MASTER OF SCIENCE IN MECHANICAL ENGINEERING

Life Cycle Assessment of Renewable Energy Technologies of Bangladesh

by

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CERTIFICATE OF APPORVAL

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TABLE OF CONTENTS

Chapter **Topic** **Page**

Chapter 1 **Introduction**

Chapter 2 **Literature Review**

Chapter 3 **LCA of Solar PV system**

Chapter 4 LCA of wind energy system

Chapter 5 Discussions and Conclusions

Appendix

LIST OF TABLES

Chapter 1

Chapter 3

Chapter 4

LIST OF FIGURES

Chapter 1

Chapter 2

Chapter 4

Abstract:

As the benefit of the renewable energy systems getting more and more clear to people, these are being introduced in small scale and large scale in both developed and developing countries. Renewable energy systems show a considerable environmental benefit over the conventional fossil based energy systems. To compare the environmental impacts between renewable and non-renewable energy systems several studies has been conducted in several location, in several condition. This thesis conducts the life cycle energy and emission analysis between two most popular PV systems: solar PV system and wind energy system in Bangladesh. For this analysis a 21.16 kWp solar PV system is selected which is located at Dhaka Bangladesh. But for the analysis of wind energy system no wind turbine or wind power plant found active in Bangladesh, although several has been installed in several locations of Bangladesh. Therefore, a wind energy system has been designed which will provide the same amount of energy output as that of the PV system. The results from this analysis show that the energy payback time for PV system and wind energy system is 5.7 and 1.71 years respectively. Therefore, it is clear that the wind energy system will generate way more energy in its life time than that of the solar PV system. From the emission analysis, it is found that the CO_2 emission intensity of the PV system is 5.28 kg CO_2/kWh_{el}. On the other hand, the wind energy system has a CO_2 emission intensity of 0.12 kg CO_2/kWh_{el}. The manufacturing of PV module in the solar PV system is found to be responsible for this huge difference of emission intensity. Wind energy system comprises of components which requires less energy and emits less greenhouse gas during its manufacturing, which caused the differences between the results.

Chapter 1

Introduction

1.1 Introduction

A move towards renewable and sustainable energy resources has become obvious because of the continuous degradation of conventional fossil fuel resources with increasing demand of energy around the world and greenhouse gas emission [1-3]. The production of sustainable energy based on renewable sources is a challenging task for replacing the fossil based fuels to get cleaner environment and also to reduce the dependency on other countries and uncertainty of fuel price. A worrying statistics is that the global production of oil and gas is approaching its maximum and the world is now finding one new barrel of oil for every four it consumes[4]. All these serious concerns related to energy security, environment and sustainability have led to a move toward alternative, renewable, sustainable, efficient and cost effective energy sources with lesser emissions.

The most common renewable energy sources are solar energy, wind energy, tidal energy, hydroelectric energy, ocean thermal energy, geothermal energy and biomass energy etc. Each renewable energy source is performing differently; one could be best option for one location/purpose/season and could not perform with that efficiency at another location/purpose/season. The solar energy sources are best in remote or under developed areas having bright sunshine[5]. Windmills are best suited near sea shore, as there winds are enough strong to get decent production of energy. Similarly, tidal, hydroelectric, geothermal, and ocean thermal energies have their importance. Among the renewable energy sources, biofuels are the most popular renewable energy source because of the availability of raw material (biomass), everywhere and round the year and also due to its suitability in transport vehicles and industries.

The life cycle assessment (LCA) of renewable energy sources is the key to observe their sustainability. There is a need to conduct LCA of renewable energy production system on the basis of their local conditions, as one energy source cannot be sustainable for all geographical locations, due to variations in resources availability, climate, environmental, economic and social conditions, policies, etc. Therefore, LCA can be used as a tool to assess the sustainability of various energy sources for different locations. LCA techniques allow detailed analysis of material and energy fluxes on regional and global scales. This includes indirect inputs to the production process and associated wastes and emissions, and the downstream fate of products in the future. LCA studies vary in their definition of the various criteria, such as, scope and goal, system boundaries, reference system, allocation method. LCA studies of renewable energy sources calculate the environmental impact and can relate the results against sustainability criteria. This thesis focuses on the modeling and results of LCA of two renewable energy sources, photovoltaic (PV) system and wind energy system to get a more holistic perspective of their environmental sustainability.

PV technology, as an example of renewable energy, directly generating electricity from solar energy, is free from fossil energy consumption and greenhouse gases (GHG) emission during its operations. Thus, it seems to be completely clean and have no environmental impacts. However, during its life cycle, it actually consumes a large amount of energy and emits some GHG during some stages such as solar cells manufacturing processes, PV module assembly, balance of system (BOS) production, material transportation, PV system installation and retrofitting and system disposal or recycling. In order to accurately investigate the environmental performance of PV systems, life cycle assessment (LCA) is usually conducted to evaluate their environmental impacts during life cycle. The two most widely-used environmental indicators, energy payback time (EPBT) and greenhouse gases (GHG) emission rate, can be used to easily evaluate the sustainability and environmental performance of PV systems.

Many comprehensive studies are performed to quantify the energy consumed in the manufacturing process of different renewable energy systems. These studies expressed the energy used in terms of energy payback time (EPBT). EPBT is defined as the years required by the renewable energy system to generate the equivalent amount of energy as it consumed over its life time including energy requirement in manufacturing, assembly, transportation, system installation, operation and maintenance and system decommissioning or recycling of the renewable energy (RE) system . As the EPBT of a RE system is derived as the energy requirements of RE system and BOS components (which includes support structures, cabling, electronic and electrical components, inverters, and batteries) divided by its annual energy output, thus it is determined by a number of factors such as type system(for PV module whether it’s a monocrystalline silicon (mc-silicon), polycrystalline silicon (pc-silicon) etc.), manufacture technologies, conversion efficiency, installation location and pattern (integrated or mounted), support structure, application type (stand-alone or grid-connected) and performance ratio (all losses included) [6]. EPBT is regarded as a perfect evaluation indicator for sustainability, through it we can clearly find out whether the specific PV system can bring a net gain of energy for user during its life time and if so to what extent. Richards and Watt [7] have followed a different approach than EPBT to assess extent of this gain of renewable energy technologies. Because one of the main problems with EPBT method is that it does not reflect the life of a product. For example, a product with longer energy payback and a longer expected life than a similar alternative may in fact generate more energy over its entire life. Richards and Watt [7] and Pick and Wagner [8]suggests that the energy yield ratio (EYR) provides a more informative indication of the potential energy saving possible. The EYR shows how many times the energy invested in the renewable energy technology is returned or paid back by the system in its entire life.

In LCA studies of solar PV system, the efficiency of the solar PV module is considered to be its efficiency under the standard test conditions (STC) of 1000 W/m^2 and 25°C. However, in actual operation of a solar PV system, STC do not prevail, particularly under tropical high humidity weather conditions where the ambient temperature is often above 30°C. It has been recorded that solar PV modules reached a temperature higher than 60°C during peak radiation hours in equatorial Singapore. Thus, its actual operating efficiency is lower than that at STC. Therefore, none of the above factors can be considered in isolation, and it is more appropriate to use EPBT from local studies for more informed decision making. Thus, there is a need for site-specific life cycle evaluation to generate insights, at least to represent a region. This paper describes a LCA study carried out for a grid connected 2.7 kWp mono-crystalline solar PV system, which has been operating in Dhaka, Bangladesh since 2014.

1.2 Background of Solar Energy:

Solar energy is the most abundant and promising renewable energy resource with higher potential to gain energy than any other renewables [9]. It can be used in two ways known as thermal route and photovoltaic route. In thermal route the heat from solar energy is used for various purposes like heating, water purification power generation, etc. on the other hand in photovoltaic route the light in solar energy is converted into electricity which can be used in lighting, pumping and power supply in rural areas where grid electricity is not reachable [10]. Solar photovoltaic (PV) has become center of attention to the oil companies and solar product manufacturers considering its high potential and they are investing heavily in this sector in recent days [11]. This is reflected in Table 1.1 where it can be seen that in 2014 alone the addition in the global power capacity from solar PV was 40 GW which led to the total of almost 177 GW. Although this is only 0.9% of the world total power capacity, its share is increasing rapidly in the recent years.

Technology	**World (GW)**		**Top countries (GW)**				
	Total	**Added in 2014**	**China**	**USA**	**Germany**	**Japan**	**India**
Bio power	93	5	10	16.1	8.8	4.7	5
Geothermal power	12.8	0.6	~0	3.5	~0	0.5	0
Hydro power	1055	37	280	79	5.6	22	45
Ocean power	0.5	~0	~0	~0	0	0	0
Solar PV	177	40	28	18	38	23	3.2
Concentrating Solar thermal power	4.4	0.9	~0	1.6	0	0	0.2
Wind power	370	51	115	66	39	2.8	22
Total renewable power capacity	**1712**	**134**	**433**	**185**	**92**	**54**	**76**

Table 1.1: Distribution of installed world renewable energy technologies in the top five countries Source: Ref. [12]

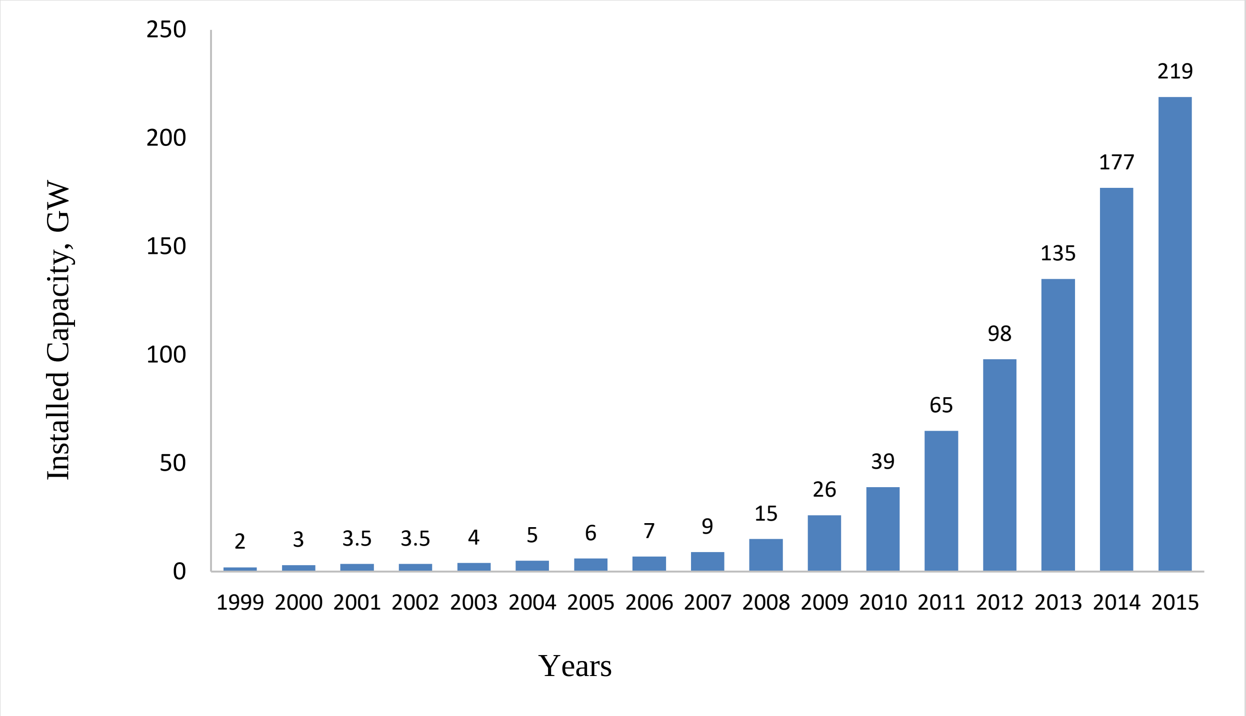


Figure 1.1: Installed PV worldwide (till 2015). Source: Ref. [13]

Figure 1.1 shows that almost 60 percent of the world solar PV capacity was installed from 2012 to 2014. In 2014, five countries added more than 1 GW of solar PV to their grid which led a total of 20 countries now with a capacity of at least 1 GW from solar PV. Asia topped all other markets by adding 60% of the global addition. China generated 200% more electricity in 2014 compared to previous year because of newly added solar PV in their grid [14].

However, because of geographic position, Bangladesh has a great potential of utilizing solar insolation. Bangladesh receives an average of 4-6.5 kWh/m^2 of solar radiation daily. This can produce a total of 1018 x10^{18} J of energy [15]. About 0.11% of this energy can meet the primary energy consumption of this country [15]. Table 1.2 shows the average monthly solar radiation in different cities of Bangladesh (Recorded from 1998 to 2008). Maximum solar radiation can be found from March – April and minimum in December – January (see Table 1.2). Rajshahi district gets the highest solar radiation with huge opportunity to harness solar energy.

Month	**Rajshahi**	**Jessore**	**Bogra**	**Dhaka**	**Barisal**	**Sylhet**
January	3.96	4.25	4.01	4.03	4.17	4.00
February	4.47	4.85	4.69	4.78	4.81	4.63
March	5.88	4.50	5.68	5.33	5.30	5.20
April	6.52	6.23	5.87	5.71	5.94	5.24
May	6.17	6.09	6.02	5.71	5.75	5.37
June	5.25	5.12	5.26	4.80	4.39	4.53
July	4.79	4.81	4.34	4.41	4.20	4.14
August	5.16	4.93	4.84	4.82	4.42	4.56
September	4.96	4.57	4.67	4.41	4.48	4.07
October	4.88	4.68	4.65	4.61	4.71	4.61
November	4.42	4.24	4.35	4.27	4.35	4.32
December	3.82	3.97	3.87	3.92	3.95	3.85
Average	**5.00**	**4.85**	**4.85**	**4.73**	**4.71**	**4.54**

Table 1.2: Average monthly solar insolation (kWh/m^2/day) at different cities in Bangladesh

Source: Ref. [16]

Annual average direct natural insolation of 1900 kWh/m^2 in Rajshahi is found to be sufficient to utilize concentrating solar power technology [17]. This technology could generate a total of 100 MW of electricity if in a 2 m^2 area the annual average radiation is 2000 kWh/m^2 [18].

Although concentrating solar power is in nascent stage the other technologies are expanding quite rapidly in Bangladesh. Among them solar home system (SHS) is the most successful one. There are 3.6 million solar home systems of a total capacity of almost 150 MW has been installed around the country [19]. Infrastructure Development Company Limited (IDCOL) is the leading organization in this sector and they have started to work with SHS since 2003 with a view to providing sustainable energy to the electricity deprived rural people. They are working on a target to install 6 million solar home systems with an estimated capacity of 220 MW by the year 2017 [20]. Under this project almost 65,000 SHS are now being installed every month resulting 58% annual increase every year. About 180,000 tons of kerosene with an estimated value of USD 225 million will be replaced by this project [20]. On the other hand grid connected solar systems are incorporated in several areas of the country which is adding new dimension in the solar energy utilization. The system provides grid quality electricity to the households, offices and small industrial enterprises. Several projects are being taken by IDCOL and Bangladesh Power Development Board (BPDB) to accomplish several mini grid projects. Seven solar mini grid plants have been installed by IDCOL in different locations of Bangladesh and several projects are under construction (see table 1.3). Moreover, 3 MW_p and $8MW_p$ of grid connected solar power plants are under construction by BPDB at Jamalpur and Rangamati, respectively. Usually a mini grid can supply electricity to 250-300 households and a market place consisting of 80-100 shops. Table 1.3 represents the approved mini grid projects financed by IDCOL.

Project location	Capacity (kW_p)	Project status
Enam Nahar, Sandwip, Chittagong	100	Operational
Kutubdia, Cox's Bazar	100	
Bagha, Rajshahi	141	
Paratoli, Raipura, Narshingdi	141	
Narayanpur, Nageshwari, Kurigram	158	
Godagari, Rajshahi	149	
Monpura, Bhola	177	
Nooner Tek, Sonargao, Narayangonj	168	Under construction
Rupsha Char, Sadar, Sirajganj	130	
Chilmari, Daulatpur, Kushtia	188	
Munmiar Char, Islampur, Jamalpur	162	
Baghutia char, Doulatpur, Manikganj	228	
Nijhum island, Hatiya, Noakhali	200	

North Channel Union, Sadar, Faridpur	162	
Char Kajal, Patuakhali	100	
Char Biswas, Patuakhali	100	
Ghaschapru, Belkuchi, Sirajganj	218.4	
Poschim Shalipur, Char Bhadrashan, Faridpur	156	

Table 1.3: Approved mini grid projects financed by IDCOL. Source: Ref. [20]

Roof-tops of the commercial and residential buildings can be utilized by installing solar PV to meet their electricity demand and to supply the surplus electricity to the grid. Installing PV systems in the residential buildings to meet a fraction of the load is a prior condition for getting electricity connection. The targeted capacity from solar roof-top project is 30 MW. As of 2014, a total of 10 MWp solar roof-top PV systems were installed. The roof-top solar PV systems are already installed in the Bangladesh Bank head office and WAPDA buildings [19]. Non-agricultural lands owned by the government are being used for Solar Park project to produce clean electricity. The electricity will be fed into the national grid of Bangladesh on commercial basis. The expected capacity addition from this project is 135 MW. Government has already identified eight sites for solar park project [19].

Solar water heating can also reduce the dependency on fossil fuels. In the urban areas industrial and commercial sectors use hot water that is produced by natural gas or electric heaters. Hence, inclusion of solar water heaters is a priority of the government to replace gas and electric heaters.

Solar irrigation is another trending technology in Bangladesh utilizing solar radiation. This is of utmost importance since the country has a huge amount of almost 1.61 million irrigation pumps out of which 1.34 million (about 83%) is running by diesel and 0.27 million (about 16%) is by electricity. These pumps are consuming 700 MW of electricity and 900 million liters of diesel every year. 1550 irrigation pumps are planned to be energized by solar power by 2017 where 38 of them are already running. IDCOL has approved a total of about 7 MW capacity solar PV project to run irrigation pumps across the country [21]. Drinking water from solar powered pumps can provide quality water to the rural people. 112 solar powered drinking water pumps have already been installed in the coastal areas of Bangladesh [19].

Hybrid renewable energy sources are getting popular in Bangladesh. The hybrid renewable energy systems can provide reliable electricity to the remote off-grid locations. There is an ongoing project to produce 7.5 MW power in Hatiya Island, Noakhali using solar-wind-diesel hybrid system [22]. A study conducted by Nandi and Ghosh suggests a wind-PV-battery hybrid system can be used as a potential technology in the remote areas of the country.

Solar charging can be an effective alternative to the conventional fossil fuel in transport sector as well [23]. So to achieve the targeted 10% electricity from renewable sources government and other organizations should utilize the solar energy to its full potential.

1.3 Background of Wind Energy:

Exploitation of wind energy largely depends upon the wind resource since the available wind energy changes by the cube of the wind speed. This leads to the necessity of selection of a suitable site for an economically viable wind energy farm using properly designed wind turbines. Depending upon the power generation capacity wind turbines are classified as micro (50W – 2 kW), small (2 kW – 40 kW), medium (40 kW – 1 MW) and large turbines (more than 1 MW) [24, 25].

World's total installed wind energy capacity is 432,419 MW at the end of 2015 where China has the largest share of almost 33.6% (see Figure 1.2). Cumulative installed wind capacity from 2000-2015 is shown in Figure 1.3. Wind energy growth is driven by competitive pricing, enhanced energy security and price stability. In 2015 alone a total of almost 63 GW (see Figure 1.4) of wind capacity has been installed worldwide out of which 48.4% in China, 13.6% in USA and 9.5% in Germany [26]. For eighth years in a row Asia topped the largest regional market in the wind energy with China in the leadership position. Germany's record installation set Europe in increasingly concentrated market. After a dismissal in 2013 US market recovered in 2014 and looks strong for another two years similar as Canada.

