^{-7}
40 t Truck RER	CO_2	7.60×10^{-2}	0.005772	0.000439
	SO_2	2.70×10^{-5}		1.56×10^{-7}
	NO_x	1.60×10^{-3}		9.23×10^{-6}
	N_2O	2.90×10^{-5}		1.67×10^{-7}
	CH_4	4.50×10^{-5}		2.6×10^{-7}
	VOC	3.30×10^{-4}		1.9×10^{-6}
	CO	7.50×10^{-4}		4.33×10^{-6}

$$\mathbf{s}=\left(s_1,s_2\right)=\left(\frac{60464.7\ \text{MJ}}{81468000\ \text{kWh}}\right)\left(\frac{470208.8\ \text{MJ}}{81468000\ \text{kWh}}\right)$$
$$=\left(0.000742\frac{\text{MJ}}{\text{kWh}}\right)\left(0.005772\frac{\text{MJ}}{\text{kWh}}\right)$$

$$\mathbf{g}=\begin{bmatrix}3.50\times10^{-1} & 7.60\times10^{-2}\\ 4.00\times10^{-5} & 2.70\times10^{-5}\\ 8.20\times10^{-4} & 1.60\times10^{-3}\\ 2.80\times10^{-5} & 2.90\times10^{-5}\\ 8.90\times10^{-6} & 4.50\times10^{-5}\\ 3.50\times10^{-4} & 3.30\times10^{-4}\\ 6.40\times10^{-4} & 7.50\times10^{-4}\end{bmatrix}\left(\frac{\text{kg}}{\text{MJ}}\right)\begin{bmatrix}0.000742 & 0\\ 0 & 0.005772\end{bmatrix}\left(\frac{\text{MJ}}{\text{kWh}}\right)$$

E.10 Transportation of electrical cables and transformers.

Table E.20: The distance of transportation of electrical cables.

Main components	Departure	Destination	Mode of transport	Fuel	Distance travelled [km]	References
Electrical cables	Bac Ninh, VN	Project site	Truck	Diesel	1578	(Google Map, 2014)

There are 10.5 km of cable 22 kV and 1.5 km of 110 kV transmission line that require transportation. The total weight per meter of 22 kV cable is approximately 22.56 kg/m and the 110 kV line is 60.706 kg/m.

Table E.21: Mass of materials per kilometre

Material	Copper	XLPE	Polypropylene	Steel pipe	Lead
Weight of 22 kV (kg/km)	16.88 kg/m	1kg/m	1kg/m	2.2 kg/m	4.52 kg/m
Weight 110 kV (Kg/km)	16.88 kg/m	9.06kg/m	4.53 kg/m	16.88 kg/m	kg/m

The total weight of the 22 kV and 110 kV cable are 236,888 kg and 91,059 kg respectively. It is assumed that the number of heavy trucks required for both cases is 8 and only one small truck is required.