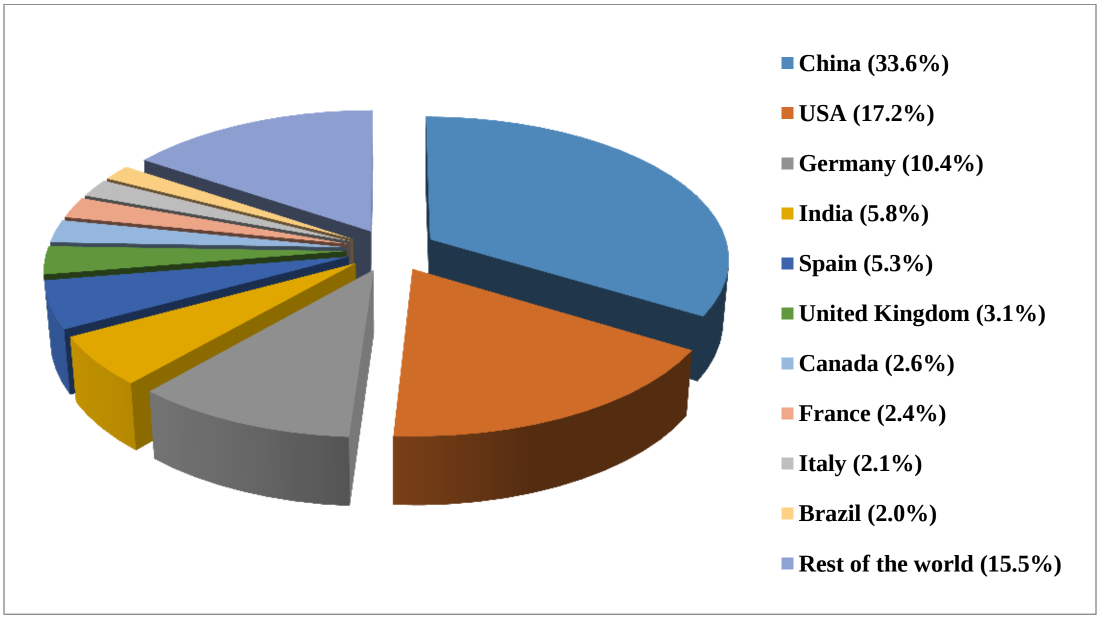


Figure 1.2: Shares of top 10 countries in cumulative wind capacities (till December 2015). Source: Ref. [26]

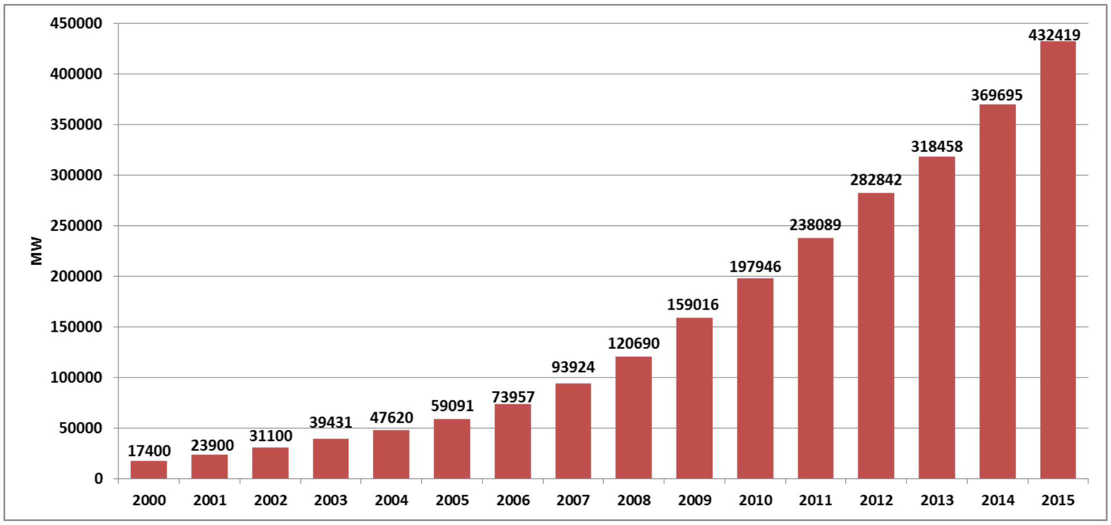


Figure 1.3: Global cumulative installed wind capacity (2000-2015). Source: Ref. [26]

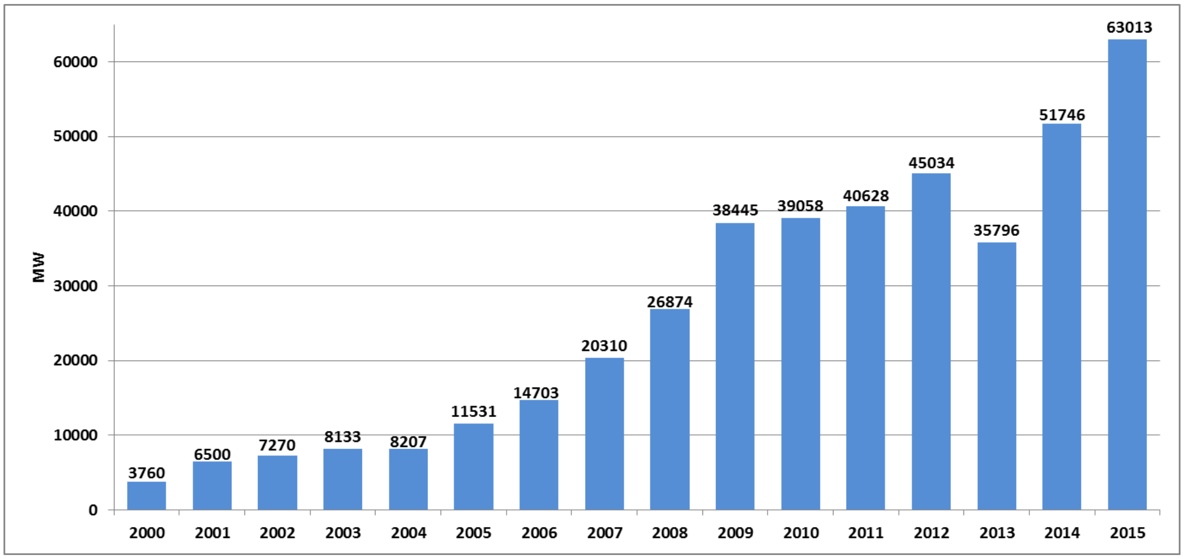


Figure 1.4: Global annual installed wind capacity (2000-2015). Source: Ref. [26]

In Bangladesh the wind speed is not satisfactory for large scale wind parks. When more than 7 m/s of wind speed is necessary for large scale grid connected wind energy, a study conducted by Bangladesh Center for Advanced Studies (BCAS) between 1996 and 1997 has found that Bangladesh has only 2.94 m/s to 4.54 m/s of average annual wind speed at a height of 25 m measured at seven different spots which are Patanga, Teknaf, Cox’s Bazar, Noakhali, char Fassion, Kutubdia and Kuakata [16]. Among them the maximum 4.52 m/s was observed at

Kuakata and the minimum 2.94 m/s was observed at Teknaf. It is also observed that wind speed in the south-eastern part of the country is higher than south-western part. Also between coastal areas and inlands, coastal areas have higher wind speed. Wind speed is found to be relatively higher from April – August and from September – March its low.

Due to lack of ground data, less wind velocity and uncertain weather condition, Bangladesh has only two completed wind energy projects at Feni and Kutubdia districts. Out of them at Sonagazi, Feni Bangladesh Power Development Board (BPDB) has implemented four grid connected wind power plants each of 225 kW capacity and at Kutubdia a wind battery hybrid power plant has been installed with fifty wind turbines each of 20 kW of capacity [22]. But due to natural calamities such as cyclone and other technical problems these plants have not been running lately. Recently, these plants are under reconstruction, repair and maintenance stage and soon they will be fully functional. Measures have been taken to install wind plant of 15 MW capacity in the coastal areas of Bangladesh including Muhuri Dam Area of Feni, Mognamaghat of Cox'sbazar, Parky Beach of Anwara in Chittagong, Kepupara of Borguna and Kuakata of Patuakhali. Also 7.5 MW of wind- solar- diesel/heavy fuel oil hybrid plant is under construction at Hatia Island, Noakhali [22]. BPDB has a plan to implement 50-200 wind power project at Parky Beach area, Anawara in Chittagong [22]. Table 1.4 represents the wind turbines that are installed by different government and non-government organizations. To bring the large segment of people under electrification who are out of reach of electricity because of unreachable grid connection and lack of natural resources, renewables like wind energy should be used in an effective way with other type of renewable energy technologies like solar photovoltaics [27, 28]. More research and development should be done in this sector to extract as much energy as possible from wind.

Organization	**Location**	**Type**	**Installed capacity (kW)**
Grameen Shakti	Grameen offices in the coastal region	3 Hybrid	4.5
	Cyclone shelter in the coastal region	Hybrid	7.5
BRAC	Coastal region	Stand-alone	0.9
	Coastal region	Hybrid	4.32
Bangladesh Army	Chittagong hill tracts	Stand-alone	0.4
IFRD	Teknaf	Stand-alone	1.1
	Meghnaghat	Stand-alone	0.6
LGED	Kuakata	Wind-PV hybrid	0.4
Total			**19.72**

Table 1.4: Wind turbine installations by different government and non-government organizations. Source: Ref. [29]

1.4 Comparative analysis:

Life cycle assessment result of some of the previous studies has been summarized in table 1.5. The variation in the result of the LCA studies are clear. These variations are caused by the location, environment and condition the plants are working on. However, no life cycle assessment study has been performed for the renewable energy technologies of Bangladesh. Therefore, no EPBT or emission intensity of any energy system has been found out. Also not much study has been performed which analyzed and compared different renewable energy technologies of the same sizing with respect to output conditions. This study performs a life cycle analysis of a solar mini-grid system and after designing a wind energy system of the similar output conditions as that of the solar system its life cycle has also been analyzed.

Author	Study	EPBT	Greenhouse gas emission rate, g-CO_2/kWh
Ito et al. [20]	LCA of PV systems	1.8 years	54
Nishimura et al. [40]	LCA of PV system	0.64 years	-
Valverde et al. [39]	LCA of PV systems	9.08 years	134
Peng et al. [38]	LCA of PV systems	0.75–3.5 years	10.5–50
Kato et al. [36]	LCA of PV systems	15.5 years	91
Guezuraga et al. [50]	LCA of wind energy systems	7 months	9
Crawford [51]	LCA of wind energy systems	12 months	-

Table 1.5: Results of LCA of previous studies

1.5 Objective of the study

a. To develop a life cycle assessment (LCA) model for renewable energy technologies in Bangladesh e.g. solar PV system, wind power plant
b. To investigate the energy input and output of a system in its life time and to calculate the energy payback time.
c. To investigate the environmental impact of each energy system and calculate the greenhouse gas emission intensity.
d. To compare the systems with respect to environmental impacts.

1.6 Thesis organization

After the introduction background on life cycle assessment, its definition and limitation has been discussed along with the studies conducted so far on solar and wind energy. Then the study of this project has been discussed in two different chapters for solar and wind energy respectively. The next chapter discussed the result of the study and future plan. The book concluded with the references.

Chapter 02

Literature Review

2.1 Life cycle assessment:

2.1.1 What is LCA?

Originally, LCA was the abbreviation of Life Cycle Analysis. However, Society of Environmental Toxicology and Chemistry (SETAC), the U.S. Environmental Protection Agency (EPA), and ISO now use LCA to represent "Life Cycle Assessment" because the word Assessment has more quantitative meaning. In Europe and Japan, researchers often use "Eco-balance" instead of LCA, but it has substantially the same meaning as LCA. Due to the complexity of the LCA method and the different purposes for LCA implementations, the concepts and methods for LCA have often had slightly different understandings: In SETAC and ISO files, the definition of LCA is constantly modified, but with further research and development, especially the standardization work on LCA by ISO, the LCA methodology has been gradually clarified.

In 1990, SETAC defined LCA as: "Life-Cycle Assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impacts of those energy and material uses and releases on the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process, or activity, encompassing extraction and processing of raw materials, manufacturing and distribution, use/reuse/maintenance, recycling, and final disposal" [30]. In addition, in 1993 they specified the methodological framework of LCA, which includes:

1. Goal and Scope Definition,
2. Life-Cycle Inventory,
3. Life-Cycle Impact Analysis, and
4. Life-Cycle Improvement Analysis.

This framework is the core method of LCA, and it is still used in the process based LCA method.

In 1996, ISO developed LCA standards for ISO14040. This standard also gives the definition of LCA: "LCA is the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle"[31]. The word "product system" here refers to an operational process of unit collections related to materials and energy and with specific function. In the LCA standard, “product” can mean both the general manufacturing production system and, for service industries, service systems. “Life cycle” refers to the continuous and interconnected stage of the production system, from the first stage of raw materials, to the final abandonment of the product.

Some other agencies also have their own descriptions for LCA, such as the definition by the U.S. EPA, which is: “LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential environmental impacts associated with identified inputs and releases, and interpreting the results to help you make a more informed decision” [32]. The 3M Corporation also uses the LCA concept in their management, defined as: “LCM is a process for identifying and managing the environmental, health, safety, and regulatory impacts and efficient use of resources in 3M products throughout their life cycle to guide responsible design, development, manufacturing, use, and disposal” [33].

Among these definitions, the definition of ISO and EPA point out that LCA needs the inputs and outputs of the process. After the identification of these elements, quantification of the emissions, which is pointed out by SETAC, should be done to guarantee the calculation of LCA is as objective as possible.

2.1.2 History of LCA

LCA appeared in the late 1960s to early 1970s. The first application of LCA can be traced back to 1969, which was carried out by Coca-Cola for the evaluation of the resource consumption and emissions associated with beverage containers. In this study, the Coca-Cola Company considered whether to replace disposable plastic containers with returnable glass bottles. By analyzing the complete life cycle, from raw material extraction to final waste disposal, they were able to track the whole process from cradle to grave, which provided quantitative analysis to compare the environment-friendly conditions of each of the two choices. This study is recognized as one of the first studies of LCA and laid the basis for life cycle inventory analysis [34]. They chose the plastic bottle as the result mainly because of the lower shipping cost and the ease of recycling. The plastic bottles were lighter than the glass bottles, so the plastic bottle packaging products have lower shipping cost. Moreover, at that time, plastic was easier to recycle than glass.

In the early 1970s, more companies in the United States and Europe began to conduct similar life cycle inventory analyses. For example, in 1975, the Japan Nomura Research Institute did a first packaging LCA study for Tetra Pak, which is a multinational food packaging and processing company [22]; and following that, Franklin Associates performed an LCA for soft-drink containers for Goodyear. The studies of this period commonly used the energy analysis method, a quantification method of resource use and environmental release, which was then known as the Resource and Environmental Profile Analysis, or “REPA.” Since this method was used by many researchers in those years, a standard methodology for this kind of study was developed.

Despite this pioneering work done in the 1970s, it was not Life Cycle Assessment in the full sense, as it was mainly based on inventory analysis. With the emergence of the global problem of solid waste during late 1970s to the mid-1980s, the REPA research method became a more utilized analysis tool. According to REPA, some consultant companies in Europe and the United States further developed this method for a range of waste management purposes. This method studied the environmental emissions and the potential impact of resource consumption in-depth. For example, the Boustead Consulting Company in the UK did inventory analysis for much of their research, and gradually formed a set of standardized methods of analysis, which laid a solid theoretical foundation for the future development of LCA.

The Society of Environmental Toxicology and Chemistry (SETAC) became the international leader of the field of LCA when they hosted the International LCA Seminar in 1990 for the first time, and at this meeting, put forward the concept and officially recognized specifications of LCA. In the years since, SETAC has continued to host seminars in which the theory and methods of LCA have evolved, and promotion and sharing of extensive LCA research has been conducted.

Even today, LCA methodology is still being researched and developed. SETAC and the International Organization for Standardization (ISO) are actively promoting the international standards for the LCA methodology. ISO has made LCA one of the most important steps of the ISO14000 environmental management system.

2.1.3 The limitations of Life Cycle Assessment

As an environmental management tool, LCA is not always appropriate for all situations, and in each decision-making process we cannot rely on LCA methodology to solve all problems. LCA only considers the ecological environment, human health, resource consumption and other aspects of environmental problems, and does not involve technology, economic or social effects such as quality, performance, costs, profit, public image, and other factors. Therefore, each decision-making process must be combined with other types of analysis and information.

The scope of LCA also does not include all environment-related issues. For example, LCA only considers the environmental impact that has already happened or will happen with certainty, but does not regard all possible environmental risks and necessary preventive and emergency measures. LCA methodology also does not require considering the restrictions of the environmental laws and regulations, but these aspects are very important when a corporation must deal with environmental policy and decision-making processes [35].

In LCA, subjectivity, choice, assumptions, and value judgments are involved in many aspects, such as the determination of system boundaries, the selection of data sources, the choosing of environmental damage types, the selection of calculation methods, evaluation process in the environmental impact assessment, etc. The common problem in the boundary definition is the circularity effects. It means that before one can complete a life cycle assessment of any material or process, one must have completed a life cycle assessment of all related materials and processes, which is almost impossible. So the researchers have to make an assumption to set the boundary to a limited spectrum, which can cause truncation error. Regardless of the assessment scope or the level of detail, all LCA contains subjective factors such as hypothesis, value judgments and trade-offs, and thus the conclusions of LCA require a full explanation to distinguish the information obtained by assumptions and subjective judgments from the knowledge by measurement using the scientific method.

Time and geographical constraints also exist in the original data and/or assessment results of LCA. Within the different times and geographic scope, the environmental data might be changed, so the corresponding evaluation results are only applicable for a certain time period and region, which is determined by the time period and geographic characteristic of the production system.

2.2 Literature on Solar LCA

It's in the mid 70's when the research on photovoltaic panel life cycle, energy consumption and environmental impact began in academic level [36]. This research was basically to find out the energy payback period estimation of monocrystalline PV systems which showed that the energy payback period of the ground silicon cells system is about 11.6 years [36]. Since then, assessment of the energy consumption and environmental effects of PV systems has gradually increased, and formed a number of important research results.

Kato et al. [37] used the ideas of Life Cycle Assessment to analyze the silicon photovoltaic systems made by abandoned materials from the semiconductor industry. As an example, he made a 3kW residential PV system and the results showed that the energy recovery period of the photovoltaic system made by the recycled silicon was about 15.5 years, and the carbon dioxide emission per unit of electricity was 91 g-CO_2/kWh.

Ito et al. [38] completed research on the potential of large-scale photovoltaic systems from an economic and environmental perspective. Using the LCA method, the researcher estimated the energy recovery cycle, life cycle carbon dioxide emission rate and the system production costs. The researcher used a hypothetical 100MW large-scale photovoltaic power plant as an example, and found the energy payback period of the power plant is 1.7 years, the carbon dioxide emission rate is 12g-CO_2/kWh, and the cost of the electricity the plant generated is 8.6 cent/kWh if the system life is 30 years. The result of payback period in this research is reasonable, but the carbon dioxide emission rate is lower than the average. Because of the different scale and model of the photovoltaic power plants considered in these studies Japanese researchers have representatively distinct results. In addition, these three researchers mainly calculated the carbon dioxide emissions of the projects during the whole life cycle, which cannot cover most of the potential environmental impacts beyond carbon dioxide.

Kannan et al. (2006) did a case study on a 2.7kWh solar photovoltaic system in Singapore. In this case study, the researcher studied the energy recovery cycle, the greenhouse gas emission reduction potential, and the cost of the system. After considering the construction phase, operation phase, and waste phase, the researcher found that the solar photovoltaic system only generated a quarter of the greenhouse gas as compared with only one half of a gas turbine generator system. However the cost of the electricity was five to seven times more than oil or gas fired power plants. The cost of the electricity from the photovoltaic system currently is lower than that because of the improvements of the technology.

Peng et al. [39] conducted a life cycle assessment of five common photovoltaic (PV) systems, i.e., mono-crystalline (mono-Si), multi-crystalline (multi-Si), amorphous silicon (a-Si), CdTe thin film (CdTe) and CIS thin film (CIS), and some advanced PV systems to examine the sustainability and environment performance of PV based electricity generation system. Result shows that the CdTe PV system presents the best environmental performance in terms of energy payback time and greenhouse gas emission rate due to its low life cycle energy requirement and relatively high conversion efficiency. On the other hand, due to high energy intensity during cell's production process the mono-Si PV system demonstrates the worst one. The EPBT and GHG emission rate of thin film PV systems are within the range of 0.75–3.5 years and 10.5–50 g CO_2-eq. /kWh, respectively. In general, the EPBT of mono-Si PV systems range from 1.7 to 2.7 years with GHG emission rate from 29 to 45 g CO_2-eq. /kWh, which is an order of magnitude smaller than that of fossil-based electricity.

Valverde et al. [40] presented an energetic and environmental life cycle assessment of a 4.2 kWp stand-alone photovoltaic system at University of Murcia which is in south-east of Spain. The energy payback time and specific CO_2 emission was calculated to be 9.08 years and 131 g/kWh respectively. The SAPV system has been environmentally compared with other supply options (diesel generator and Spanish grid) showing lower impacts in both cases. The results show the CO_2-emission reduction potential of SAPV systems in southern European countries and point out the critical environmental issues in these systems.

Nishimura et al. [41] studied the environmental load and energy payback time of a high concentration photovoltaic power generation system (hc-pV) and a multi crystalline silicon photovoltaic power generation system are studied. The study shows for a PV of 100 MW size, the total impacts of the hc-pV installed in Toyohashi is larger than that of the hc-pV installed in Gobi desert by 5% without consideration of recycling stage. The EPT of the hc-pV assumed to be installed in Gobi desert is shorter than EPT of the hcpV assumed to be installed in Toyohashi by 0.64 year. From these results, the superiority to install PV in Gobi desert is certificated. Comparing with hcpV and mc-Si PV, the ratio of the total impacts of mc-Si PV to that of hcpV is 0.34 without consideration of recycling stage. The EPT of hcpV is longer than EPT of mc-Si PV by 0.27 year. The amount of global solar radiation contributing to the amount of power generation of mc-Si PV is larger than the amount of direct solar radiation contributing to the amount of power generation of hcpV by about 188 kW h/(m^2 year) in Gobi desert. Consequently, it appears that using mc-Si PV in Gobi desert is the best option.

In the research of Pacca et al. [42], the effects of the energy recovery cycle, carbon dioxide emissions and energy production rate parameters of the whole life cycle of PV systems was observed. Research also showed that the solar-radiation intensity, the location of components, and the conversion efficiency of solar-radiation can influence the final result.

Ito et al. [20] did LCA for six different large-scale PV systems. The researcher considered the mining phase, production phase, transport phase, power plant construction, and operation phase. The research also calculated the energy recovery cycle of the system and the carbon dioxide emission rate. The results showed that the energy payback period of large-scale photovoltaic thin film battery system is only 1.8 years, and its carbon dioxide emission rate is 43-54g CO_2/kWh.

Most of the researchers used traditional LCA methodology to assess the environmental effects of the photovoltaic industry. However, there are also some researchers who have used hybrids of LCA. For example, Zhai [43] combined traditional LCA and EIO-LCA as a hybrid LCA, and used this method to analyze energy consumption; he found that the result from his hybrid LCA was 60% higher than the traditional LCA result. This meant that the energy consumption of processes other than the production process, such as transportation and logistics, was significant. The other reason for higher impacts is that EIO-LCA reduces the truncation error. The truncation error is explained in chapter three. In addition, transparency in reporting assumptions and defining the basis of analysis is critical in the publication of LCA results. At first glance, the results of different researchers can appear contradictory. However it is possible to understand the reason why results might not the same if the assumptions underlying the analysis are clearly articulated. Therefore, the clarity of the assumptions in this thesis are critical to understanding the results.

The economic evaluation tool, LCC, incorporated with LCA establishes the relation between environmental impact and economic cost of the product throughout the life cycle. This combined method builds a comprehensive evaluation system of both the estimated environmental impacts and estimated economic costs.

Kannan et al. [11] divided the life cycle of the product into three phases when using LCA and LCC. These three phases include energy consumption, environmental emissions and economic costs. This method has been successfully applied to a case study of a power plant in Singapore. This study reveals that GHG emission of the solar PV system is less than one-fourth that from an oil-fired steam turbine plant and one-half that from a gas-fired combined cycle plant. However, the cost of electricity is about five to seven times higher than that from the oil or gas fired power plant. Tapia et al. [44] also applied LCA and LCC together to assess six water treatment processes in Amsterdam, Netherlands, and were able to select a water treatment method that has a good financial condition and creates the least financial risk and environmental impacts.

Steen [45] used the integration method in the analysis of the environmental cost of the life cycle of various products. This study mainly tried to import the LCA methods into LCC. In the study, the researcher found that LCA is a good supplement in the risk analysis for LCC. Senthil et al. [26] imported various functions of LCC into the LCA system and proposed a new model that he called Life Cycle Environmental Cost Analysis (LCECA), which has both environmental assessment and environmental cost analysis functions.

Today, the integration method of LCA and LCC has already become a part of evaluation and project management software, some of which have even become commercial products, such as PTLaser and TcAce, which are developed respectively by Sylvatica [46] and The American Association of Chemical Engineering [47]. PTLaser primarily helps companies analyze and determine the solution that has the least environmental load and the most economic benefit. In this process, the software not only has all the attributes of LCA, but also a number of LCC features. For example, the software defines non-linear relationships, includes unintended factors, introduces multi-group schemes for multivariate sensitivity analysis, and defines uncertain system parameters to do Monte Carlo uncertainty analysis. The TcAce software utilizes a method called Total Cost Assessment, which imports the evaluation method of LCA into a complete LCC system and can also help to choose which part of the LCA evaluation result to use, according to the actual situation of subjects. Both the PTLaser and TcAce software systems integrate LCA and LCC, but use different integration forms: PTLaser puts various functions of LCC into the LCA system, whereas TcAce uses parts of the evaluation data from LCA as a supplement to LCC in order to calculate the environmental costs.

2.3 Literature on Wind Energy LCA

Several LCAs have been conducted on Wind Energy so far. Previous studies exhibit notable differences, including the design and rated output of wind turbines studied, the life cycle methodology employed, and the resulting conclusions about wind energy. These studies used deterministic methods where single values were chosen for inputs. For example, the input energy required to extract and refine steel has typically been selected as a discrete value. In reality, the input energy varies depending on the method of refinement (i.e., electric arc furnace or blast furnace), the type of steel product (i.e., plate steel versus rebar or galvanized coil), and the country of manufacture. This variability has led to energy input values in previous studies that range from 20.7 to 55 mega joules per kilogram of steel (MJ/kg) [48]. Assuming discrete values for other parameters, such as the lifespan of a wind turbine, air emissions from various life stages, and apportionment of life cycle costs, also contributed to variability in the results of previous studies.

Tremec et al. [49] conducted LCA of two wind energy system of 4.5MW and 250W to compare their environmental impact. All stages of life cycle (manufacturing, transports, installation, maintenance, disassembly and disposal) have been analyzed and sensitivity tests have been performed. According to the indexes (PEPBT (primary energy payback time), CO_2 emissions, etc.), the results show that wind energy is an excellent environmental solution provided first, the turbines are high efficiency ones and implemented on sites where the wind resource is good, second, components transportation should not spend too much energy and, third, recycling during decommissioning should be performed correctly. This study proves that wind energy should become one of the best ways to mitigate climate change and to provide electricity in rural zones not connected to the grid.

Weinzettel et al. [50] performed a prospective life cycle assessment (LCA) study of one floating offshore wind turbine. The results indicate similar environmental impacts of electricity production using floating wind power plants as using non-floating offshore wind power plants. They suggest that the most important stage in the life cycle of the wind power plants is the production of materials and credits that are connected to recycling these materials at the end-of-life of the power plant are substantial.

Life cycle assessment of two existing wind turbines, a 1.8 MW-gearless turbine and a 2.0 MW turbine with gearbox, is carried out to quantify the environmental impact by Guezuraga et al. [51]. Both technologies were compared by means of material usage, carbon dioxide emissions and energy payback time based on the cumulative energy requirements for a 20 year life period. For a quantitative analysis of the material and energy balances over the entire life cycle, the simulation software GEMIS® (Global Emission Model of Integrated System) was used. The results showed that the largest energy requirement contribution was derived mainly from the manufacturing phase, representing 84.4% of the total life cycle, and particularly from the tower construction which accounts for 55% of the total turbine production. The average energy payback time for both turbines was found to be 7 months and the emissions 9 gCO_2/kWh.

A study of Crawford [52] presents the results of a life cycle energy and greenhouse emissions analysis of two wind turbines and considers the effect of wind turbine size on energy yield. According to him many previous life cycle energy studies of wind turbines are based on methods of assessment now known to be incomplete. These studies may underestimate the energy embodied in wind turbines by more than 50%, potentially overestimating the energy yield of those systems and possibly affecting the comparison of energy generation options. The issue of incompleteness associated with many past life cycle energy studies was addressed in his study. Energy yield ratios of 21 and 23 were found for a small and large scale wind turbine, respectively. The embodied energy component was found to be more significant than in previous studies, emphasized here due to the innovative use of a hybrid embodied energy analysis approach. The life cycle energy requirements were shown to be offset by the energy produced within the first 12 months of operation. The size of wind turbines appears to not be an important factor in optimizing their life cycle energy performance.

To directly compare the environmental impacts, net-energy inputs, and life-cycle cost of two systems: a stand-alone small wind turbine system and a single-home diesel generator system, Fleck et al. [53] conducted a life cycle assessment. The primary focus for the investigation is the emission of greenhouse gases (GHG) including CO_2, CH_4, and N_2O. These emissions were calculated over the life-cycle of the two systems which provide the same amount of energy to a small off-grid home over a twenty-year period. The results showed a considerable environmental benefit for small-scale wind power. The wind generator system offered a 93% reduction of GHG emissions when compared to the diesel system. Furthermore, the diesel generator net-energy input was over 200 MW, while the wind system produced an electrical energy output greater than its net energy input. Economically, the conclusions were less clear. The assumption was made that diesel fuel cost over the next twenty years was based on May 2008 prices, increasing only in proportion to inflation. As such, the net-present cost of the wind turbine system was 14% greater than the diesel system.

However, a larger model wind turbine would likely benefit from the effects of the ‘economy of scale,’ producing superior results both economically and environmentally.

Lenzen et al. [54] conducted a life cycle assessment of wind turbines in Brazil and Germany for finding the effect of geographic variability in life cycle assessment. Their results demonstrate the importance of adequately considering the background system of the local economy. They have found considerable difference in the in the primary-energy embodiment of wind turbines produced in Germany and Brazil. The main reason for these differences is the higher conversion efficiency of the Brazilian electricity generation system (above 90%).

Another study of Lenzen [12] presented a comprehensive analysis of 72 life cycle assessments conducted on wind energy between 1977 and 2001. They identify the primary causes of variability in life cycle input energy and CO_2 (eq.) emissions from wind energy LCAs. Their data reveals that the results from wind turbine LCAs vary significantly. Turbine rated capacities range from 0.3 to 6,600 kW. Hub heights range from 11.6 m to 100 m. Basic turbine designs include two and three-blade rotors, upwind and downwind configurations, and onshore and offshore installation. Rotor diameter, expected lifespan, and the assumed load factor are other factors that varied. The LCA analysis method and the study scope also caused considerable differences among the studies. For example, 40 of 72 studies used process analysis methods, while the remaining 32 used input/output techniques or variations thereof. Regarding the scope of analysis, some studies adopted very narrow scopes, focusing only on specific stages of a turbine life cycle, such as manufacturing. Others considered the entire life cycle, from raw material extraction to turbine recycling.

In these studies, energy intensity is defined as the amount of input energy consumed over the life cycle of a wind turbine per unit of electrical output (kWh_{in}/kWh_{out}). Likewise, CO_2 (eq.) intensity is the amount of CO_2 (eq.) emitted over the life cycle of a wind turbine per unit of electrical output (g-CO_2 (eq.)/kWh_{out}). The values of energy intensity in past studies ranged from 0.014 to 1.016 kWh_{in}/kWh_{out}, and the values for CO_2 intensity ranged from 7.9 to 123.7 g-CO_2 (eq.)/kWh_{out}. These ranges, spanning nearly two orders of magnitude, reflect the variability in LCA results and illustrate the impact of using discrete values for inputs.

To investigate the causes of this variance, Lenzen et al. [12] analyzed the intensity values using statistical regression. They observed considerable scatter within the data, and deduced that the scatter is primarily caused by three factors:

1. Values of input energy and emissions assumed for each material

2. Use of process analysis verses input/output methods

3. Analysis scope (the specific life cycle stages that were analyzed)

Chapter 3

LCA of Solar PV system

3.1 Description of the System

To analyze the LCA of a solar PV system in Bangladesh, this study takes into account a 21.16 kWp solar PV system installed at the rooftop of prime minister's office of Bangladesh. It was inaugurated on December, 2009. It's located at Bir Uttam Ziaur Rahman Road and about half a kilometer from Farmgate, Dhaka. This is the first rooftop project in Bangladesh and is installed by Rahimafrooz Limited. From then onwards, various government institutions and the private sector have embraced solar solutions as a form of alternative form to meet the partial energy required. Rahimafrooz is a major player in the development of rooftop solutions and systems installer for Bangladesh. This project was followed by 20.30 kWp rooftop project at Bangladesh bank, Motijheel, and 32.75 kWp at WAPDA Building, Motijheel, and 37.5 kWp Solar Roof Top System on15th floor of Bidyut Bhaban etc.

The 21.16 kWp SAPV system consists of 132 mono crystalline silicon modules, 160 Wp each, mounted on the rooftop with galvanized steel supporting structure. The PV generator covers a total area of 170 m^2 and tilted 24° over the horizontal for maximizing the annual electricity production. The PV generator is connected with five charge regulator which control the charge of a bank of batteries from the PV generator. The bank of batteries is made up of 48 open lead acid batteries connected in series (1320Ah) offering 96V of nominal voltage. It is connected to four inverter of 3 kVA capacity each, which feed the AC loads. Table 3.1-3.4 includes the technical specifications of the components and figure 3.2 shows the circuit diagram of the facility. The output of the system is an average of 51 kWh/day. Atypical PV system is shown in figure 3.1.

To record electrical and meteorological data a monitoring system was installed. It recorded data in every 30 minutes and stored in a data base. Data related to DC generator power, current and voltage, state of charge of the bank of batteries and AC consumed power were recorded. Also average solar radiation, cell and ambient temperature was taken.

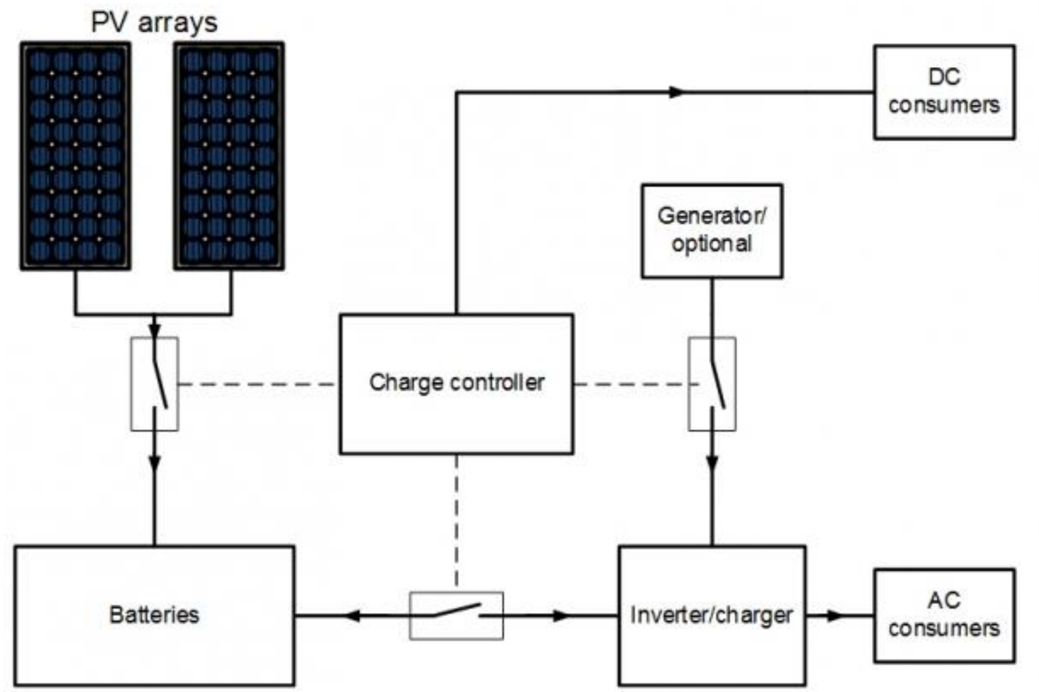


Figure 3.1: A typical PV system [55]

PV Module Specification	
Cell Type	Mono-crystalline (mc) silicon
Cell thickness	250 micron
Rated Power	160 Wp
Number of module	132
Nominal Voltage	24V
Model	BP 4160N
Mechanical Characteristics	
Solar Cells	72 mono crystalline cells (125mm x 125 mm) connected in series
Front Cover	High Transmission 3.2mm tempered anti reflective coated glass
Back Cover	White Polyester
Frame	Silver Anodized Aluminum

Dimensions	1593 x 790 (mm)
Weight	15.4 kg
Electrical Characteristics	
Max power voltage	35.4V
Max Power current	4.5A
Short Circuit current	5.1 A
Open Circuit voltage	43.6V
Module Efficiency	12.7%

Table 3.1: Technical Specification of the PV module

Inverter	
Model	Outback (VFX3048E)
Nominal DC Input Voltage	48 VDC
Continuous Power rating at 25°C	3000 VA
AC Voltage/Frequency	230VAC/ 50 Hz
Maximum output current	35 A
Continuous AC output at 25°C	13 A
Typical Efficiency	93%
Input voltage range	42 – 68 VDC
Weight	27.7 kg
No of inverter	4

Table 3.2: Technical specification of Inverter

Charge Regulator	
Model	Outback (FLEXmax-60)
Nominal Voltage	48 VDC
Maximum output current	60A
PV Open Circuit Voltage (VOC)	150 VDC absolute maximum coldest conditions / 145 VDC start-up and operating maximum
Standby Power Consumption	Less than 1 Watt typical
Power Conversion Efficiency	98.1% @ 60 Amps in at 48 VDC System voltage - Typical
Operating Temperature Range	Minimum -40° to maximum 60° C (Power capacity of the controller is automatically derated when operated above 40° C)
Weight	11.65 lbs. (5.3 kg)
No of charge regulator	5

Table 3.3: Technical specification of charge regulator

Battery	
Type	Solar deep cycle industrial battery
Nominal Voltage	2 V
Capacity (Ah)	1320
Total Capacity (kWh)	126.72
Weight (kg)	92.27
No of batteries	48