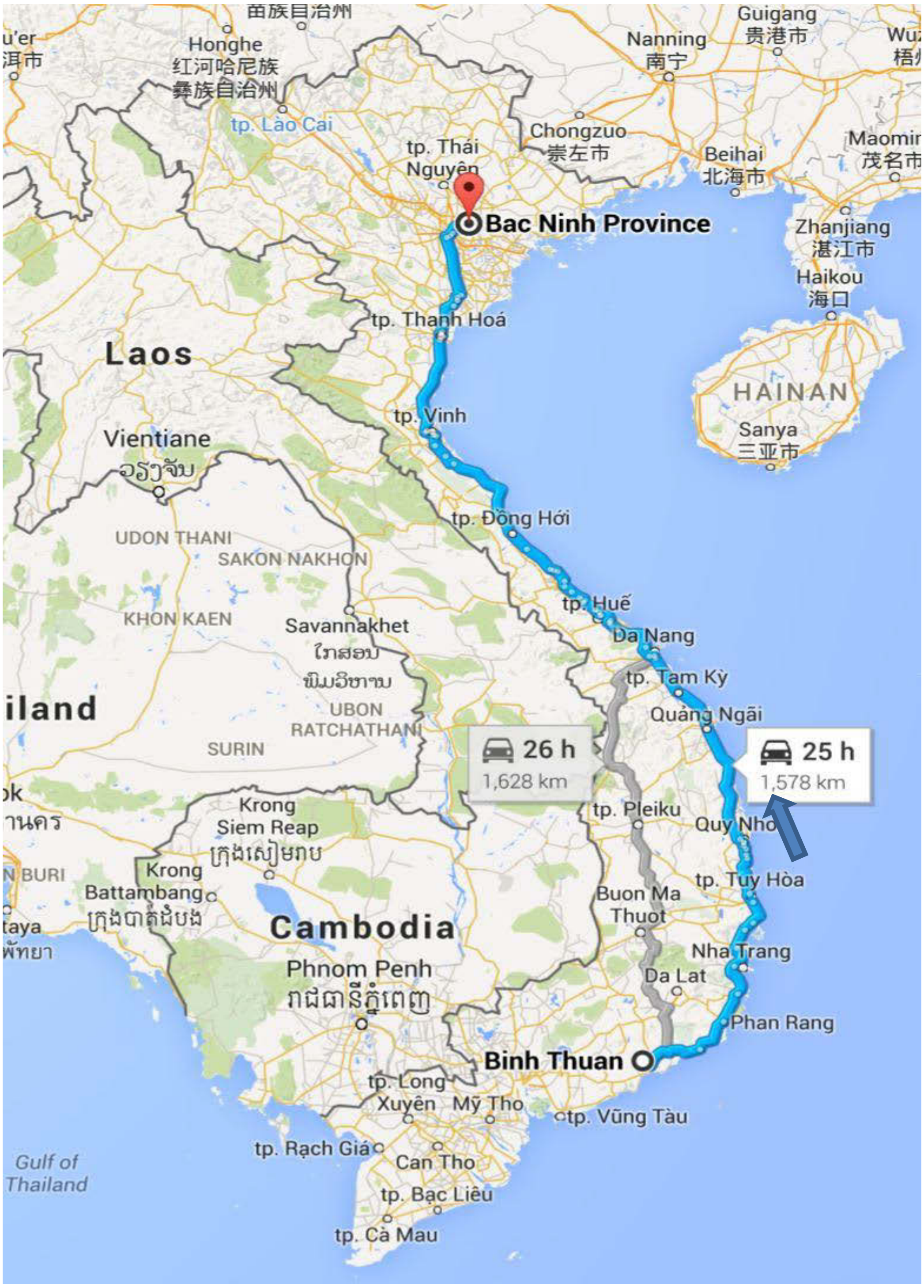


Figure E.9: Distance estimation for transportation of electrical cables and transformers (Google Map, 214).

Table E.22: Resulting of cables transportations.

Modes	Formulation	Diesel [kg]	Final energy consumption [MJ]	
16 t Truck RER	$0.089\frac{\text{kg}}{\text{tkm}}(1\times10\text{ t}\times1578\text{ km})$	1404.42	$3.81\frac{\text{MJ}}{\text{t.km}}(1\times10\times1578)\text{ t.km}$	60121.8
40 t Truck RER	$0.036\frac{\text{kg}}{\text{t.km}}(8\times40\text{ t}\times1578\text{ km})$	18178.56	$1.54\frac{\text{MJ}}{\text{t.km}}(8\times40\times1578)\text{ t.km}$	777638.4

Table E.23: Inventory list after calculation during transportation stages of cables.

Inventory list	Transportation stages of cables			
	Input		Scaling factor Vector s [MJ/kWh]	Output
	Environmental flows (matrix B, kg/MJ unit)			Environmental flows (matrix g) material emissions [kg/kWh]
Truck 16t RER	CO_2	3.50×10^{-1}	3.6899×10^{-5}	1.29×10^{-5}
	SO_2	4.00×10^{-5}		1.48×10^{-9}
	NO_x	8.20×10^{-4}		3.03×10^{-8}
	N_2O	2.80×10^{-5}		1.03×10^{-9}
	CH_4	8.90×10^{-6}		3.28×10^{-10}
	VOC	3.50×10^{-4}		1.29×10^{-8}
	CO	6.40×10^{-4}		2.36×10^{-8}
truck 40t RER	CO_2	7.60×10^{-2}	0.00048	3.63×10^{-5}
	SO_2	2.70×10^{-5}		1.29×10^{-8}
	NO_x	1.60×10^{-3}		7.64×10^{-7}
	N_2O	2.90×10^{-5}		1.38×10^{-8}
	CH_4	4.50×10^{-5}		2.15×10^{-8}
	VOC	3.30×10^{-4}		1.57×10^{-7}
	CO	7.50×10^{-4}		3.58×10^{-7}

Table E.24: The distance of transportation of transformers.

Main components	Departure	Destination	Mode of transport	Fuel	Distance travelled (km)	References
Transformers	Bac Ninh, VN	Project site	Truck	Diesel	1578	(Google Map, 2014)

There are twenty 1.8 MVA transformers and one 45 MVA transformers. The weight of these are approximately 4,497.5 kg/unit and 15,500 kg/unit respectively. It is assumed that the number of small 10 t trucks (10 t RER) required for both cases is two.

Table E.25: Resulting of tower and foundation transportations.

Modes	Formulation	Diesel [kg]	Final energy consumption [MJ]	
16 t Truck RER	$0.089\frac{\text{kg}}{\text{t.km}}\left(2\times10\text{ t}\times1578\text{ km}\right)$	2808.84	$3.81\frac{\text{MJ}}{\text{t.km}}\left(2\times10\times1578\right)\text{ t.km}$	120243.6

Table E.26: Inventory list after calculation during transportation stages of tower and foundation.

Inventory list	Transportation stages of tower and foundation			
	Input		Scaling factor Vector s [MJ/kWh]	Output
	Environmental flows (matrix B, kg/MJ unit)			Environmental flows (matrix g) material emissions [kg/kWh]
Truck 16t RER	CO_2	3.50×10^{-1}	0.000332	0.000116
	SO_2	4.00×10^{-5}		1.33×10^{-8}
	NO_x	8.20×10^{-4}		2.72×10^{-7}
	N_2O	2.80×10^{-5}		9.3×10^{-9}
	CH_4	8.90×10^{-6}		2.96×10^{-9}
	VOC	3.50×10^{-4}		1.16×10^{-7}
	CO	6.40×10^{-4}		2.13×10^{-7}
truck 16t RER	CO_2	3.50×10^{-1}	5.72×10^{-5}	2×10^{-5}
	SO_2	4.00×10^{-5}		2.29×10^{-9}
	NO_x	8.20×10^{-4}		4.69×10^{-8}
	N_2O	2.80×10^{-5}		1.6×10^{-9}
	CH_4	8.90×10^{-6}		5.09×10^{-10}
	VOC	3.50×10^{-4}		2×10^{-8}
	CO	6.40×10^{-4}		3.66×10^{-8}