Table 3.4: Technical Specification of battery

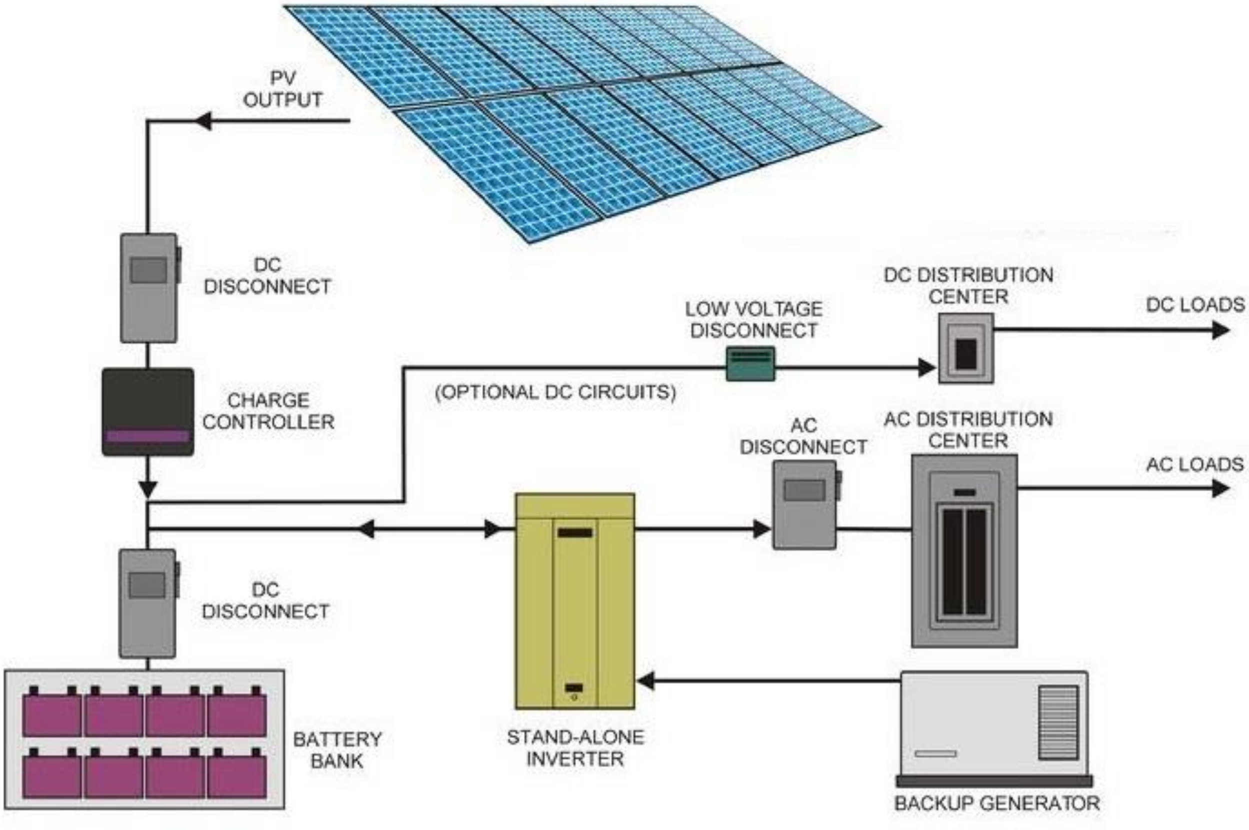


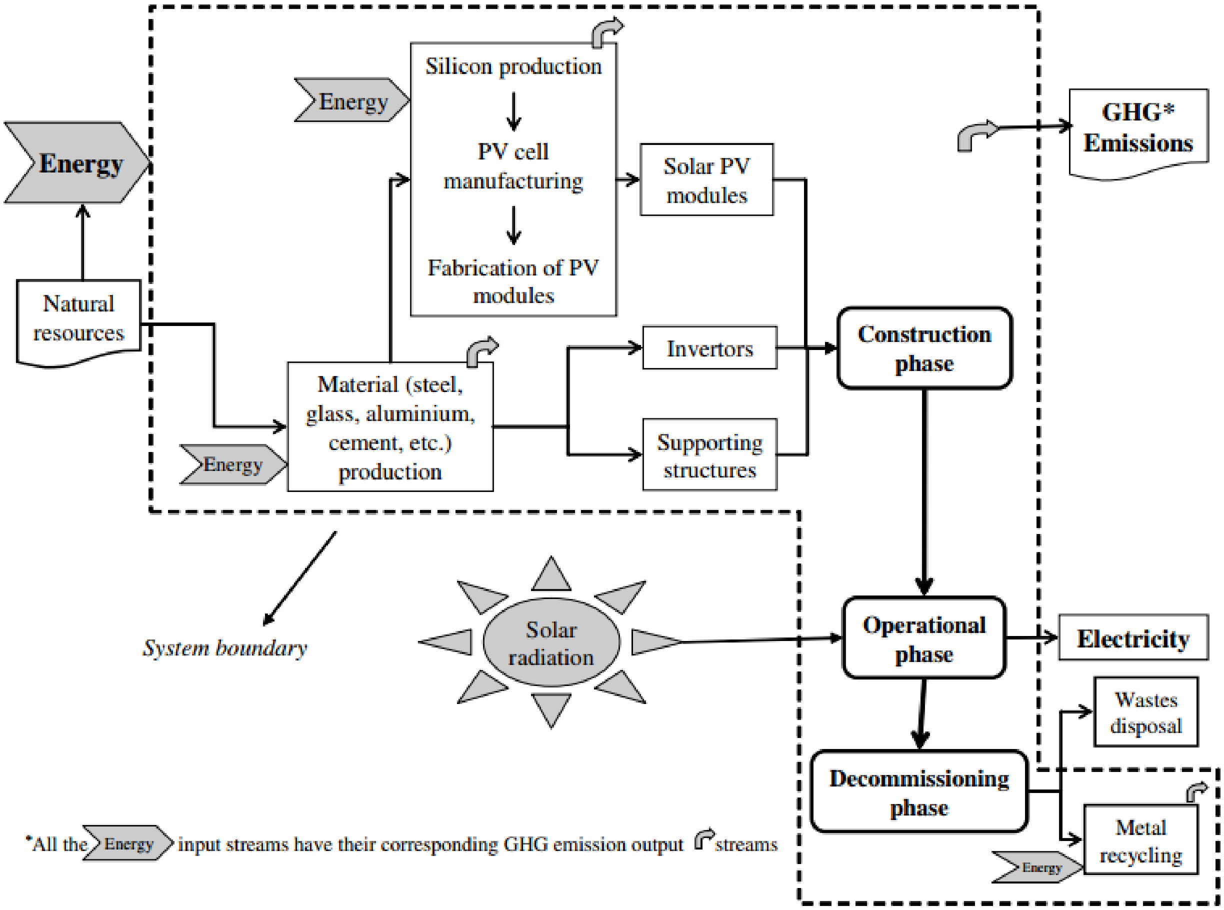
Figure 3.2: **Circuit Diagram of the PV facility [55]**

3.2 Life Cycle Assessment

To find out the life cycle energy and greenhouse gas emission by the system into consideration a life cycle analysis has been conducted. Unlike many other countries, Bangladesh doesn't have any life cycle database available for general use, let alone the input output data for products of all sectors of economy. Hence a process analysis was performed for the life cycle assessment. Most of the life cycle energy content and emission factor data were taken from studies conducted in other countries. This is the first life cycle study for any sectors in Bangladesh. Generally life cycle analysis consists of a life cycle cost analysis. But as this study is concentrated on environmental aspects of the renewable energy systems, only life cycle energy and GHG emission analysis are shown here. The life cycle of solar PV system is comprised of three major steps as (i) construction phase (ii) operation and maintenance phase and (iii) decommissioning phase. The methodology followed in this analysis comprises the following sections.

3.3 Goal and Scope Definition

A life-cycle assessment generally starts with the definition of the goal and the scope of the assessment to be undertaken. This comprises three elements: application determination, system definition and definition of the subject of the study: the functional unit [16]. The system determination or the objectives of this study have already been described in the introduction. The system definition or the system boundary of a typical standalone PV system is shown in figure 3.3. It establishes the scope of the analysis. It indicates which production processes are taken into account and those that are not. The third part of the goal and scope definition is the functional unit, which is a description of the product (or the function of the product) under study and the quantity in which this will be represented. In this study we will consider a functional unit of 18.615 kWh of electrical energy. All indicators of the study such as energy use, emissions and cost are indexed based on the functional unit.



*All the Energy input streams have their corresponding GHG emission output streams

Figure 3.3: **LCA boundary of the solar PV system**

3.4 Life cycle inventory analysis

First thing to do about the inventory analysis is the collection of material inventory for the total PV system. The amount of new material and recycled material also needs to be considered if the data is available because of the significant amount of embodied energy difference between the two types. Also the life time of each system must be previously defined in order to take into account input of materials due to replacements. In some cases the functional unit can be substituted for another more suitable posterior calculation.

The life cycle energy use data is to be determined. It is an inventory of the energy inputs for each process during the three phases of the PV system life. The energy requirements should be considered initially as thermal and electrical energy forms separately and then converted into equivalent primary energy using specified conversion efficiencies. These energy requirements are calculated separately for each component setting a value of embodied energy per functional unit. Finally the total embodied energy is solved according to these values and the created material inventory.

The GHG emission levels for each energy input must be defined. In order to calculate the electricity inputs, a fuel mix must be adopted according to the specific location where the system is operating. In this study the emissions are presented as embodied emissions for each component of the PV system.

The total energy that the system produces in its life time is to be calculated. It is usually approximated from the estimated life time and the definition of a typical irradiance and performance ratio for the system. In this study we have used this data from the record provided by Rahimafrooz Limited.

Some environmental factors or indicators are to be determined. I will use the energy payback time (EPBT) and the equivalent CO_2 emission factor. Analysis of the other impacts, like emissions to water, to soil or risk to human health is beyond of the scope of this study.

3.5 Material Inventory

Being a renewable energy system, PV solar system hardly involves any material inflow during the operation and decommissioning phases. Only in the construction phase material inflow in involved. Since some recycling networks are working in Bangladesh, therefore part of the material inflow in some components comes from recycled material. These percentages are detailed below. A list of materials that were used in constructing the given facility is provided in table 3.5 and the relative amount can be understood from the plot in figure 3.4.

In standalone photovoltaic system the battery life time is a limiting factor. The lead acid battery's life time in a SAPV facility depends strongly on the level of use (autonomy, charge- discharge rates and protections from the charge regulator) and the maintenance of them (mainly refilling of distilled water and pH control). In this case the batteries at the facility are specific for PV uses and the charge regulators implement different functions (equalization charge, floating charge and protection under deep discharge) to protect them and to maximize their life time. The long period of autonomy and the low levels of load let us take as optimistic assumption a life time of 10 years for them, so we include a double amount of batteries in the construction phase. However, it is known that in developing countries many SAPV systems are implemented with batteries of lower quality and with more stressful discharging cycles, which should be taken into account for the considered life time.

Element	Materials	Unit	Mass (kg)
160 Wp PV module	Mono-crystalline silicon, aluminum	132	2032.8
Charge regulator	Mixed	5	26.5
Inverter	Mixed	4	110.8
Lead Acid Batteries (1320Ah)	Lead, lead oxide, lead sulphate etc.	96	8857.92
Supporting Structure	Galvanized Steel		2000
Cables	Copper		45

Table 3.5: Material Use in the SAPV system

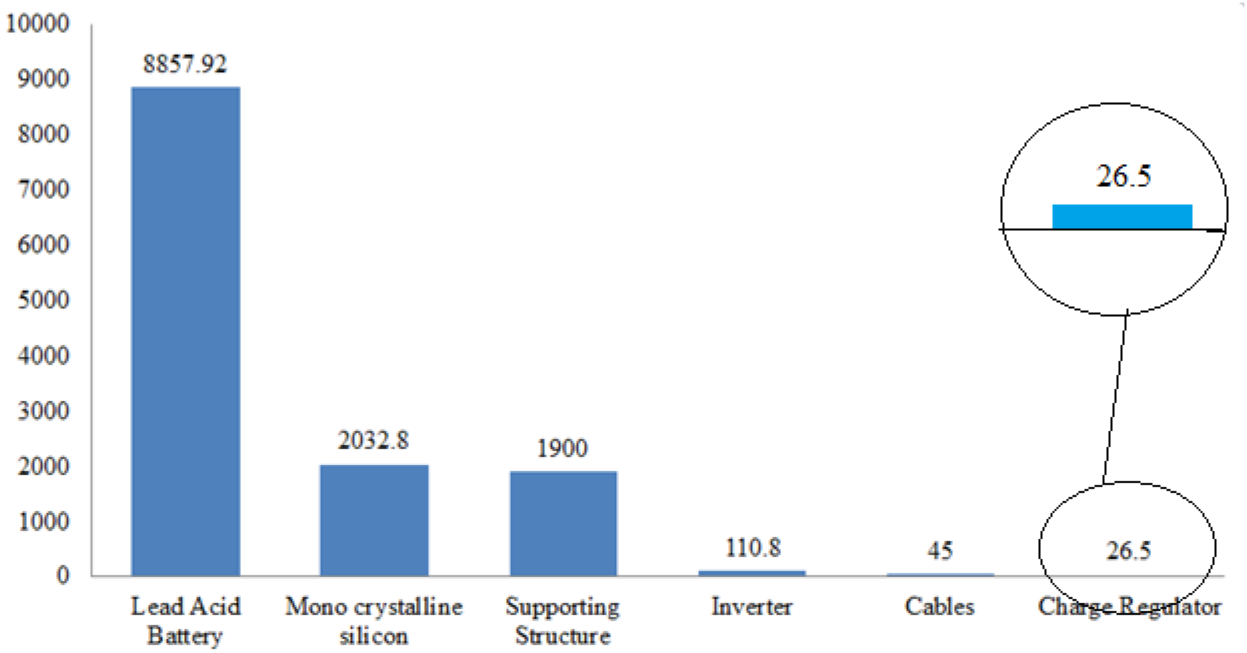


Figure 3.4: The solar PV system material inventory

3.6 Life cycle energy use

Energy is consumed in different stages of the system life: manufacturing, assembly, transportation, installation and recycling of PV module, supporting structure and their accessories, balance of system (BOS) component which include inverter, charge regulator and battery. This energy is known as embodied energy. LCA studies for photovoltaics show a high variation in results and conclusions. Critical issues during modeling of a life cycle inventory (LCI) are: few data availability (few producers provide reliable and verifiable data), power mixes assumed for the material production processes and process-specific emissions. Moreover, a LCA study for each material should be a site-specific study. This presents some difficulties in photovoltaics since the construction process of some components may have been carried out in different steps and/or different countries having different energy conditions. In the following analysis a life cycle energy analysis of 21.16 kWp PV system in PM's office of Bangladesh has been analyzed. Since most of the energy components are in the form of process thermal energy, embodied energies in this analysis are calculated in the form of process thermal energy (MWh_{th}). For clarity a thermoelectric conversion efficiency of 35% is assumed for converting all electric inputs into primary energy.

Hence,

1 MJ (= 1/3.6 kWh_{th}) of primary energy is equivalent to (0.35/3.6) = 0.09722 kWh of electrical energy.

3.7 Construction of mono-crystalline silicon PV module

Crystalline (C-Si) PV modules have been the most desirable choice for years and dominate approximately 85–90% of the global PV market at domestic level [56]. Conversion efficiencies provided by manufacturers are usually expressed under STC (irradiance of 1000 W/ m^2, 25 °C). C-Si PV modules naturally operate inversely proportional to temperature (0.4% efficiency gain or penalty per each degree C). The conversion efficiency of PV is affected by the following factors [11]: (i) the operating orientation and temperature greatly influence the module efficiency; (ii) an increase in working temperature would decrease the conversion efficiency of PV modules, and (iii) efficiency losses occur at inverters and electrical transfer wiring.

Dones and Frischknecht [57] stated that majority of GHG emission associated with PV system is generated by overall module production process. The electrical energy consumed during production is drawn from non-renewable plants (e.g., fossil fuel plant). GHG emission linked to present PV systems for mono-crystalline (mc-Si) and multi-crystalline silicon is mostly derived from electricity demand in production phase which is between 80% and 90% of total energy requirement. Multi-crystalline Si has a higher GHG emission due to additional material needed for larger surface area in order to yield equal power output. The authors claimed that if all electricity supplies for PV productions were generated entirely from fossil fuel plants, the GHG emission and other combustion products would roughly double [57]. In contrast, if the electricity consumed for PV production was generated by a combination of fossil fuel and renewable energy power plants, the GHG emission would be reduced [57].

The overall process of silicon manufacturing to final assemblies of PV module is shown in figure 3.5. The processes includes carbothermic/quartz reduction (removing oxygen from silica), metallurgical grade silicon (MG-Si) purification, solar grade (SOG) or electronic grade (EG) silicon construction, silicon ingot crystallization, wafer slicing, PV module assembly and concludes with module and laminate construction [58].

Firstly, the silica (also known as silicon dioxide, SiO_2) is collected, placed into an arc furnace and undergo carbothermic reduction process (using carbon electrodes with wood, charcoal and coal). This process draws a huge amount of energy whilst a considerable amount of output product gas, CO_2 is emitted into the atmospheres.

Silica is reduced into metallurgical grade silicon (MG-Si, at least 98% purity) but needs to be further refined and purified due to the presence of impurities. Purification process produces an output of either electronic grade silicon (EG-SI, 9N purity or 99.9999999%) or solar grade silicon (SoG-Si, 6N purity or 99.9999%). Silicon purification is described by various methods such as Siemens process, modified Siemens process, Czochralski process or Schumacher process depending on the purity of silicon required for certain PV application.

Siemens process plays a large role in determining the silicon’s grade and purity levels. Efficiency is crucial in PV application; therefore silicon is required to be in a high grade of purity. The process uses Hydrogen (H_2) and trichlorosilane ($SiHCl_3$) to produce high purity poly silicon and silicon tetrachloride ($SiCl_4$). It has to operate at a high working temperature condition (typically 1100–1200 °C) for an optimum reaction to occur [59].

The main drawback of Siemens process is that it consumes a huge amount of energy due to its high working temperature in the reaction chamber. Lately, various solar modules were produced using modified Siemens process because it requires less energy. The process temperature is approximately 800°C therefore energy usage would be lower [60, 61] and this affects the overall performance of the PV system life cycle. Apart from the traditional methods, a number of novel processes are currently being developed (e.g., fluidized bed reactor process). Fluidized bed reactors can reduce energy usage by 570 MJ primary energy for producing 1 kg of mc-Si relative to Siemens process [39].

Several studies have been performed to find out the embodied energy requirement for the production of mc-Si PV module since the beginning of the PV industry to evaluate its sustainability. It can be seen that energy consumption varies for manufacturing of PV modules among different studies. The variation can be attributed to various assumption and system boundary. Table 3.6 summarizes the most recent life cycle energy values for mono-crystalline solar PV modules with breakdown of energy consumption in different stages of manufacturing.

Authors	Year	Si-Feedstock (MJ/m^2)	MG-Si (MJ/m^2)	CZ Process (MJ/m^2)	Wafer Process (MJ/m^2)	Cell Production (MJ/m^2)	Module Assembly (MJ/m^2)	Frame	Total (MJ/m^2)
Yue et al. [62]	2014	1231.6	-	1436.8	307	308.8	615.8	-	3900
Fthenakis et al. [63]	2012	-	446	1841	581	643	772	379	4662
Laleman et al. [64]	2011	-	2397	432	-	-	684	-	3513
LuandYang [65]	2010	-	162	1119	432	-	684	-	2397
DeWild – Scholten [66]	2009	-	728	1266	-	389	477	-	2860

Jungbluth et al. [56]	2009	888	141	1208	562	595	466	-	3860
Alsema [67]	2000	1800	450	2300	250	550	350	-	5700

Table 3.6: Energy requirement for manufacturing mono-crystalline silicon photovoltaic module

In this study I chose the data from one of the most recent study by Fthenakis et al. [63] where they conducted a comprehensive life cycle analysis based on actual process data from the manufacturing of mc-Si PV modules and found that the embodied energy of a medium efficiency PV module is to be 4662 MJ/m^2. This is equivalent to 1.295 MWh_{th}/m^2 (10.78 MW_{th}/kWp).

Ten percent of the module weight is considered as the aluminum frame. Recycling rates for aluminum for building and transport application range from 60-90 percent in advanced countries. For Bangladesh it is assumed to be 30%.