$$\mathbf{s}=\left(s_1,s_2\right)=\left(\frac{120243.6\times0.225\text{ MJ}}{81468000\text{ kWh}}\right)\left(\frac{120243.6\times0.775\text{ MJ}}{1629360000\text{ kWh}}\right)$$

$$=\left(0.000332\frac{\text{MJ}}{\text{kWh}}\right)\left(5.71935\times10^{-5}\frac{\text{MJ}}{\text{kWh}}\right)$$

$$\mathbf{g}=\begin{bmatrix}3.50\times10^{-1} & 7.60\times10^{-2}\\ 4.00\times10^{-5} & 2.70\times10^{-5}\\ 8.20\times10^{-4} & 1.60\times10^{-3}\\ 2.80\times10^{-5} & 2.90\times10^{-5}\\ 8.90\times10^{-6} & 4.50\times10^{-5}\\ 3.50\times10^{-4} & 3.30\times10^{-4}\\ 6.40\times10^{-4} & 7.50\times10^{-4}\end{bmatrix}\left(\frac{\text{kg}}{\text{MJ}}\right)\begin{bmatrix}0.000332 & 0\\ 0 & 5.72\times10^{-5}\end{bmatrix}\left(\frac{\text{MJ}}{\text{kWh}}\right)$$

E.11 Installation of wind turbines

Although there is a lot of additional equipment is required for the construction of a wind turbine, such as bulldozers, graders, excavators, loaders, artic dump trucks, water trucks, concrete pumps and cranes, in this research the focus is mainly on the excavator, concrete pump and a 550 t crane. However, it can be noted that many hours of pre-job planning goes into designing an erection schedule to meet transport and site deadlines which are neglected here.

Table E.27: Equipment used for erection of turbines bases.

Process	Number of foundations	Number of foundations per day	Working hours assumed 8 hours/day	Average number of equipment hours
Dig foundation hole (excavator)	20	1	8	160
Pour concrete (cement mixer)	20	1.5	8	240
Pour concrete (concrete pump)	20	1.5	8	240
550 t crane	20	0.33	8	480
Total hours				1120

Table E.28: The total hours using machine for installation of transformers and cable (account for average).

Installation	Number of units	Number of estimated hours per unit	Average estimated hours per unit	Total number of equipment hours
1.8 MVA Transformers	20	24 - 48	30	600
45 MVA Transformer	1	48 - 72	60	60
Total				660

It is assumed that the fuel required to pour the concrete, drive the 80 t excavator, and drive the large crane is 27.285 litre diesel/hour (Circular No. 06/2005 / TT-BXD, 2005). The scaling factor is calculated based on:

$$\frac{27.285\ \text{litres/hour}\ \times 1780\ \text{hour}}{1629360000\ \text{kWh}} = \frac{48567.3}{1629360000\ \text{kWh}}\frac{\text{litres}}{\text{kWh}} = 2.98\times 10^{-5}\left(\frac{\text{litres}}{\text{kWh}}\right)$$

where 1 MJ = 0.28 kWh and 1 litre diesel is nearly equal 1kg diesel.

The crane operation is estimated based on personal communication; it took on average about three days for each turbine erection. Obviously this is dependent on the weather conditions, for example, if the wind speed exceeds the safe conditions.

Table E.29: The total emissions from construction stage.

Environmental flows (matrix B, kg/MJ unit)		**Environmental flows (matrix B, kg/kWh unit)**	**Environmental flows (matrix *g*) material emissions [kg/kWh]**
CO_2	7.60×10^{-2}	2.74×10^{-1}	8.17×10^{-6}
SO_2	2.70×10^{-5}	9.72×10^{-5}	2.90×10^{-9}
NO_x	1.60×10^{-3}	5.76×10^{-3}	1.72×10^{-7}
N_2O	2.90×10^{-5}	1.04×10^{-4}	3.10×10^{-9}
CH_4	4.50×10^{-5}	1.62×10^{-4}	4.83×10^{-9}
VOC	3.30×10^{-4}	1.19×10^{-3}	3.55×10^{-8}
CO	7.50×10^{-4}	2.74×10^{-1}	8.17×10^{-6}

The total emissions for a turbine erection, in kWh, is quite a small percentage of the project, although it is eligible for calculation and inclusion.

E.12 Operation and maintenance of wind turbines

While the wind farm generates power there is no emission or very small amounts of emission so this can be ignored. The maintenance services do cause emissions since vehicles are used during maintenance.

Table E.30: Operation and maintenance transport emissions.

Inventory list	Input		Scaling vector	Environmental flows
	Environmental flows		MJ/kWh	(matrix g, kg/kWh unit)
	(matrix B, kg/MJ unit)			
16 t Truck RER	CO_2	3.50×10^{-1}	1.50×10^{-5}	5.24×10^{-6}
	SO_2	4.00×10^{-5}		5.99×10^{-10}
	NO_x	8.20×10^{-4}		1.23×10^{-8}
	N_2O	2.80×10^{-5}		4.19×10^{-10}
	CH_4	8.90×10^{-6}		1.33×10^{-10}
	VOC	3.50×10^{-4}		5.24×10^{-9}
	CO	6.40×10^{-4}		9.58×10^{-9}

Table E.31: Total inspection maintenance of wind farm.