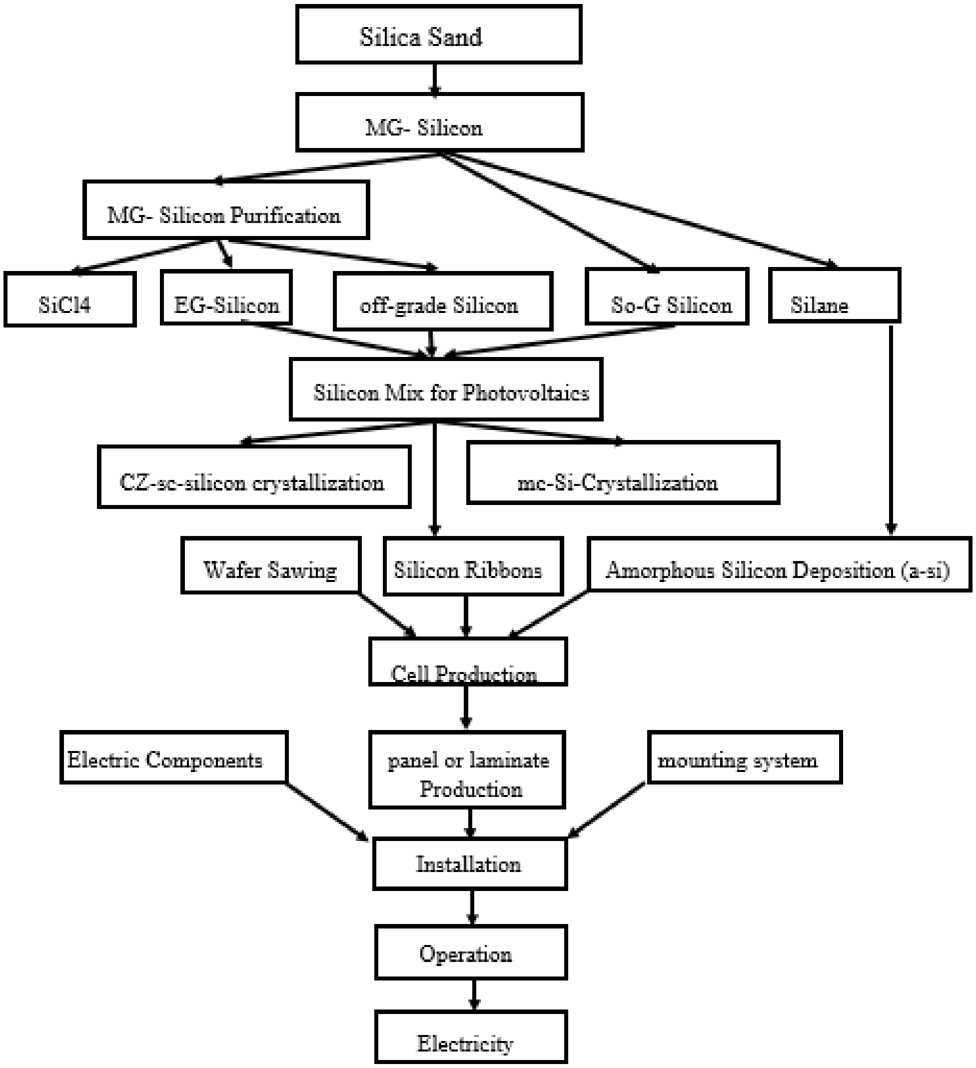


Figure 3.5: **The manufacturing process of silicon based PV module [60]**

3.8 Manufacture of BOS components

There are few available data about energy requirements for charge regulators and inverters manufacturing, especially for small and medium size facilities. Kato et al. [37] estimated a 0.5 MWh_{th} for energy requirements for the inverters in a 3 kW residential PV system (0.17 MWh_{th}/kWp). Alsema [67] and Rydh and Sanden [68] used values of 1 MJ/W_{el} (0.277 MWh_{th}/kW_{el}) for inverters as well as for charge regulators, estimated over the size of the electronic devices, not over the size of the facility.

For battery energy requirements Rydh and Sanden [68] made a complete review of the different technologies. Batteries used in this analysis is manufactured by Rahimafrooz Batteries Limited, Bangladesh. Rahimafrooz has lobbied actively in getting a law formulated and enacted for the safe disposal of the used batteries in Bangladesh. It has ensured proper facilities and establishments for collecting (buying back) and breaking used batteries safely in an isolated location in Savar, Dhaka. Simultaneously, it has also made huge investments in setting up a smelting plant to recycle the recovered lead from the used batteries. However, since no exact data is available regarding the amount of batteries actually collected back for recycling, it is assumed that 50% of the lead acid batteries come from the recycled materials.

PV modules are installed over a galvanized steel supporting structure. For the supporting structure and cables the energy use is estimated based on their specific energy consumptions. We consider that 90% of the steel and 40% of the copper come from recycled materials.

Table 3.7 summarizes the values used in this study for the energy requirement per unit in the production of each component. Note that when a recycling network for the component exists part of the energy requirement is reduced since generally production from recycled material is energetically less expensive.

Element	Manufacturing from new materials		Manufacturing from recycled material		Total Energy required (MWh_{th})
	Energy	Unit	Energy	Unit	
mc-Si PV module [67]	1.295	MWh_{th}/m^2	-	-	215.12
Al module frame [69]	41.7	kWh_{th}/kg	2.08	kWh_{th}/kg	5.66
Charge Regulator [68]	277	kWh_{th}/kW_{el}	-	-	9.97
Inverter [68]	277	$kWhth/kW_{el}$	-	-	0.83
Lead acid battery [68]	331	kWh_{th}/kWh	242	kWh_{th}/kWh	36.30
Steel Galvanized [70]	9.72	kWh_{th}/kg	2.5	kWh_{th}/kg	6.44
Cables [70]	19.44	kWh_{th}/kg	13.9	kWh_{th}/kg	0.78

Table 3.7: Energy requirement for production of the SAPV system

From the material inventory, technical specification and per unit energy values, the total energy required for the construction of different components of PV system is determined. All the energy terms for different component adds up to 278.204 MWh$_{th}$. This is the energy requirement for the manufacturing stage of the 21.16 kWp SAPV system.

3.9 Transport

An extra amount of energy is required in the construction phase for transporting different elements to the installation site. Energy consumed for transporting all the materials associated with the solar PV system is estimated according to specific transportation energy assumption. No data is available for the specific transportation energy consumption for Bangladesh. Hence, it is extracted from the energy consumed in the transport sector (MJ) and the total transport (t-km). The total transport is obtained by dividing the millions of metric ton by kilometers travelled. As of the Asian Development Bank report the transportation energy consumption in Bangladesh for the year 2010 is 3 Mtoe (million ton of oil equivalent) [71] and according to The World Bank database total transport in railway sector is 710 million ton km [72] . It is assumed that railway transport is about 3 percent of the total transport of the country [73]. As calculated from the limited data the average transportation energy intensity for Bangladesh is found to be 5.3 MJ/t-km. PV modules are brought from India; Inverter, Charge regulator from Spain and supporting structure, cables are manufactured in Gazipur. Batteries are manufactured in Savar, Dhaka. Notice that we assume all the BOS components' energy inputs were taking place at the respective suppliers' site. Therefore, transport from raw materials producer to suppliers is neglected. The total embodied energy use in the transporting for the PV facility is 9944.3 kWh$_{th}$, which is about 3.6% of the total embodied energy for the facility in the construction phase. Table 3.8 includes transportation energies for different component in the PV system.

Element	Origin (Distance Travelled, km)	Transportation Energy (MWh$_{th}$)
PV module	India (2330)	6.97
Battery	Savar (30)	0.39
Charge Regulator	Spain (8860)	0.35
Inverter	Spain (8860)	1.44
Supporting structure	Gazipur (30)	0.09
Cable	Gazipur (30)	0.0035
Aluminium	Gazipur (30)	0.7

Table 3.8: Transportation energy for different component in the PV system

3.10 Operational phase:

In the operational phase, there is no external source of energy supply for PV modules, structures, cables and electric devices. Although control systems are established, they draw energy from the solar PV module itself. Five charge regulators maximum consumption accounts for 131.25 kWh/year, while four inverter consumes a maximum of 126 kWh/year. Since the PV facility has no mobile part and all the components except the batteries have long term guarantees, the maintenance and repairing energy can be neglected.

3.11 Decommissioning phase:

3.11.1 Recycling process:

At the end of the life cycle, the solar PV system generates a substantial amount of waste. PV modules recycling could save two thirds of the necessary energy for wafer production and several research institutes and companies are working on recycling concepts for thin film modules and modules with crystalline cells. However, the possibility of recycling not damaged wafer or glass from PV modules does not exist in Bangladesh. Therefore it is assumed that the solar PV modules would be landfilled after removing the aluminium frames. Ten percent of the module weight is considered as aluminium frame.

No recycling processes are considered for electronic devices i.e. charge regulator, inverter) in the PV facility. For simplicity, recycling processes for metals (aluminium, steel and copper) are considered to consume the same energy as the energy requirement to produce and manufacture them from the recycled material.

Regarding recycling lead-acid batteries, the recycling process is different from the production process using recycled materials. The value 0.688 kWh_{th} of energy consumption per kg of recycled lead-acid batteries is assumed [74].

3.11.2 Transport to recycling plants:

We assume batteries and metals would be recycled in the plant they have been manufactured. Hence distance will be considered accordingly. The fraction of the metal and batteries sent to the recycling plant is according to portion recycled as assumed when calculating the energy requirement. Table 3.9 shows the energy consumption in the decommissioning phase for the different elements in the given PV facility.

Element	Recycling process (kWh_{th})	Transport to recycling plants (kWh_{th})	Total (kWh_{th})
PV frames	422.8	3.14	425.94
Supporting structure	5000	79.5	5079.5
Cables	1112	3.59	1115.59
Lead acid battery	6112	195.61	6307.61
Total	12646.8	281.85	12928.63

Table 3.9: Energy consumption in the decommissioning phase for the PV facility

3.12 EPBT analysis of the solar PV system

Accumulating all the energy values from manufacturing, transport, operation and recycling stage the total embodied energy of the SAPV system is found to be 302.88 MWh_{th}. Table 3.10 summarizes the result of the analysis. Figure 3.6 shows the comparative distribution of embodied energy at the facility separately. As discussed in the earlier section energy payback time is defined as the ratio of embodied energy, converted to electrical energy, to the annual electricity production.

$$\text{EPBT} = \frac{E_{EMB,th}\,\eta_{th-el}}{E_{USE,el}}$$

Assuming a best thermoelectric conversion efficiency of η_{th-el} to be about 35%, the embodied energy for the PV system is equivalent to 106 MWh_{el}.

Average electricity generation from the PV facility the prime minister's office is 51 kWh/day. This means that the annual electricity production is 18615 kWh_{el}/year. Hence, according to the above equation an EPBT of 5.69 years or 5 years and 8 months is obtained. Therefore the PV facility will generate almost 3.5 times the energy it consumes in its lifetime (estimated in 20 years).

Element	Embodied energy (MWh_{th})
PV module (frameless)	222.1
Module frames	6.78
Charge Regulators	11.13
Inverters	5.77
Lead acid battery	43
Supporting structure	11.6
Cables	2.5
Total	302.88

Table 3.10: LCA for the PV facility: Total Embodied Energy

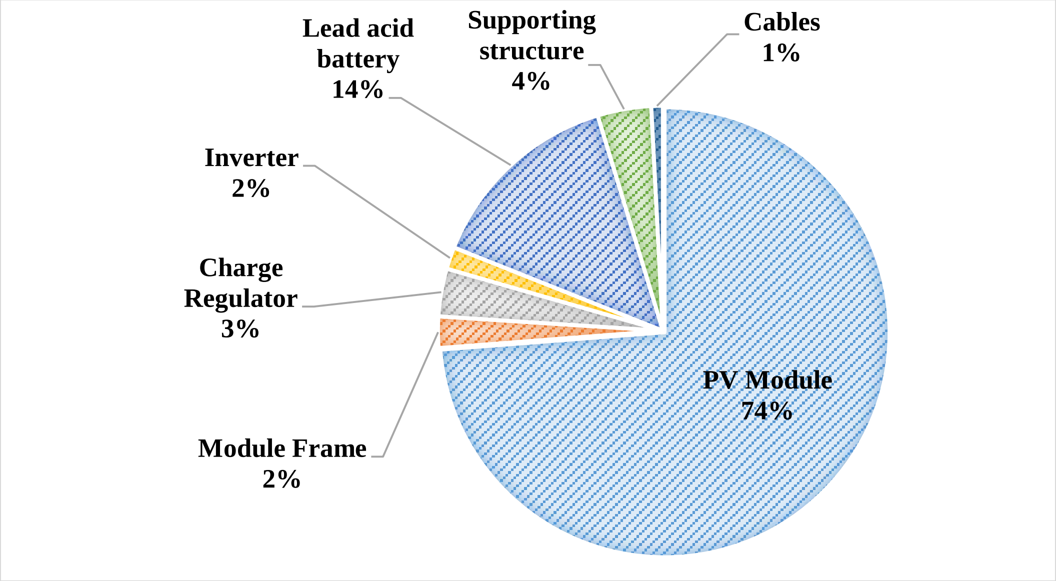


Figure 3.6: Distribution of life cycle energy use in the PV facility: embodied energy

3.13 Emission intensity of the PV system:

Emission intensity is the emission per unit electricity produced. To find the emission intensity of the PV system, it is necessary to find out the CO_2 emission during the production of the PV system. The CO_2 emission due to the production of the PV system can be determined by multiplying all energy and material inputs by their corresponding emission factors.

Emission factors depend upon the type of component produced and also the country it is produced in, because all components don't consist of the same process in manufacturing. Also different countries have different fuel mix for the production of electricity, which is used to manufacture those components. In the total CO_2 emissions per kWh, the numerator presents the CO_2 emissions from fossil fuels consumed for electricity generation, while the denominator presents the total electricity generated, coming from fossil fuels, but also from nuclear, hydro, geothermal, solar, biofuels, etc. As a result, the emissions per kWh vary a lot across countries and from year to year, depending on the generation mix. Now, all the components of the system are not produced in Bangladesh. Hence, we need to analyze the emission factor corresponding to the country they have been manufactured in. As discussed in the earlier sections, in this study PV components are manufactured in India; charge regulator and inverter in Spain; battery, supporting structure, cable in Bangladesh. Therefore, we have analyzed the emission factor in these three countries.

For PV module production emission factor, the fuel mix in India is found to be 65.4% coal, 19.1% hydro, gas 8.6%, oil 0.5%, diesel 0.3% and other 3.8% for the year 2014. Total CO_2 emission from the power generation sector was 727.4 million tonnes CO_2 [75]. Hence, from the total installed capacity of electricity generation, the emission factor was calculated as 0.98 kg CO_2/kWh_{el}. This is equivalent to 0.343 kg CO_2/kWh_{th}. CH_4, SO_2 or NO_x emissions are ignored due to uncertainties in primary resources of energy use.

Similarly, emission factor for Spain electricity system is found to be 0.44 kg CO_2/kWh_{el} [76]. Table 3.11 shows all the emission factors used in this analysis.

Element	Production from new materials	Production from recycled materials	Recycling process
mc-Si PV module [75]	0.343 kg CO_2/kWh_{th}	-	-
Charge Regulator [76]	0.44 kg CO_2/kWh_{th}	-	-
Inverter [76]	0.44 kg CO_2/kWh_{th}	-	-
Lead acid battery [77]	0.22 kg CO_2/kWh_{th}	0.22 kg CO_2/kWh_{th}	0.04 CO_2/kWh_{th}
Supporting structure [70]	2.82 kg CO_2/kg	0.45 kg CO_2/kg	0.45 kg CO_2/kg
Al frames [78]	19.53 kg CO_2/kg	0.85 kg CO_2/kg	0.85 kg CO_2/kg
Cables [70]	5.57 kg CO_2/kg	3.98 kg CO_2/kg	3.98 kg CO_2/kg

Table 3.11: Emission factor for the elements in the PV facility

Now to find out the emission from transportation of the component, CO_2 emission factor for transportation in Bangladesh is required to be determined. As of Labib et al. [79] total CO_2 emission from the transportation sector in Bangladesh for the year 2010 was 2,163,255 tonne. From the discussion in the earlier section about the total transport (t-km) in Bangladesh in year 2010, the emission factor is determined as 0.091 kg CO_2 per ton and km.

Finally, total embodied CO_2 for the facility was calculated and resulted as 97.69 metric tons. Table 3.12 shows the embodied CO_2 per element and per phase.

The distribution of the embodied CO_2 is shown in figure 3.7. The total amount of CO_2 emissions due to transport is 614.5 kg which is about 0.6% of the total CO_2 for the facility. Embodied emission for recycling sum 1172.413 kg, 1.2% of the total. Manufacturing of the PV module gives out most of the CO_2 emitted for the PV system. It accounts for 77.9% of the total CO_2 emitted for the PV facility.

Now, to calculate emission intensity the total CO_2 emitted is divided by the total electrical energy generated by the 21.16 PV system. The total electrical energy generated by the system is 18,615 kWh_{el}. Therefore, the CO_2 emission intensity for the PV system is 5.28 kg CO_2/kWh_{el}.

Elements	Emission in the construction Phase (kg CO_2)	Emission in the decommissioning Phase (kg CO_2)	Total
mc- Si PV module	76611.31	-	76611.31
Charge regulator	4562.17	-	4562.166
Inverter	2188.13	-	2188.134
Battery	9484.18	189.2495	9673.432
Supporting structure	1379.46	814.914	2194.374
Cable	222.15	107.5337	329.6866
Al frame	2680.42	60.71578	2741.134
Total	97127.82	1172.413	98300.24

Table 3.12: Embodied CO_2 emission for the PV system

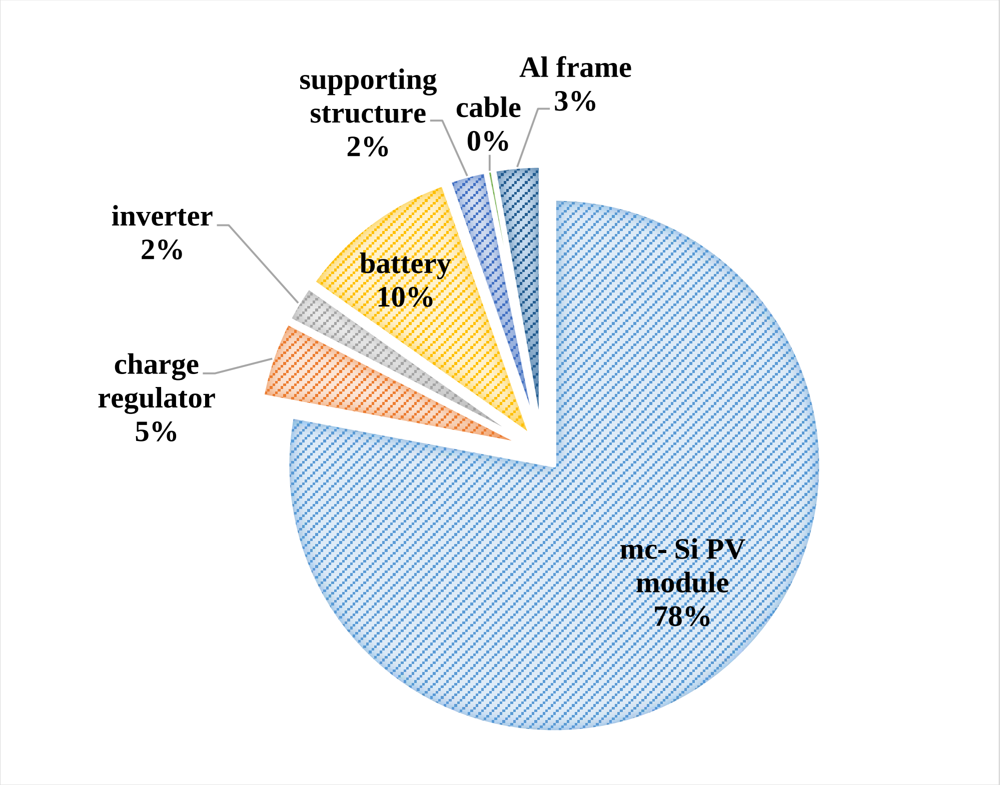


Figure 3.7: Distribution of embodied CO_2 emission for the PV facility

Chapter 4

LCA of wind energy system

4.1 Wind Turbine

A wind turbine (WT) is a machine which converts kinetic energy from the wind into mechanical energy which is converted to electric energy. WTs can produce energy only in response to a resource that is immediately available: the wind; since is not possible to store the wind and use it a later time, the output of a WT is thus inherently fluctuating and non-dispatchable. For this reason any system to which a WT is connected must take this availability into account. Figure 4.1 represents a typical wind turbine.

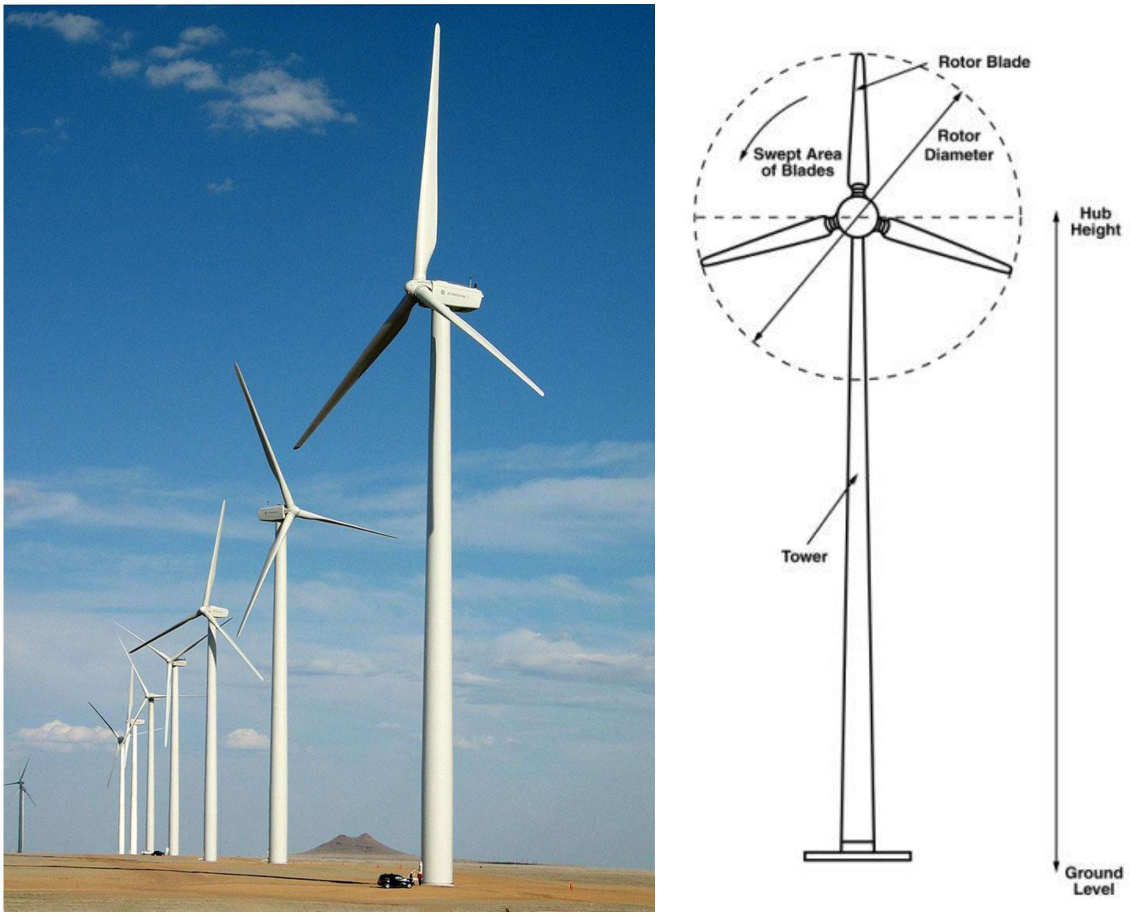


Figure 4.1: **Typical Wind Turbine**

4.2 Main components in WTs

Today, the most common design of WT is the horizontal axis wind turbine (HAWT). That is, the axis of rotation is parallel to the ground. The principal subsystem of a typical HAWT includes rotor, drive train, generator, nacelle and yaw system, tower and foundation and control system. Figure 4.2 shows the basic components of a wind turbine.

Rotor

The rotor consists of the hub and blades of the wind turbine. The blades transform the kinetic energy into rotational energy, using the same aerodynamic principles as an airplane wing. They can be rotated around their longitudinal axis, called pitch, to maximize the energy yield from the wind. The blades are mounted to the hub.

Drive Train

The drive train consists of the other rotating parts of the WT downstream of the rotor. These typically include a low-speed shaft, a gearbox, and a high-speed shaft. Other drive train components include the support bearings, one or more couplings, a brake, and the rotating parts of the generator.

The gearbox transforms the rotational energy from the hub, which is usually in a high torque with low speed format, into low torque – high speed format required by the generator.

Hydraulic system

The pitch mechanism in a WT is usually driven by oil pressure. An oil pump, control valves and actuators are needed to rotate the blades into their designated position. A mechanical rotor brake is often also hydraulically actuated.

Generator

The generator in a WT is located on the high-speed side of the gearbox, and converts rotational energy into electrical energy. It consists of a rotor creating a rotating magnetic field, which itself then induces a voltage in the stator. There are different types of generators; common types used in wind turbines are synchronous generators, as well as single or double fed asynchronous generators.

A synchronous generators produce current, which alternates with the same frequency as the rotor rotates. Asynchronous generators rotate slightly faster than their output current oscillates.

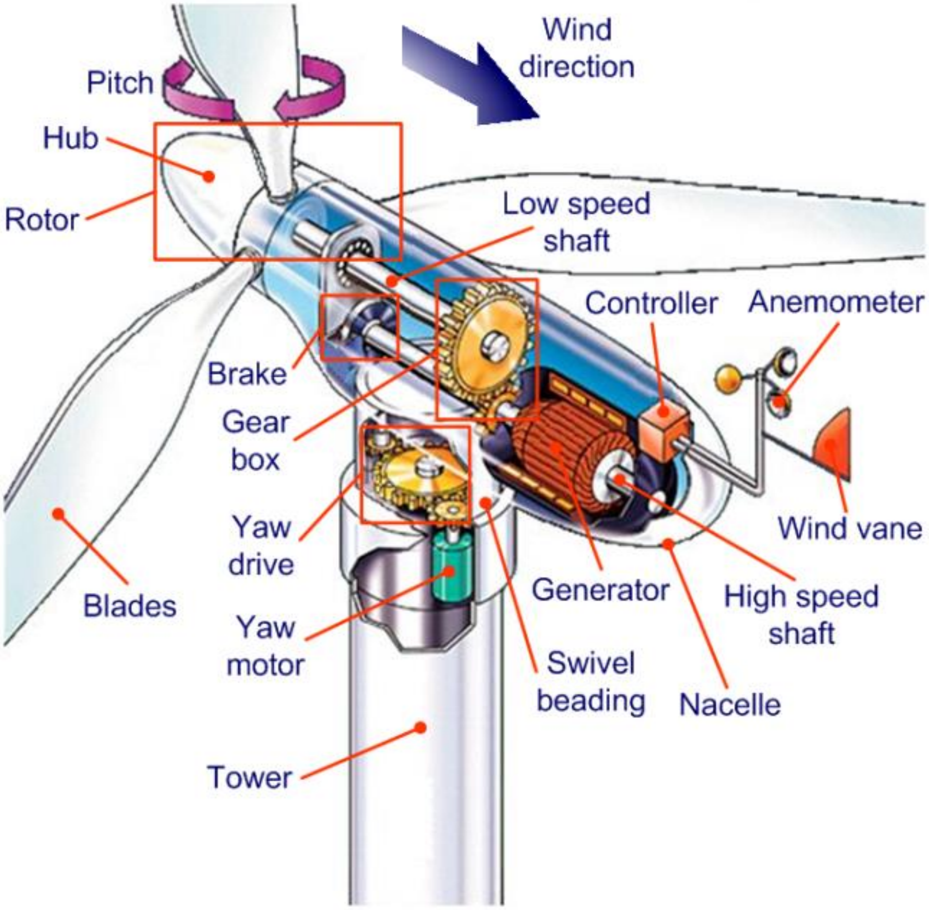


Figure 4.2: Main components of a wind turbine [80]

Nacelle and yaw system

This part includes the WT housing, the machine bedplate or main frame, and the yaw orientation system, required to keep the rotor shaft properly aligned with the wind. The main frame provides for the mounting and proper alignment of the drive train components. The nacelle cover protects the contents from the weather.

Tower and foundation

The principal types of tower design currently in use are the free-standing types using steel tubes, lattice towers, and concrete towers. The stiffness of the tower is a major factor in WT system dynamics because of the possibility of coupled vibrations between the rotor and the tower.

Control system

The control system supervises operational data and supports control of the turbine operation. It can detect some abnormalities during operation, for example when a sensor detects a high temperature and triggers an alarm or shuts down the generator rotation. Furthermore, it controls the pitch system to maximize the energy production.

A WT control system includes: sensors (speed, position, temperature, current etc.), controllers (Mechanical mechanisms, electrical circuits), power amplifiers (electrical amplifiers, hydraulic pumps, and valves), actuators (motors, pistons, magnets, and solenoids), and intelligence (Computers and microprocessors).

4.3 Wind Turbine Technology

The use of wind energy for grid-connected electricity generation gained attention in the late 1970s. Early wind turbines experienced relatively poor performance due to a number of technical problems, including blade failures and difficulties in regulating power output. However, as technological challenges were addressed, wind turbines became more reliable, efficient, and cost-effective. Since the 1970s, wind turbine technology has become increasingly more sophisticated. Over the past decade, wind technology has focused on increasing the electrical output and conversion efficiency of turbines while reducing the capital investment costs.

One of the most noticeable developments in wind technology is the increasing amount of energy that can be captured by a single turbine. The power in wind is proportional to air density, the rotor swept area, and the cube of the wind velocity [80].

$$\text{Power} = \frac{\rho\, A\, V^3}{2}$$

Where,

ρ= Air density (kg/m^3)

A = Swept area of the wind turbine motor (m^2)

V = Wind speed (m/s)

Turbines with a larger swept rotor area are able to capture considerably more energy than smaller units. Available energy also increases as wind speed increases. As mentioned earlier, wind speed generally increases with height above the ground. Therefore, wind turbines with a taller hub height (distance from ground to the rotor hub) are able to capture more energy than shorter units. Wind manufacturers have taken advantage of these relationships, and it is reflected in the development of wind turbines with taller hub heights and larger swept areas. As of early 90’s, a wind turbine with a capacity of 500 kW and a 37-m swept rotor diameter was considered state-of-the-art [80]. By 2002, the capacity of the largest wind turbines had reached 2 MW, with rotor diameters of nearly 100 m. There are even 4-5 MW wind turbine prototypes under development.

At the component level, wind turbine technology has changed substantially over the past decade. Developments have occurred in blade design and manufacturing materials. Turbine blades are now typically made of lightweight plastic resins that are reinforced with fiberglass matting. This is generically referred to as glass fiber reinforced plastic (GRP). GRP flexes to tolerate the stresses caused by wind turbulence, thus reducing the likelihood of blade failure [81].

Power control technologies have enhanced the amount of wind power that is converted to electricity. For example, stall and active stall technologies use the aerodynamic design of a turbine blade to prevent the rotor from “over-spinning” under high wind conditions. Where other wind turbines had to be stopped under these conditions, turbines using stall regulation can continue generating electricity near maximum capacity. Pitch regulation is another power regulation technology that performs a similar function. Pitch regulation allows the turbine blades to rotate in response to changing wind conditions. Under low wind conditions, the pitch can be adjusted to maximize contact area between the blade and the wind, so as to increase power capture. Under high wind conditions, the pitch can be adjusted to reduce contact area and prevent damage to the turbine.

Also, wind turbine drive/generator combinations have been improved to allow for increased energy capture at moderate and low wind speeds. Generators with large power output, while able to produce more electricity, require higher wind speeds to rotate the drive shaft and begin generation. Consequently, the generator has a higher “start-up” speed and is unable to produce electricity in low wind conditions. Smaller generators require less torque on the drive shaft to begin generating and have lower start-up speeds.

As a result, wind turbines with smaller generators are more suited for lower wind profiles. These developments reflect a trend towards specializing wind turbines for high or low wind profiles.

4.4 Energy Content and Emission Factors of Materials

The energy content and emission factors of materials used to construct wind turbines can greatly affect the energy and emissions intensity of wind power. Energy inputs are needed for the extraction and refining of raw materials and manufacture of wind turbine components. These energy inputs are referred to as “embodied energy,” or “indirect energy,” because they do not directly contribute to electricity generation by a wind turbine. In contrast, the energy in wind that is captured by a wind turbine is a direct energy source because it contributes directly to electricity generation. Other life cycle phases of a wind turbine, such as transportation and construction, will also produce CO_2 (eq.), sulfur oxides (SO_x), and nitrous oxides (NO_x), among other regulated air pollutants. These are referred to as “indirect emissions,” as they are emitted during the nonoperational life cycle stages of the wind turbine.

A wide range of values for material energy content and emission factors has been used in previous LCAs. For example, in summarizing the values from eleven studies, Lenzen and Munksgaard [12] found that a wide range of values has been used for the energy content of copper. The values averaged 86.2 mega joules (MJ) of input energy per kilogram of copper produced (MJ/kg); however, the standard deviation of these values is 65.5. This suggests that a range of energy content values from 20.7-151.7 MJ/kg copper represents one standard deviation from the average. Wide ranges were also found for the energy content of steel, concrete, and GRP.

The input energy and indirect emissions of a wind turbine depend largely on its material composition, the country in which it is manufactured, and recycling of materials. Modern wind turbines consist predominantly of steel, concrete, and glass fiber reinforced plastic, although other materials are present in relatively smaller quantities. Most of the material mass used in a wind turbine is found in the tower and foundation. Turbine towers are almost exclusively constructed of steel, although there is some limited use of concrete towers [12]. Foundations are typically reinforced concrete, and account for the majority of the mass of a wind turbine. Lenzen and Munksgaard [12] indicate the tower accounts for 23.3% of the total turbine mass (on average). The foundation may account for nearly three times as much, or 60.3% of the total mass (on average). Because steel and concrete account for such a large portion of the mass, selecting discrete values for the energy content and emission factors of these materials can lead to significant variances in the results of an LCA.

Assumptions about the recycling of materials can also affect LCA results. Recycling can impact input energy and indirect emissions at either end of the life cycle: during raw materials extraction/refining or during wind turbine decommissioning. The use of recycled materials in turbine manufacturing results in less input energy and emissions because the energy consumed and emissions resulting from the recycled material are less than that of virgin material. Likewise, recycling material at the end of the wind turbine’s life cycle reduces the amount of input energy and emissions resulting from future use of the material. If applied as a credit to LCA results, this can save a substantial amount of input energy and avoid associated air emissions. Lenzen and Munksgaard [12] also report that recycling 75-100% of the material in a wind turbine can result in an energy savings of 12.5-31.9% of the total input energy requirement.

For a better result this analysis consider recycling the materials at the end of their life. Materials are considered to be recycled at the rate as considered in the solar PV system. Concrete foundation and glass fiber reinforced plastic, which were absent in the SAPV analysis, are considered to be landfilled after the end of their life time. Similar to the SAPV system 90% of the steel, 40% of the copper and 35% aluminium are considered to be recycled at the end of system life.

4.5 Life Cycle Analysis Method

Just as the energy content and emissions factors for materials are sources of output variability, the method of analysis can also result in output variability. There are two primary methods for conducting LCAs: process analysis (PA) and input-output (I/O) analysis. Both techniques have been applied in wind energy LCAs before. Although both methods are valid, each has inherent differences and drawbacks that can affect the life cycle energy and emissions balance of a wind turbine.

PA is a bottom-up approach to account for the embodied energy and emissions in materials. Using PA, each material in a wind turbine is traced back to its manufacturing process. The energy input required to produce each material and the emissions resulting from the production are assessed. The mass of each material is then multiplied by the appropriate energy and emission factor. In the final life cycle assessment, the energy consumed and emissions resulting from each material are summed over the entire turbine system.

PA is a practical method that allows a researcher to analyze specific systems based on the materials unique to the system. Nevertheless, it has shortcomings that must be recognized. PA estimates the direct energy requirements and emissions from the production of basic materials; however, the PA method is complicated by boundary truncation decisions due to system complexity. Boundary truncation occurs when the entire life cycle is not analyzed, resulting in an incomplete LCA. For example, higher-order processes such as transportation or engineering services that support the turbine manufacture are excluded. As a result, values of energy and emissions intensity calculated using PA are typically smaller than values calculated using I/O analysis [82]

I/O analysis differs from PA in that it is a top-down approach. I/O analysis is a macro-economic method that assesses the economic inputs and environmental emissions of an entire sector of the economy [82]. National input-output tables are compiled by relating the energy use and emissions resulting from a sector of the economy to the monetary value of products developed in that sector. In this manner, the life cycle energy and emissions of a wind turbine can be calculated by equating the monetary value added during a life cycle stage to the energy and emissions of a particular economic sector. For example, the NOx emissions resulting from wind turbine transport can be identified by determining the monetary value of transporting the turbine and multiplying this cost by the NOx emissions per dollar value (NOx/$) of the U.S. transportation economic sector.

I/O analysis is more comprehensive than PA, which evaluates only the raw material inputs to a product. I/O includes the impacts from higher order activities such as management, transportation and construction. This broader analysis leads to a more consistent definition of the system boundary. However, I/O analysis is subject to several limitations, the most recognized of which is the lack of detail and specificity. Because I/O analysis considers each economic sector as a whole, it assumes each sector produces one “average” product. In reality, each sector encompasses several products, different quality grades of each product, and differently priced products. For example, the price difference between two automobiles may be large (i.e., Ford Taurus vs. Porsche), but the emissions resulting from manufacturing the cars may be similar. Additionally, input-output tables are restricted to a limited number of economic sectors.

Because of the inherent limitations of PA and I/O analysis, a hybrid analysis technique came into practice. A hybrid technique integrates the two methods by filling the “gaps” in PA data with data from I/O analysis. In a hybrid LCA methodology the most significant life cycle pathways are extracted from an I/O analysis and substituted with system-specific data derived via PA. In effect, the hybrid technique is a process analysis assessment where higher-order processes are estimated from input-output tables. The use of hybrid techniques in wind energy assessments allows specific wind turbines to be assessed while maintaining a broad system boundary.

For Bangladesh the Input/output table is compiled by the Planning Commission, Government of the People’s Republic of Bangladesh, and the Bangladesh Institute of Development Studies (BIDS). The Bangladesh I-O table is grouped commodity by commodity and includes only 79 sectors. The wind turbine industry is not included in the I/O tables. Hence, it is not possible to use I/O analysis to conduct the life cycle assessment. Therefore, in this thesis only process analysis is used to perform the life cycle energy and greenhouse gas assessment. However, since one of the prime target of this study if to compare the two renewable energy system: SAPV system and a wind energy system, with respect to energy payback time (EPBT) this will not effect on this result significantly. Because EPBT is a ratio of energy to energy. But there might be a significant change in the analysis of the greenhouse gas analysis. Should enough data be available in the future, it is expected that an analysis with hybrid PA and I/O analysis or only an I/O analysis will bring out a better result for LCA of renewable energy systems in Bangladesh.

4.6 Application of Monte Carlo Simulation to Wind Energy

Current literature reveals that material energy content and emissions factors, the life cycle assessment method, and the analysis scope are significant sources of variance in wind energy LCAs. This variance makes data interpretation difficult. Using a probabilistic analysis technique such as Monte Carlo simulation accounts for the variability that exists in model parameters. Monte Carlo simulation allows factors such as the energy content and emissions of wind turbine materials to be assigned probability distributions. As a result, model output consists of a range of values and associated probabilities of occurrence, rather than single values obtained by deterministic methods.

Monte Carlo simulation has been used extensively in many fields of study, including finance, physics, environmental risk, and energy systems research. A limited number of wind turbine studies have applied Monte Carlo techniques to account for variability of the wind resource and uncertainty associated with system reliability and energy conversion efficiency. It has been used to optimize the design of wind turbines and the placement of turbines in wind farms. Wind turbine LCAs can benefit from the use of Monte Carlo simulation by accounting for the variability and uncertainty that occurs in model inputs. Factors that exhibit a wide range of possible values, such as the energy content and emission factors of materials, can be assessed in a probabilistic manner. Likewise, the uncertainty in factors such as the lifespan of a wind turbine can be addressed using these techniques.

4.7 Methodology

This thesis evaluates the life cycle energy and emission for a hypothetical wind energy system at any suitable location in Bangladesh, determined by availability of the desired wind speed. For the simplicity of comparison and since these is no wind energy system is in operation in Bangladesh, the wind energy system considered under analysis here will have the same output as the SAPV system. Monte Carlo simulation will be applied to take into consideration the uncertainty of the energy output, sizing of the turbine and the material and energy flow associated to the wind energy system.

Data collection includes energy and emission factors for different component of the system. Wind speed data for any specific location in not necessary to be collected since the wind turbine sizing will be done in accordance of the SAPV system considered in the previous chapter of the thesis. To be more specific the power curve of the wind turbine provided by the turbine manufacturer will be used to estimate the annual energy production of the selected turbine. Considering the uncertainty of the performance of the turbine at practical field, which is the prime concern in this method of selecting the wind turbine size, Monte Carlo simulation will consider an availability factor and standard deviation factor. These factor are discussed in a later section.

Once the wind turbine model is selected, the PA analysis method is used to determine the distribution of life cycle energy intensity and CO_2 emission intensity. The PA model requires collecting the material specific energy content value, emission factor and assessing the material mass composition of the wind turbine. The distributions of energy and emission intensity values are calculated for each location by summing the energy inputs and air emissions over all life stages included in the study scope.