Maintenance	Fuel	Distance			
		[km]	x 2 [km]	1 year [km]	20 years [km]
Inspection by car	Diesel	20	40	40	800

Table E.32: Resulting of tower and foundation transportations.

Modes	Formulation	Diesel [kg]	Final energy consumption	[MJ]
16 t Truck RER	$0.089\frac{\text{kg}}{\text{tkm}}\left(8\text{ t}\times 800\text{ km}\right)$	569.6	$3.81\frac{\text{MJ}}{\text{t.km}}\left(8\times 800\right)\text{ t.km}$	24384

For replacement parts, the calculation for the gearbox is accounted for by including one replacement before the end the life cycle of the wind farm (20 years). The calculation for replacement parts is below.

Table E.33:Data adapted from Table 4.5.

		Tons/unit	kg/kWh
Gearbox	Cast iron	6.104	7.492512×10^{-5}
	Chromium steel	6.104	7.492512×10^{-5}
	Rubber	0.28	3.436932×10^{-6}

Table E.34: Data adapted form Table 4.5.

Inventory list	rotor			
	Input		Scaling factor Vector s [kg/kWh]	Output
	Environmental flows (matrix B, g)			Environmental flows (matrix g) material emissions [g/kWh]
rubber	CO_2	3398.00	7.492512×10^{-5}	0.254596
	SO_2	16.06		0.001203
	NO_x	10.61		0.000795
	N_2O	0.1		7.49×10^{-6}
	CH_4	0.06		4.5×10^{-6}
	VOC	0.18		1.35×10^{-5}
	CO	1.06		7.94×10^{-5}
Chromium steel	CO_2	2306	7.492512×10^{-5}	0.172777
	SO_2	14.5		0.001086
	NO_x	9.5		0.000712
	N_2O	0.05		3.75×10^{-6}
	CH_4	0.04		3×10^{-6}
	VOC	0.16		1.2×10^{-5}
	CO	0.93		6.97×10^{-5}
Cast iron	CO_2	3114.00	3.436932×10^{-6}	0.010703
	SO_2	14.58		5.01×10^{-5}
	NO_x	8.89		3.06×10^{-5}
	N_2O	0.09		3.09×10^{-7}
	CH_4	0.06		2.06×10^{-7}
	VOC	0.18		6.19×10^{-7}
	CO	1.57		5.4×10^{-6}

E.13 Recycling and landfill of wind turbines

Table E.35: Material type and disposal method considered.

Material type	Removal Scenario
Steel	90% Recovery 10% losses in landfill
Copper	95 % recovery 5% losses in landfill
Epoxy	Landfill 100%
Plastic PVC	Landfill 100%
Other plastics	Combusted 100%
Rubber	Combusted 100%
Fibre glass	Landfill 100%

Table E.36: Material type and disposal method considered.

Material (1kg) Recycle	CO_2 [g]	SO_2 [g]	NO_x [g]	N_2O [g]	CH_4 [g]	NM VOC [g]	CO [g]	MJ/kg (calc.)
	CO2 –e							
Steel	1819							9.7
Copper	3431							9.4
Emission per kg	**material**	**disposal**						
Plastic (polyester/epoxy)	4680	3.6	6	0.16	0.24	0.36	87.52	0.4
Rubber	3510	2.7	4.5	0.12	0.18	0.27	65.66	

Table E.37: The total materials in dismantling stage.

	[kg/kWh]										
Steel	8.65×10^{-5}	1.582×10^{-3}	3.42×10^{-4}	1.2×10^{-2}	5.09×10^{-3}	4.66×10^{-3}	1.55×10^{-5}	8.355×10^{-3}	9.675×10^{-3}	1.8305×10^{-2}	1.42×10^{-5}
Copper	8.25×10^{-9}	5.39×10^{-3}	6.926×10^{-3}	1.09×10^{-4}	1.552×10^{-5}						
Plastic (polyester/epoxy)	2.34×10^{-4}	1.25×10^{-7}	6.44×10^{-6}	8.34×10^{-6}							
Rubber	3.44×10^{-9}	7.95×10^{-6}									

Table E.38: Total materials in dismantling stage and the credit entry emissions.

	[kg/kWh]	Emission [g/kWh]
Steel	0.060435	98.94 CO_2 e (recycle 90%)
Copper	1.24×10^{-2}	40.42 CO_2 e (recycle 95%)
Plastic (polyester/epoxy)	0.000249	
Rubber	7.95×10^{-6}	

Table E.39: The total emission under landfill stage.

g/kWh	CO_2	SO_2	NO_x	N_2O	CH_4	NMVOC	CO_2
Plastic (polyester/epoxy)	1.16532	0.000896	0.001494	3.98×10^{-5}	5.98×10^{-5}	8.96×10^{-5}	0.021792
Rubber	0.027905	2.15×10^{-5}	3.58×10^{-5}	9.54×10^{-7}	1.43×10^{-6}	2.15×10^{-6}	0.000522

Appendix F

F.1 Emissions of manufacture stage

The total emissions:

Table F.1: Emissions at manufacturing stage.