Emission and energy factors were than multiplied by the mass of each component of the systems. Monte Carlo simulation were used to take into account the data variability of different parameters. Based on the type of data a probability distribution is selected for each parameters. This will give a result with a range of output with a minimum, a maximum and an average value depending upon their probability distribution set by the parameters. This will give an idea how our output will change with the change of over different conditions.

4.8 Scope of Analysis

A comprehensive scope of analysis is considered for this study to obtain the most holistic life cycle assessment of wind energy as shown in the figure 4.3. Life cycle stages are clearly shown inside the system boundary. The stages include raw material production, component manufacture (Nacelle, tower, blade, and foundation), construction, operation and decommissioning. Grid connection was excluded from the analysis because the PV system considered was also an off-grid system. Additionally, grid connection requirement are dependent upon the proximity of the generator to the local power grid and the availability of a nearby power substation, which is driven by many site-specific factors such as aesthetics, terrain, land ownership etc. this introduces many external factors that are not impacted by the type of electricity generation system.

Wind turbine decommissioning and recycling are also included in the analysis. Because, previous studies also identified recycling as a factor that significantly affect the energy and emission intensity of a wind turbine. Since, in the wind turbine a significant amount of the material composition is steel and there are better facility for recycling of steel in Bangladesh, in this study recycling is considered at the end of the life cycle. Also, if recycled materials are used to manufacture a turbine or any turbine materials are recycled, the emission and energy consumption will likely to be reduced.

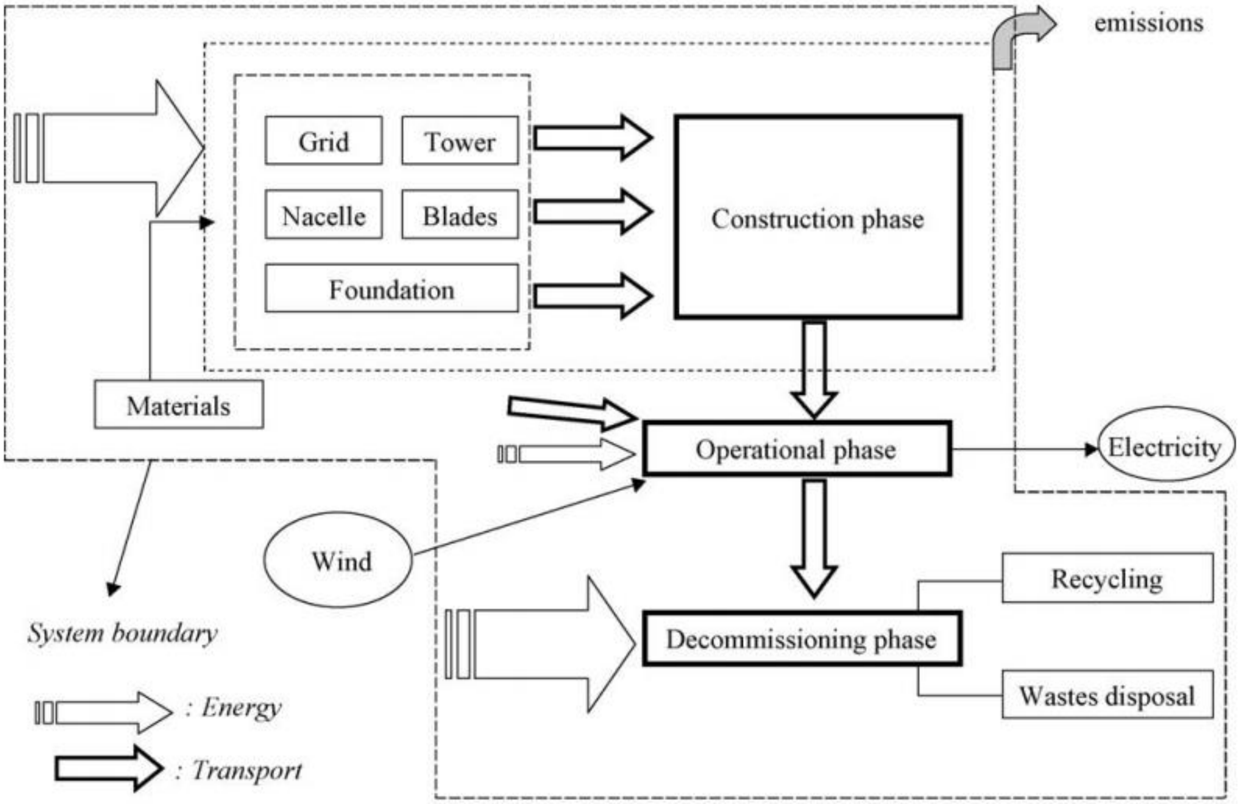


Figure 4.3: Scope of analysis flow diagram

4.9 Functional Unit

In order to properly compare two system, the energy flows and emissions of each system must be calculated based on a single reference value. This value is referenced to as functional unit (the quantified performance of a product system for use as a reference unit) of the study and represents a product or service that is provided by both systems in an identical quantity and quality. The functional unit of this study is the production of 18.615 MWh of AC electrical energy per year over the twenty year life of the system. As mentioned earlier this is the energy produced by a 21.16 kWp SAPV system at prime minister's office, Dhaka. In the earlier section embodied energy of the solar PV system was calculated and to compare the SAPV system with the wind energy system same system output is assumed.

4.10 The wind system: Wind power estimate

For this study I have examined a specific wind turbine model: Southwest Wind power’s Air X which has a rated power of 400 W, a 1.17 m diameter rotor, and charges batteries at either 12 or 24 V. Other wind turbine model with higher rated power could also be used and would reduce the system sizing to meet the functional unit, but due to data unavailability of the material inventory I have used this turbine model.

However, no data are available to predict the performance of the turbine Air X turbine at the specified location by the functional unit. It was thus necessary to calculate the number of required turbines based on estimated energy production. To do so, the power curve method of calculating the monthly energy output of the turbine was used.

The power curve method uses the manufacturer provided power curve subdivided into bins of wind speed intervals. These data were obtained from the user manual of the wind turbine. The power curves shown in figure 4.4 and 4.5 gives the performance of AIR-X wind turbine. The AIR-X is rated with a “band-width” of power for a given wind speed. This is an attempt to cover the variability in turbine output due to different levels of wind turbulence. During smooth, steady wind, outputs are along the upper curve. During turbulent wind conditions, the power output could drop towards the lower curve. [83]

Wind regime data in the form of a frequency distribution were used, grouped into equivalent wind speed bins. For this study, a location in Kaptai was selected to represent the average conditions of the area specified by the functional unit. The frequency distribution of wind speed of Kaptai is shown in table 18. [84]

Using the power curve method and the above assumption, the average monthly energy production was calculated to be 49 kWh per turbine. This translates into continual operation of 67.63W, or for a 400W rated power turbine, a capacity factor of 0.17. In order to meet the functional unit, 31.68 turbines would be needed, however, the integer value of 32 turbines were needed as an overestimate. The technical specifications of the turbine are provided at table 4.1 and schematic diagram at figure 4.6. [83]

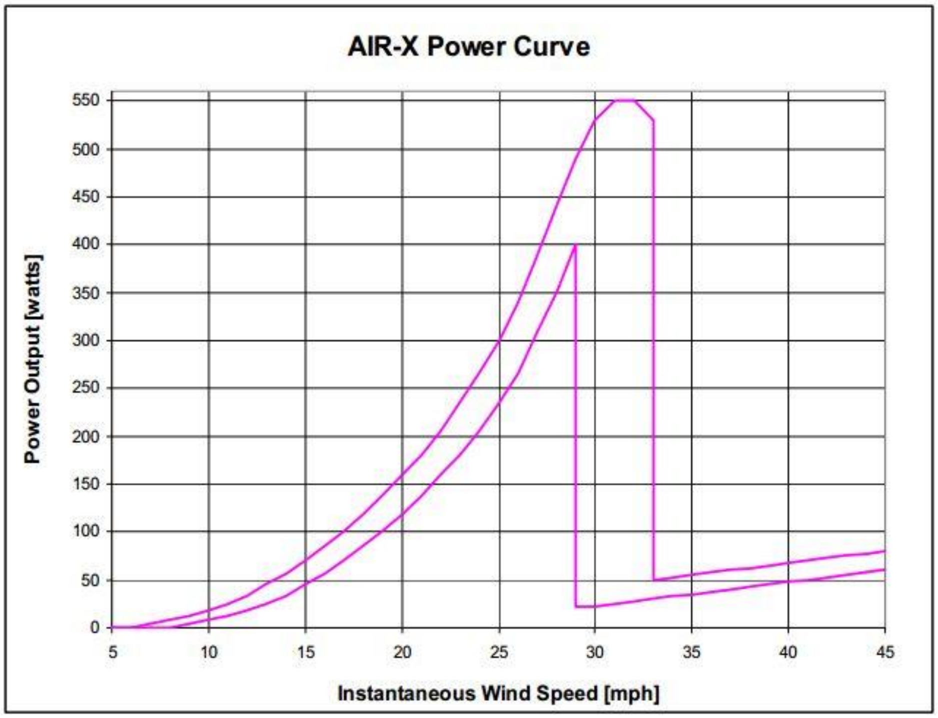


Figure 4.4: Power curve for Air X turbine (Power output) [83]

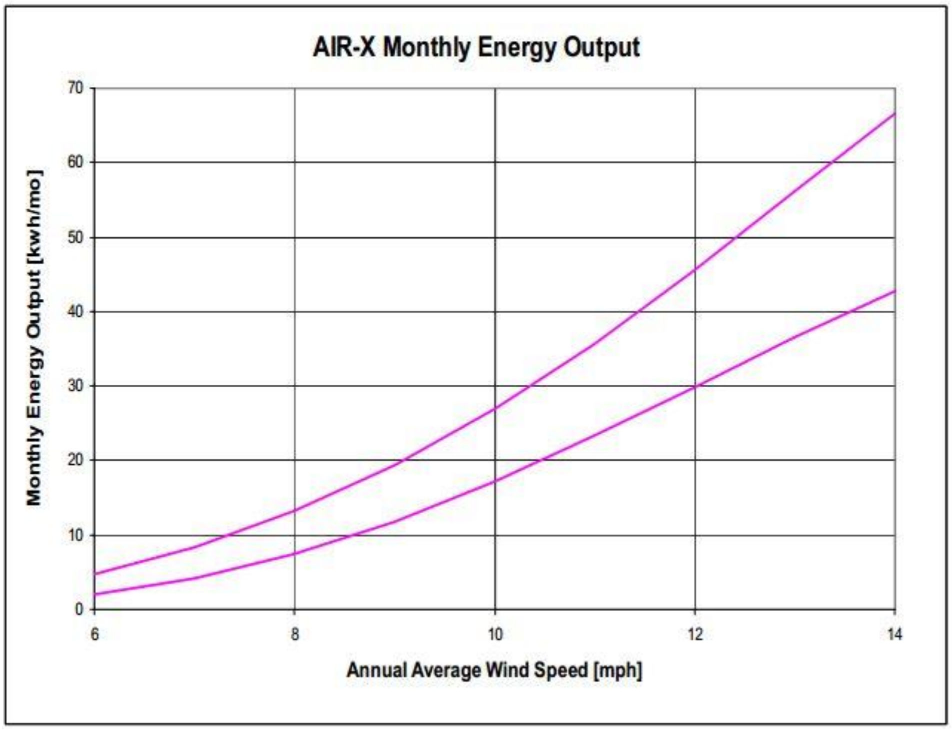


Figure 4.5: Power curve for Air X turbine (Monthly energy output) [83]

Speed (m/s)	Total hour of the month (%)	Frequency distribution (hour)
0-1	3.22	23
1-2	11.32	85
2-3	23.05	179
3-4	22.71	169
4-5	15.72	117
5-6	11.15	83
6-7	5.63	32
7-8	2.55	19
8-9	2.69	20
9-10	0.53	5
10-11	0	0
11-12	0	0
12-13	0.13	1

Table 4.1: Frequency distribution of wind speed in Kaptai *(2003)*

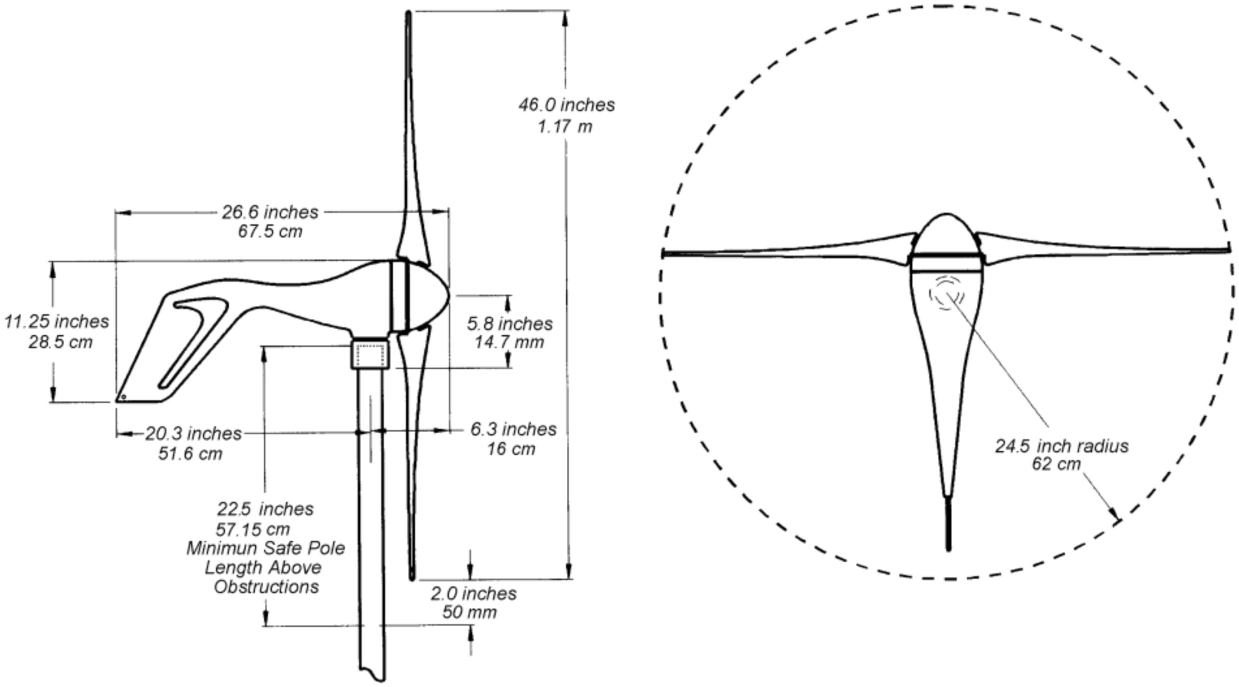


Figure 4.6: Schematic diagram of Air x turbine (400 W) [83]

Rotor Diameter	46 inches (1.15m)
Weight	13 lbs. (5.85 kg)
Mount	1.5’’ schedule 40 pipe (1.9” OD, 48 mm)
Start-up wind speed	7 mph (3.13 m/s)
Voltage	12 and 24 VDC
Rated Power	400 Watts at 28 mph (12.5 m/s)
Turbine Controller	Microprocessor based smart integral regulator with peak power tracking
Blades (three)	Carbon fiber composite
Body	Cast aluminium
kWh/month	38 kWh/month @12 mph (5.4 m/s)
Warranty	3 years Limited warranty
Survival Wind speed	110 mph (49.2 m/s)
Over speed protection	Electronic torque controller

Table 4.2: Technical specification of an Air X 400W turbine [83]

4.11 Life cycle energy analysis

Life cycle energy analysis focuses on the energy incurred during the lifespan of a wind turbine and estimates the energy payback period, or the time required to pay back the energy. Payback considers the initial energy input to manufacture and install the components of the wind turbine, the annual operating and maintenance energy and the energy saved from the recycling at the end of the system life span. Data is gathered from recent literature and wind turbine manufacturers. Probability distributions are then assigned to model parameters. Table 4.3 lists those parameters and the associated probability distributions used in the Monte Carlo simulation of life cycle energy.

Parameter	Assumed Distribution		Reference
Power Curve Deviation (%)	Uniform	Mean = 0.00	[12]
		Std. Deviation =2.00	
Turbine Availability (%)	Triangular	Min = 90	[12, 54]
		Max = 100	
		Peak = 95	
Wind Turbine Life (Years)	Triangular	Min = 15	[82]
		Max = 30	
		Peak = 22.5	

Table 4.3: Assignment of probability distribution to different parameters for LCA

A triangular distribution is a continuous probability distribution with a probability density function shaped like a triangle. It is defined by three values: the minimum value a, the maximum value b, and the peak value c. This is really handy as in a real-life situation we can often estimate the maximum and minimum values, and the most likely outcome, even if we don't know the mean and standard deviation.

The triangular distribution has a definite upper and lower limit, so we avoid unwanted extreme values. In addition the triangular distribution is a good model for skewed distributions. The sum of two dice is often modelled as a discrete triangular distribution with a minimum of 2, a maximum of 12 and a peak at 7.
On the other hand, a uniform distribution, sometimes also known as a rectangular distribution, is a distribution that has constant probability.

To calculate the actual annual energy output it is necessary to adjust the annual energy output for minor deviations. The actual power output from the turbine may deviate from the power curve by as much as ±5% due to short-term variability in the wind. Under gusty conditions some wind energy is absorbed by flexures in the rotor blades, which results in more or less power output than that anticipated from the power curve. Because power curve developed from or validated with empirical data, it is believed a normal distribution represents deviations from the power curve expected values more accurately than the triangular distribution. To account for this source of variability, the expected annual power output is multiplied by a power curve deviation factor (normal distribution, mean = 0%, std. dev = 2%). A standard deviation of 2% results in a probability distribution that spans approximately +/- 5% from the power curve value.

To calculate annual energy output, it is also necessary to adjust the annual energy output for turbine down-time. The wind turbine may be off-line as much as 10% of the time for routine or unscheduled maintenance and repair. Therefore, the amount of time the turbine is operating and generating electricity ranges from 90% to nearly 100%. To account for turbine availability, the expected annual energy output is multiplied by a turbine availability correction factor, which is the fraction of time the turbine is operational (triangular distribution, 90% to 100%, peak = 95%).

4.12 Wind energy payback time and emission intensity

Energy payback time and emissions intensity relate the environmental impacts of a wind turbine to the electricity generated over its lifespan. Energy payback time and emissions intensity can be calculated by using the following two equations [85]:

$$\text{EPBT} = \frac{\text{Total Energy Output over the Life Span (kWh)}}{\text{Electricity Production Per Year }(\frac{\text{kWh}}{\text{year}})}$$

$$\text{Emission intensity} = \frac{\text{Total Indirect Emission (kg)}}{\text{Lifetime Electricity Production (kWh)}}$$

In the second equation “total indirect emission” refers to CO_2 emission only. Sox and NOx emissions are avoided in this analysis. Values for total input energy and total indirect emissions are calculated for each life stage using process analysis (PA) and are then summed for all life stages. EPBT and emissions intensity values provide a basis for comparing wind turbines to other sources of electricity generation for our study: PV system. Energy sources that exhibit smaller EPBT and emissions intensity values are considered more favorable from an environmental impact perspective.

4.13 Process analysis

Process Analysis is conducted to determine the input energy consumed and the indirect emissions resulting from the production of raw materials used in a wind turbine. Data required to perform the analysis includes a material mass composition of the wind turbine under study and energy content and emission factors for each material. The most prevalent materials (excluding concrete for the foundation) are steel and aluminium for Air X turbine. Copper and GRP are found in relatively small amounts. Table 4.4 lists the material composition of each turbine. Excluding the material in the turbine foundation, steel comprises almost 60% of the mass in the turbine. Aluminium comprises 19.5% of the turbine mass, followed by copper and GRP, which together account for 22.5% of the turbine mass.

The mass of concrete and steel rebar used in a foundation can vary significantly based on soil conditions at a particular site and foundation design preferences. Because of the uncertainty in these factors, historical project records and general design guidelines were used to assign probability distributions. Concrete was assigned a uniform distribution from 15-30 kg. This represents the maximum and minimum mass of concrete actually used for the foundation of a single wind turbine. The mass of steel rebar used in the foundation is represented by a concrete-to-rebar ratio. From a review of previous wind turbine applications, the mass of concrete ranges from 21.8 to 41.5 times the mass of rebar. Therefore, the concrete-to-rebar ratio is assigned a uniform distribution from 21.8 to 41.5.