g/kWh	Total rotor	Total nacelle	Total tower	Total basement	Total Transformers	Total Cables	Total
CO_2	1.244211	0.000518	3.681352	5.616753	0.237786	1.05863	11.83925
SO_2	0.00595	2.92×10^{-6}	0.023128	0.008255	0.001051	0.005723	0.04411
NOx	0.00384	1.91×10^{-6}	0.015151	0.020485	0.000637	0.004012	0.044127
N_2O	2.88×10^{-5}	1.44×10^{-8}	0.000112	3.08×10^{-5}	6.62×10^{-6}	3.21×10^{-5}	0.00021
CH_4	1.82×10^{-5}	8.67×10^{-9}	6.39×10^{-5}	2.05×10^{-5}	6.33×10^{-6}	2.69×10^{-5}	0.000136
VOC	6.73×10^{-5}	3.05×10^{-8}	0.000255	6.15×10^{-5}	0.000122	0.000168	0.000674
CO	0.000438	1.77×10^{-7}	0.001481	0.000537	0.000864	0.001084	0.004404

Environmental Impacts by category:

Table F.2: Acidification in manufacture stage, the amount of SO_2 equivalent = 0.075685 g/kWh.

g/kWh	Total rotor	Total nacelle	Total Tower	Total basement	Total Transformers	Total Cables	Total rotor
CO_2	0	0	0	0	0	0	0
SO_2	0.00595	2.92×10^{-6}	0.023128	0.008255	0.001051	0.005723	0.04411
NOx	0.002688	1.34×10^{-6}	0.010606	0.01434	0.000446	0.002808	0.030889
N_2O	2.02×10^{-5}	1.01×10^{-8}	7.84×10^{-5}	2.16×10^{-5}	4.63×10^{-6}	2.25×10^{-5}	0.000147
CH_4	0	0	0	0	0	0	0
VOC	5.38×10^{-5}	2.44×10^{-8}	0.000204	4.92×10^{-5}	9.76×10^{-5}	0.000134	0.000539
CO	0	0	0	0	0	0	0

Table F.3: Global Warming Potential in manufacture stage, the amount of CO_2 equivalent = 11.90533 kg/kWh.

g/kWh	Total rotor	Total nacelle	Total Tower	Total basement	Total Transformers	Total Cables	Total rotor
CO_2	1.244211	0.000518	3.681352	5.616753	0.237786	1.05863	11.83925
SO_2	0	0	0	0	0	0	0
NOx	0	0	0	0	0	0	0
N_2O	0.008582	4.29×10^{-6}	0.033376	0.009178	0.001973	0.009566	0.06258
CH_4	0.000469	2.23×10^{-7}	0.001645	0.000528	0.000163	0.000693	0.003502
VOC	0	0	0	0	0	0	0
CO	0	0	0	0	0	0	0

Table F.4: Photo-Oxidant Potential in manufacture stage, the amount of C_2H_4 equivalent = 0.003722 g/kWh

g/kWh	Total rotor	Total nacelle	Total Tower	Total basement	Total Transformers	Total Cables	Total rotor
CO_2	0	0	0	0	0	0	0
SO_2	0.000286	1.4×10^{-7}	0.00111	0.000396	5.04×10^{-5}	0.000275	0.002117
NOx	0.000108	5.35×10^{-8}	0.000424	0.000574	1.78×10^{-5}	0.000112	0.001236
N_2O	0	0	0	0	0	0	0
CH_4	1.09×10^{-7}	5.2×10^{-11}	3.83×10^{-7}	1.23×10^{-7}	3.8×10^{-8}	1.61×10^{-7}	8.16×10^{-7}
VOC	2.8×10^{-5}	1.27×10^{-8}	0.000106	2.56×10^{-5}	5.08×10^{-5}	6.99×10^{-5}	0.00028
CO	8.76×10^{-6}	3.54×10^{-9}	2.96×10^{-5}	1.07×10^{-5}	1.73×10^{-5}	2.17×10^{-5}	8.81×10^{-5}

F.2 Emissions for transportation

Table F.5: Total Emissions form Transportation.

g/kWh	Rotor and nacelle	Tower and foundation	Cables	Transformers	Total
CO_2	152.0762	0.699	4.92×10^{-2}	0.136	152.9604
SO_2	0.011625	0.000186	1.44×10^{-5}	1.56×10^{-5}	0.011841
NOx	0.2395	0.009839	7.94×10^{-4}	0.000319	0.250452
N_2O	0.009517	0.000188	1.48×10^{-5}	1.09×10^{-5}	0.009731
CH_4	0.430622	0.000267	2.18×10^{-5}	3.47×10^{-6}	0.430914
VOC	0.101309	0.00216	1.70×10^{-4}	0.000136	0.103775
CO	0.186703	0.004805	3.82×10^{-4}	0.00025	0.19214

F.3 Emissions of construction, operation and maintenance service stages

Table F.6: Total emissions from construction, operation and maintenance.

g/kWh	Construction	Maintenance services	Replacement	Total
CO_2	8.17×10^{-3}	5.24×10^{-3}	0.438076	4.51×10^{-1}
SO_2	2.90×10^{-6}	5.99×10^{-7}	0.002339	2.34×10^{-3}
NOx	1.72×10^{-4}	1.23×10^{-5}	0.001538	1.72×10^{-3}
N_2O	3.10×10^{-6}	4.19×10^{-7}	1.15×10^{-5}	1.50×10^{-5}
CH_4	4.83×10^{-6}	1.33×10^{-7}	7.71×10^{-6}	1.27×10^{-5}
VOC	3.55×10^{-5}	5.24×10^{-6}	2.61×10^{-5}	6.68×10^{-5}
CO	8.17×10^{-3}	9.58×10^{-6}	0.000155	8.33×10^{-3}

F.4 Emission of recycling and landfill stages.

Table F.7: The total materials in dismantling stage and the credit entry emissions.

	[kg/kWh]	Emission [g/kWh]
Steel	0.060435	98.94 CO_2 e (recycle 90 %)
Copper	1.24×10^{-2}	40.42 CO_2 e (recycle 95 %)

Table F.8: The total emission under landfill stage.

g/kWh	Plastic (polyester/epoxy)	Rubber	Total
CO_2	1.16532	0.027905	1.193225
SO_2	0.000896	2.15×10^{-5}	0.000918
NOx	0.001494	3.58×10^{-5}	0.00153
N_2O	3.98×10^{-5}	9.54×10^{-7}	4.08×10^{-5}
CH_4	5.98×10^{-5}	1.43×10^{-6}	6.12×10^{-5}
VOC	8.96×10^{-5}	2.15×10^{-6}	9.18×10^{-5}
CO	0.021792	0.000522	0.022314

Appendix G

Table G.1: The total Life Cycle Inventory results of various parts in wind turbine.

g/kWh	Low voltage transformer	Tower	Blade	Blade extender	Hub
CO_2	0.14258	3.68023	0.76635	0.199469	0.278392
SO_2	0.00063	0.023121	0.003393	0.001254	0.001303
NO_x	0.00038	0.015146	0.002223	0.000822	0.000795
N_2O	4.03×10^{-6}	0.000112	1.64×10^{-5}	4.33×10^{-6}	8.05×10^{-6}
CH_4	3.83×10^{-6}	6.39×10^{-5}	9.36×10^{-6}	3.46×10^{-6}	5.36×10^{-6}
VOC	7.33×10^{-5}	0.000255	3.74×10^{-5}	1.38×10^{-5}	1.61×10^{-5}
CO	0.000519	0.00148	0.000218	8.04×10^{-5}	0.00014

g/kWh	Generator	Gearbox	Main shaft	Basement	
CO_2	0.169685	0.4061057	0.242575	5.616753	
SO_2	0.001067	0.0021781	0.001525	0.008255	
NO_x	0.000699	0.001378	0.000999	0.020485	
N_2O	3.68×10^{-6}	1.05×10^{-5}	7.36×10^{-6}	3.08×10^{-5}	
CH_4	2.94×10^{-6}	7.50×10^{-6}	4.21×10^{-6}	2.05×10^{-5}	
VOC	1.18×10^{-5}	2.55×10^{-5}	1.68×10^{-5}	6.15×10^{-5}	
CO	6.84×10^{-5}	0.0001877	9.78×10^{-5}	0.000537	

$$\text{matrix } \mathbf{g} = \begin{bmatrix} 0.14258 & 3.68023 & 0.76635 & 0.199469 & 0.278392 & 0.169685 & 0.4061057 & 0.242575 & 5.616753 \\ 0.00063 & 0.023121 & 0.003393 & 0.001254 & 0.001303 & 0.001067 & 0.0021781 & 0.001525 & 0.008255 \\ 0.00038 & 0.015146 & 0.002223 & 0.000822 & 0.000795 & 0.000699 & 0.001378 & 0.000999 & 0.020485 \\ 4.03\times10^{-6} & 0.000112 & 1.64\times10^{-5} & 4.33\times10^{-6} & 8.05\times10^{-6} & 3.68\times10^{-6} & 1.05\times10^{-5} & 7.36\times10^{-6} & 3.08\times10^{-5} \\ 3.83\times10^{-6} & 6.39\times10^{-5} & 9.36\times10^{-6} & 3.46\times10^{-6} & 5.36\times10^{-6} & 2.94\times10^{-6} & 7.50\times10^{-6} & 4.21\times10^{-6} & 2.05\times10^{-5} \\ 7.33\times10^{-5} & 0.000255 & 3.74\times10^{-5} & 1.38\times10^{-5} & 1.61\times10^{-5} & 1.18\times10^{-5} & 2.55\times10^{-5} & 1.68\times10^{-5} & 6.15\times10^{-5} \\ 0.000519 & 0.00148 & 0.000218 & 8.04\times10^{-5} & 0.00014 & 6.84\times10^{-5} & 0.0001877 & 9.78\times10^{-5} & 0.000537 \end{bmatrix} \tag{G.1}$$

$$\text{matrix } \mathbf{q}_{AP} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.7 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}; \text{ matrix } \mathbf{q}_{POCP} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.7 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\text{matrix } \mathbf{q}_{GWP} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 298 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 25.75 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{G.2}$$

$$\mathbf{h}_{AP} = \sum_{j=1}^{n} \left(\mathbf{q}_{AP}\right)_j \mathbf{g}_i; \; \mathbf{h}_{GWP} = \sum_{j=1}^{n} \left(\mathbf{q}_{GWP}\right)_j \mathbf{g}_i; \; \mathbf{h}_{POCP} = \sum_{j=1}^{n} \left(\mathbf{q}_{POCP}\right)_j \mathbf{g}_i \tag{G.3}$$

Tables G.2, G.3 and G4 list the amounts of the emission equivalents after calculation based on (5.4) in the Life Cycle Impact Assessment in terms of each component characterized in the three categories $\mathbf{h}_{AP}$, $\mathbf{h}_{GWP}$ and $\mathbf{h}_{POCP}$.

Table G.2: Acidification potential (AP) of each component in SO_2 equivalent/fU.

$\frac{g}{kWh}$	**LV transformer**	**Tower**	**Blade**	**Blade extender**	**Hub**	**generator**	**gearbox**	**Main shaft**	**Basement**
SO_2-eq	0	0	0	0	0	0	0	0	0
SO_2-eq	0.00063	0.023121	0.003393	0.001254	0.001303	0.001067	0.002178	0.001525	0.008255
SO_2-eq	0.000266	0.010602	0.001556	0.000575	0.000557	0.000489	0.000965	0.000699	0.01434
SO_2-eq	2.82×10^{-6}	7.84×10^{-5}	1.15×10^{-5}	3.03×10^{-6}	5.64×10^{-6}	2.58×10^{-6}	7.35×10^{-6}	5.15×10^{-6}	2.16×10^{-5}
SO_2-eq	0	0	0	0	0	0	0	0	0
SO_2-eq	5.86×10^{-5}	0.000204	2.99×10^{-5}	1.1×10^{-5}	1.29×10^{-5}	9.44×10^{-6}	2.04×10^{-5}	1.34×10^{-5}	4.92×10^{-5}
SO_2-eq	0	0	0	0	0	0	0	0	0
Total	0.000957	0.034006	0.004991	0.001843	0.001878	0.001568	0.00317	0.002243	0.022665

Table G.3: Global Warming Potential (GWP) of each component in CO_2 equivalent.

$\frac{g}{kWh}$	LV transformer	Tower	Blade	Blade extender	Hub	generator	gearbox	Main shaft	Basement
CO_2-eq	0.14258	3.68023	0.76635	0.199469	0.278392	0.169685	0.406106	0.242575	5.616753
CO_2-eq	0	0	0	0	0	0	0	0	0
CO_2-eq	0	0	0	0	0	0	0	0	0
CO_2-eq	0.001201	0.033376	0.004887	0.00129	0.002399	0.001097	0.003129	0.002193	0.009178
CO_2-eq	9.86×10^{-5}	0.001645	0.000241	8.91×10^{-5}	0.000138	7.57×10^{-5}	0.000193	0.000108	0.000528
CO_2-eq	0	0	0	0	0	0	0	0	0
CO_2-eq	0	0	0	0	0	0	0	0	0
Total	0.14388	3.715251	0.771478	0.200848	0.280929	0.170857	0.409428	0.244877	5.626459

Table G.4: Photon Oxidant Chemical Potential (POCP) of each component in C_2H_4 equivalent.

$\frac{g}{kWh}$	LV transformer	Tower	Blade	Blade extender	Hub	Generator	Gearbox	Main shaft	Basement
C_2H_4-eq	0	0	0	0	0	0	0	0	0
C_2H_4-eq	3.02×10^{-5}	1.11×10^{-3}	1.63×10^{-4}	6.02×10^{-5}	6.25×10^{-5}	5.12×10^{-5}	1.05×10^{-4}	7.32×10^{-5}	3.96×10^{-4}
C_2H_4-eq	1.06×10^{-5}	4.24×10^{-4}	6.22×10^{-5}	2.30×10^{-5}	2.23×10^{-5}	1.96×10^{-5}	3.86×10^{-5}	2.80×10^{-5}	5.74×10^{-4}
C_2H_4-eq	0	0	0	0	0	0	0	0	0
C_2H_4-eq	2.30×10^{-8}	3.83×10^{-7}	5.62×10^{-8}	2.08×10^{-8}	3.22×10^{-8}	1.76×10^{-8}	4.50×10^{-8}	2.53×10^{-8}	1.23×10^{-7}
C_2H_4-eq	3.05×10^{-5}	1.06×10^{-4}	1.56×10^{-5}	5.74×10^{-6}	6.70×10^{-5}	4.91×10^{-6}	1.06×10^{-5}	6.99×10^{-6}	2.56×10^{-5}
C_2H_4-eq	1.04×10^{-5}	2.96×10^{-5}	4.36×10^{-6}	1.61×10^{-6}	2.80×10^{-6}	1.37×10^{-6}	3.75×10^{-6}	1.96×10^{-6}	1.07×10^{-5}
Total	8.18×10^{-5}	1.67×10^{-3}	2.45×10^{-4}	9.06×10^{-5}	9.43×10^{-5}	7.71×10^{-5}	1.58×10^{-4}	1.10×10^{-4}	1.01×10^{-3}

Table G.5: Environmental emission equivalent of each component in functional Unit [g/kWh].

$\frac{g}{kWh}$	LV transformer	Tower	Blade	Blade extender	Hub	generator	gearbox	Main shaft	Basemen
SO_2-eq	0.000957	0.034016	0.004991	0.001843	0.001878	0.001568	0.00317	0.002243	0.022665
CO_2-eq	0.14388	3.716373	0.771478	0.200848	0.280929	0.170857	0.409428	0.244877	5.626459
C_2H_4-eq	8.18×10^{-5}	0.00167	0.000245	9.06×10^{-5}	9.43×10^{-5}	7.71×10^{-5}	0.000158	0.00011	0.001006

Appendix H

Table H.1: The total energy input required to produce electrical cables.

Material	[Kg/m]	Total weight	Energy consumption Factors [MJ/kg]	Total energy input required [MJ]
Copper	16.88	177240	78.200	13860168
XLPE	1	10500	45.700	479850
Polypropylene	1	10500	45.700	479850
Steel pipe	2.2	23100	34.26	791406
Lead	4.52	47460	35.6	1689576
Copper	16.88	25320	78.200	1980024
XLPE	9.06	13590	45.700	621063
Polypropylene	4.53	6795	45.700	310531.5
Steel pipe	16.88	25320	34.26	867463.2
Lead	13.354	20031	35.6	713103.6
Total				**21793035**

Table H.2: The total energy input required to produce transformers.

Material	kg material	energy consumption factors [MJ/kg]	Total energy consumed for production [MJ]
Copper profile	20121.7	78.2	1573517
Electrical steel	50003.36	34.26	1713115
Steel sheet	24089.2	53	1276728
Steel profile	21272.4	29.3	623281.3
Total			**5186641**

Table H.3: The total energy input required for transportation stages.

Diesel [kg]	The total diesel [kg]	the total energy material factors [MJ]
40 t Heavy truck RER	551.80	76384
	1412.43	595832
	1404.42	470208.8
	2808.84	777638.4
16 t Normal truck RER	1785.6	23622
	2038.374	60464.7
	10991.89	60121.8
	18178.56	120243.6
Total	**39171.91**	**2184515**

During construction stage, the total energy input required is 48567.3 kg. The diesel consumed is converted as 2708471 MJ of energy.

Table H.4: Energy consumed in Operation and maintenance stages.

Diesel [kg]	The total diesel	The energy material factors [MJ]
16 t Truck RER	569.6	24384

Table H.5: The maintenance of the gearbox.

	Kg/unit	Mass of 20 units [kg]	Energy consumed factor [MJ/kg]	Total energy consumed
Cast iron	6104	122080	29.11	3553749
Chromium steel	6104	122080	21.11	2577109
Rubber	028	560	40.3	22568
Total				6153426

The decommissioning normally accounts for 2 % of the total electricity generated [A13].

Table H.6: The uncertainty assumptions for analysis.

Climate change CO2 equivalent	Indicators	Index from Pedigree matrix	Percentage of uncertainty [%]	Weighted average SO_2-eq [%]	Weighted average CO_2-eq [%]	Weighted average C_2H_4-eq [%]
Manufacture stage	U3	10 %	37.41	82.58 %	81.0 %	60.44 %
	U4	30 %				
	U5	20 %				
Turbine transportation and installation stage	U3	10 %	17.32	11.21 %	7.63 %	24.50 %
	U4	10 %				
	U5	30 %				
Power generation and maintenance stages	U3	5 %	22.91	3.94 %	3.10 %	5.76 %
	U4	20 %				
	U5	10 %				
Decommissioning	U3	10 %	36.7	2.28 %	8.21 %	9.29 %
	U4	25 %				
	U5	25 %				

Appendix I

Calculation for uncertainty analysis

I.1 Uncertainty for global warming (CO_2eq)

Table I.1: Uncertainty for unit process of all wind farm configurations.

Unit processes	Indicators	Uncertainty factor	Standard deviation [SD %]	Weighted average SO_2-eq	Weighted average CO_2-eq	Weighted average C_2H_4-eq
Manufacture stage	U3	10 %	37.41	82.58 %	81.0 %	60.44 %
	U4	30 %				
	U5	20 %				
Turbine transportation and installation stage	U3	10 %	17.32	11.21 %	7.63 %	24.50 %
	U4	10 %				
	U5	30 %				
Power generation and maintenance stages	U3	5 %	22.91	3.94 %	3.10 %	5.76 %
	U4	20 %				
	U5	10 %				
Decommissioning	U3	10 %	36.7	2.28 %	8.21 %	9.29 %

Table I.2: The summary of total emission equivalent of the wind farm.

Emission equivalent	The mass of emission	Unit
Global warming	14.69	gCO_2-eq/kWh
Acidification potential	0.092	gSO_2-eq/kWh
Ozone depletion	0.006158	gC_2H_4-eq/kWh

Table I.3: The range value of CO_2 equivalent in Global Warming Potential.

	CO2-equivalent				
	Manufacture stage	**Turbine transportation and installation stage**	**Power generation & maintenance stages**	**Decommissioning**	**Global warming**
Upper level	12.49	1.15	0.47	1.27	15.38
Lower level	11.3	1.09	0.44	1.15	14
Standard deviation	30.3021 %	1.3215 %	0.7102 %	3.013 %	35.347 %
z_0.025	1.96				

Table I.4: The range value of SO_2 equivalent in acidification.

SO2					
	Manufacture stage	Turbine transportation & installation stage	Power generation & maintenance stages	Decommissioning	Acidification
1	0.6815	0.04837	0.02132	0.01850	0.76965
1	-0.52953	-0.02774	-0.01407	-0.01430	-0.58565
SD	30.8932 %	1.9416 %	0.9027 %	0.8368 %	34.5742 %
z_0.025	1.96				

Table I.5: The range value of SO_2 equivalent in acidification.

C_2H_4					
	Manufacture stage	**Turbine transportation and installation stage**	**Power generation and maintenance stages**	**Decommissioning**	**Photo smog**
1	0.4469	0.08468	0.02622	0.06740	0.62519
1	-0.43945	-0.08166	-0.02551	-0.06625	-0.61287
SD	22.6106 %	4.2434 %	1.3196 %	3.4094 %	31.5831 %
z_0.025	1.96				

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