Data for the energy content and emission factors of the five primary materials (steel, GRP, concrete, copper, and oil products) was gathered, and probability distributions were assigned based on the general methodology discussed earlier. The assigned distributions are listed in Table 4.4. Given the mass of each material and the energy content and emission factors, the input energy and indirect emissions are calculated for each material in the wind turbine [85]:

Energy = Mass * Energy Content

Emission = Mass * Emission Factor

The total input energy and emissions resulting from the manufacture of raw materials can then be summed over all materials in the turbine.

Material	Components	Mass per turbine (g)
Stainless Steel	Bolts, Bearings, Shaft, Base	2876.3
Galvanized Steel	Internal Support components	579.0
Aluminium	Body, Circuit Board*, Magnet	1155.9
Copper	Wires in generator and 1 m cables	605.1
GRP	Blades, Nose. Cone, O-rings	736.3
Total		5952.6 (5.95 kg)

Table 4.4: Inventory Data for Air X turbine organized by mass of each material category considered [53]

Material	Parameter	Assigned Distribution	
Stainless Steel	Energy Content (MJ/kg) [52] [49]	Triangular	Min: 57
			Peak: 121
			Max: 185
	CO_2 Emission Factor (kg-CO_2(eq.)/kg) [52] [49]	Triangular	Min: 4
			Peak: 7
			Max: 10
Galvanized Steel	Energy Content (MJ/kg) [52] [49]	Triangular	Min: 5
			Peak: 30
			Max: 55.3
	CO_2 Emission Factor (kg-CO_2(eq.)/kg) [49] [52]	Triangular	Min: 0.153
			Peak: 2.5
			Max: 7
Steel Rebar	Energy Content (MJ/kg) [53]	Triangular	Min: 20
			Peak: 40
			Max: 61.5
	CO_2 Emission Factor (kg-CO_2(eq.)/kg)	Triangular	Min: 0.05

	[53]		Peak: 1.8
			Max: 3
Aluminium	Energy Content (MJ/kg) [52]	Triangular	Min : 155
			Peak : 258
			Max : 360
	CO_2 Emission Factor (kg-CO_2(eq.)/kg) [52]	Triangular	Min : 7.5
			Peak: 12
			Max : 15.5
Copper	Energy Content (MJ/kg) [51]	Triangular	Min: 20.7
			Peak:85
			Max:151.7
	CO_2 Emission Factor (kg-CO_2(eq.)/kg) [51]	Triangular	Min:5
			Peak: 6.3
			Max:8.9
GRP	Energy Content (MJ/kg) [12]	Uniform	Min: 24.5
			Max: 106
	CO_2 Emission Factor (kg-CO_2(eq.)/kg) [12]	Triangular	Min: 1.5
			Peak:3
			Max:4
Concrete	Energy Content (MJ/kg) [86]	Triangular	Min: 1.3
			Peak: 3
			Max: 5.1
	CO_2 Emission Factor (kg-CO_2(eq.)/kg) [86]	Triangular	Min: 0.15
			Peak: 0.2
			Max: 0.835
	Concrete to Rebar ratio [86]	Uniform	Min: 21.8
			Max: 41.5
	Mass of Concrete in foundation [86]	Uniform	Min: 20
			Max: 40

Table 4.5: Assignment of probability distribution for process analysis

4.14 LCA of Wind Result and Analysis

All these data discussed in the earlier sections were given input to the Microsoft excel spreadsheet. For all the parameters other than the fixed one's, (i.e. for energy content, emission factor, concrete mass, concrete to rebar ratio etc.) random variables were generated using excel function based on the probability distribution assigned to them. For triangular distribution excel built-in function is not available. However, a logic function has been used to create random variables for triangular distribution. An example of the logic function is provided below for a hypothetical condition. Finally, all energy contents were multiplied by the mass of each component, added together and Monte Carlo simulation was run. Each Monte Carlo Simulation run consisted of 10,000 iteration and resulted in a frequency distribution of output values for the given turbine at the given location. An example of Monte Carlo simulation has been discussed in Appendix A with logic function.

4.15 Energy Payback time

From 10,000 simulated results for Energy payback time, minimum, maximum and the average EPBT was determined. For this analysis the minimum, maximum and average EPBT was found to be 1.60, 1.80 and 1.71 year respectively. This means that the energy that has been required manufacture, install and operate the wind energy system, an equivalent amount of energy will be generated in almost 19 to 22 months of the starting of the system. From the probability distribution the most likely time to pay back the money is 1.8 years (20 months). The frequency and relative frequency value between the minimum and maximum EPBT are shown in table 4.6. The relative frequency distribution for the EPBT is shown in figure 4.7.

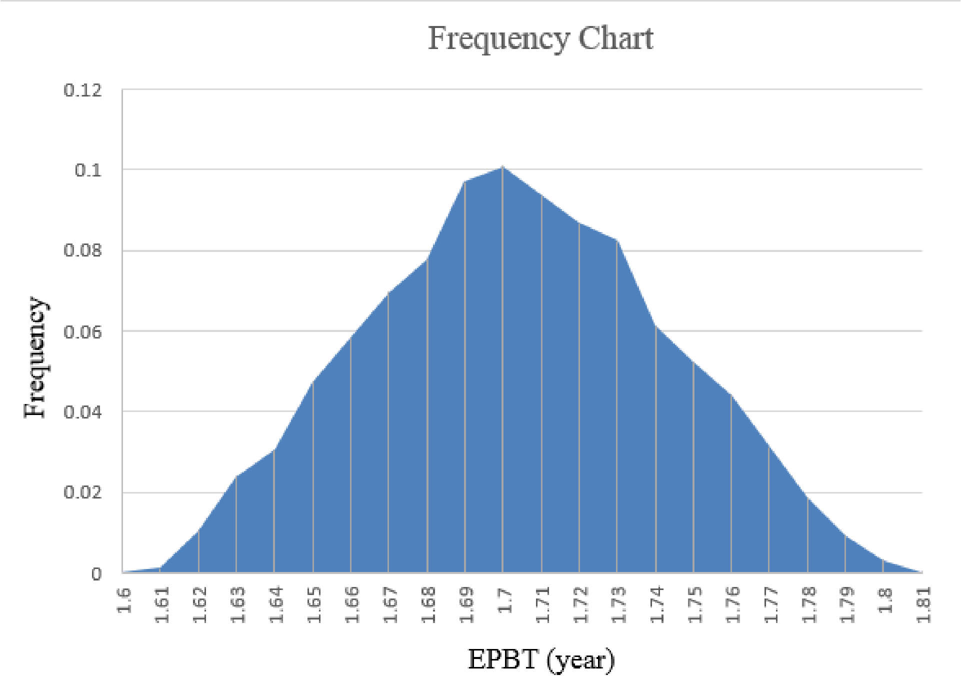


Figure 4.8: Frequency chart for EPBT for Air X turbine

EPBT Ranges	Frequency	Relative frequency
1.59	0	0
1.61	27	0.27 %
1.63	300	3 %
1.65	835	8.35 %
1.67	1261	12.61 %
1.69	1761	17.61 %
1.71	1926	19.26 %
1.73	1646	16.46 %
1.75	1179	11.79 %
1.77	708	7.08 %
1.79	329	3.29 %
1.81	28	0.28 %

1.83	0	0
Total	10,000	100%

Table 4.6: Frequency and relative frequency of the EPBT time values

4.16 Emission Intensity

In the similar way as for the EPBT, simulation for emission intensity was run for 10,000 iterations. From the result obtained the total emission over the life cycle of the system was found to be an average of 2180.07 kg CO_2 over the entire life time. The minimum and maximum was observed to be 1230.05 and 3681.53 kg CO_2. Therefore, the average emission intensity from the system is 0.12 kg CO_2 /kWh$_{el}$. The frequency of indirect emission is shown in table 4.7. Frequency distribution of indirect emission is shown in figure 4.9. The frequency chart (table 4.7) reads in a way that the emission between 1200 and 1400 kg CO_2 occurs for 135 times. Therefore the maximum frequency of emission occurs between 2000 and 2200 kg CO_2. Among all the emissions the average emission intensity is 2180.07 kg CO_2.

Range of Indirect Emission	Frequency
1200	0
1400	135
1600	649
1800	1065
2000	1380
2200	1589
2400	1548
2600	1289
2800	966
3000	678

3200	450
3400	189
3600	57
3800	5
Total	10,000

Table 4.7: Frequency of Indirect emission from the wind energy system

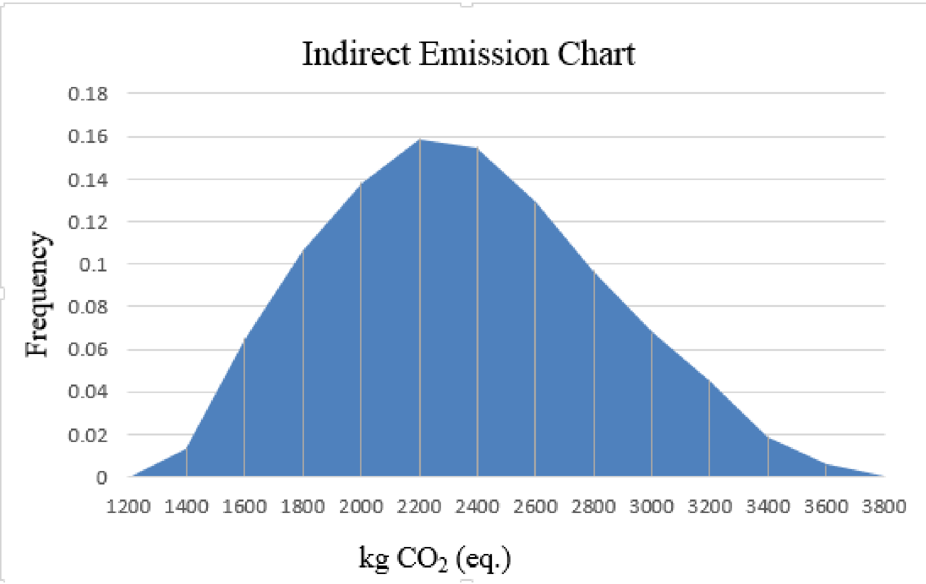


Figure 4.9: Frequency chart for indirect emission from the wind energy system

Chapter 05

Discussions and Conclusions

5.1 Discussions

The LCA of solar PV system and the wind energy system in this analysis yields the following results: EPBT for PV system and wind energy systems are 5.69 years and 1.6-1.8 years (average = 1.71 years) respectively. Emission intensity for solar PV system: 5.28 kg CO_2/kWh_{el} and for wind energy system: 0.12 $kgCO_2/kWh_{el}$ (average).

These results show huge variation between the environmental impact wind energy and solar PV system. This variation is mainly because of the PV module which is the main component in the solar PV system. As shown in the table 3.10, embodied energy spent behind PV module is almost 74% of the total embodied energy of the whole system. The next most energy consuming component is battery with only 14% embodied energy followed by supporting structure with 5% embodied energy. This is because manufacturing PV module is a complex process and other components require significantly less amount of energy to manufacture. On the other hand the most prevalent component in the wind energy system is concrete and steel, which requires way small energy than PV module does and emission from their manufacturing is also very small.

As emission factor for PV module is kg CO_2 per amount of energy consumed for manufacturing (which is much higher than any other component), the total emission from PV module is much higher resulting in a large emission intensity of the PV system.

For the wind energy system the foundation consists of almost 60% of the mass. Although the mass of the concrete in the wind turbine system (640kg-1280kg) is greater than mass of steel (66.24-109.38 kg), the embodied energy for steel is higher than that of concrete. As can be seen in this analysis maximum energy content for concrete is 5 MJ/kg, when the minimum of the three different types of steel: galvanized steel has an energy content in the range of 5-55.3 MJ/kg. Therefore, this results into a small amount of embodied energy of wind energy system.

Similarly, the indirect emission for steel varies from 4-10 kg CO_2/kg., whereas values for concrete range from 0.15-0.835 kg CO_2/kg. As a result of wide distribution ranges, variations in steel input factors have significantly more impact on the energy and emissions variability even though there is generally more concrete than steel.

5.2 Conclusion:

Therefore, the wind energy system will generate 11-13 times the energy that it consumes in it life time when the PV system generates only 3.5 times the input energy. And PV system will produce 44 times the emission of that of the wind energy system in its lifetime. Therefore, it is quite clear that a wind energy system of the same size as that of a PV system will have significantly better environmental impact.

In conclusion, from all these results and discussions it is clearly depicted that this study fulfills all four objective of the study.

- Life cycle assessment model has been created for both solar and wind energy technology.
- Energy payback time for both solar and wind are found. They are 5.69 and 1.71 years respectively.
- Emission intensity for both the systems are found to be 5.28 and 0.12 kg CO_2/kWh_{el}.
- The comparison of the two systems show that wind energy system provide better environmental benefit than solar energy system.

5.3 Future Work

- Since the LCA data base are not available for free, more updated data can be collected from the data providers to get more realistic life cycle assessment results. Several LCA data providers are there such as GAMESA, GEMIS, Ecoinvent etc.
- Conduct LCA study for other energy systems as well. There are other renewable energy sources in Bangladesh as well such as Biomass, hydro-electric energy etc. Life cycle assessment of these sources can also be carried out to broaden the study in future.
- Apply I/O or hybrid analysis method to perform the LCA. Although hybrid analysis is the best method of analysis, due to unavailability of data of related sectors in the national input output table I/O method can’t be followed. An I/O or hybrid analysis can be performed upon availability of the national input output table.
- Life cycle cost analysis can also be added in the analysis.
- Compare the LCA study of renewable and non-renewable energy systems.

Chapter 6

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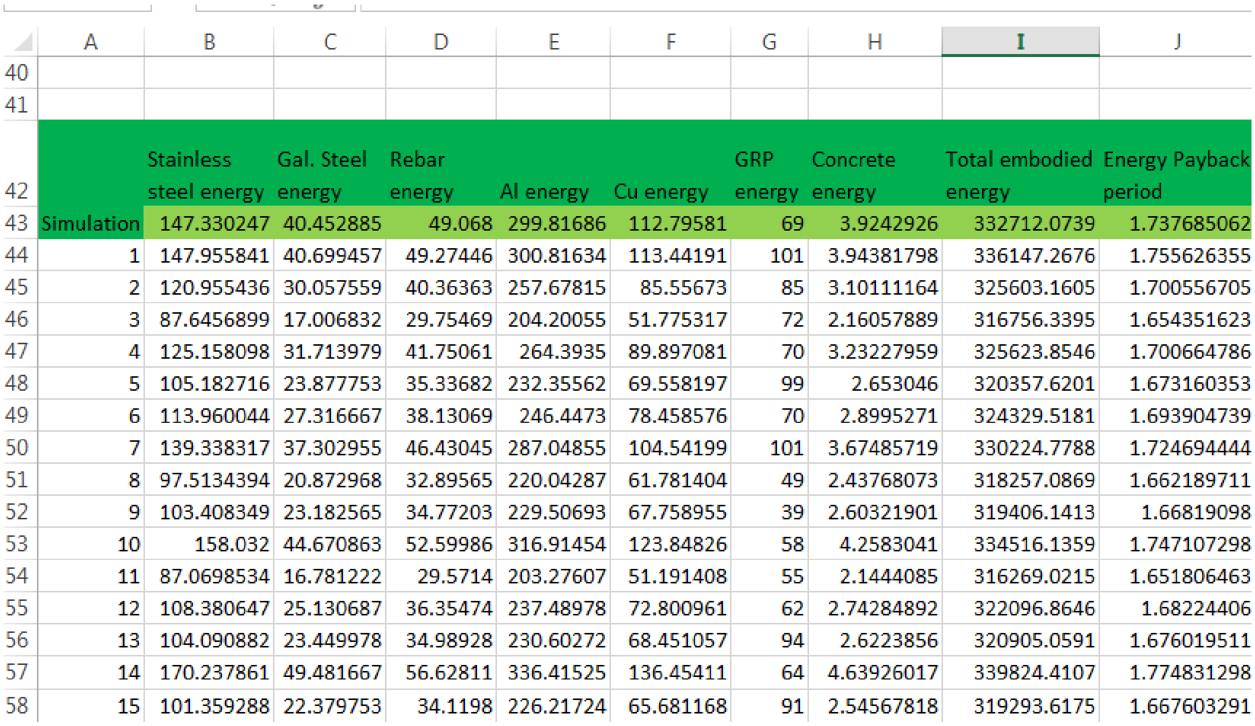
Appendix A

Sample Calculation



	A	B	C	D	E	F	G	H	I	J
40										
41										
42		Stainless steel energy	Gal. Steel energy	Rebar energy	Al energy	Cu energy	GRP energy	Concrete energy	Total embodied energy	Energy Payback period
43	Simulation	147.330247	40.452885	49.068	299.81686	112.79581	69	3.9242926	332712.0739	1.737685062
44	1	147.955841	40.699457	49.27446	300.81634	113.44191	101	3.94381798	336147.2676	1.755626355
45	2	120.955436	30.057559	40.36363	257.67815	85.55673	85	3.10111164	325603.1605	1.700556705
46	3	87.6456899	17.006832	29.75469	204.20055	51.775317	72	2.16057889	316756.3395	1.654351623
47	4	125.158098	31.713979	41.75061	264.3935	89.897081	70	3.23227959	325623.8546	1.700664786
48	5	105.182716	23.877753	35.33682	232.35562	69.558197	99	2.653046	320357.6201	1.673160353
49	6	113.960044	27.316667	38.13069	246.4473	78.458576	70	2.8995271	324329.5181	1.693904739
50	7	139.338317	37.302955	46.43045	287.04855	104.54199	101	3.67485719	330224.7788	1.724694444
51	8	97.5134394	20.872968	32.89565	220.04287	61.781404	49	2.43768073	318257.0869	1.662189711
52	9	103.408349	23.182565	34.77203	229.50693	67.758955	39	2.60321901	319406.1413	1.66819098
53	10	158.032	44.670863	52.59986	316.91454	123.84826	58	4.2583041	334516.1359	1.747107298
54	11	87.0698534	16.781222	29.5714	203.27607	51.191408	55	2.1444085	316269.0215	1.651806463
55	12	108.380647	25.130687	36.35474	237.48978	72.800961	62	2.74284892	322096.8646	1.68224406
56	13	104.090882	23.449978	34.98928	230.60272	68.451057	94	2.6223856	320905.0591	1.676019511
57	14	170.237861	49.481667	56.62811	336.41525	136.45411	64	4.63926017	339824.4107	1.774831298
58	15	101.359288	22.379753	34.1198	226.21724	65.681168	91	2.54567818	319293.6175	1.667603291

Figure: A portion of the Monte Carlo simulation from Excel model

Case Study: Simulation 1

Logic Function used for the Stainless Steel energy: =IF(I14<=($F$16-$E$16)/($G$16-$E$16),SQRT(I14*($G$16-$E$16)*($F$16-$E$16))+$E$16,$G$16-SQRT((1-I14)*($G$16-$E$16)*($G$16-$F$16)))

Logic Function used for the Galvanized Steel energy: =IF(I14<=($F$17-$E$17)/($G$17-$E$17),SQRT(I14*($G$17-$E$17)*($F$17-$E$17))+$E$17,$G$17-SQRT((1-I14)*($G$17-$E$17)*($G$17-$F$17)))

Logic Function used for the Rebar energy: =IF(I14<=($F$18-$E$18)/($G$18-$E$18),SQRT(I14*($G$18-$E$18)*($F$18-$E$18))+$E$18,$G$18-SQRT((1-I14)*($G$18-$E$18)*($G$18-$F$18)))

Logic Function used for the Aluminum energy: =IF(I14<=($F$19-$E$19)/($G$19-$E$19),SQRT(I14*($G$19-$E$19)*($F$19-$E$19))+$E$19,$G$19-SQRT((1-I14)*($G$19-$E$19)*($G$19-$F$19)))

Logic Function used for the Cupper energy: =IF(I14<=($F$20-$E$20)/($G$20-$E$20),SQRT(I14*($G$20-$E$20)*($F$20-$E$20))+$E$20,$G$20-SQRT((1-I14)*($G$20-$E$20)*($G$20-$F$20)))

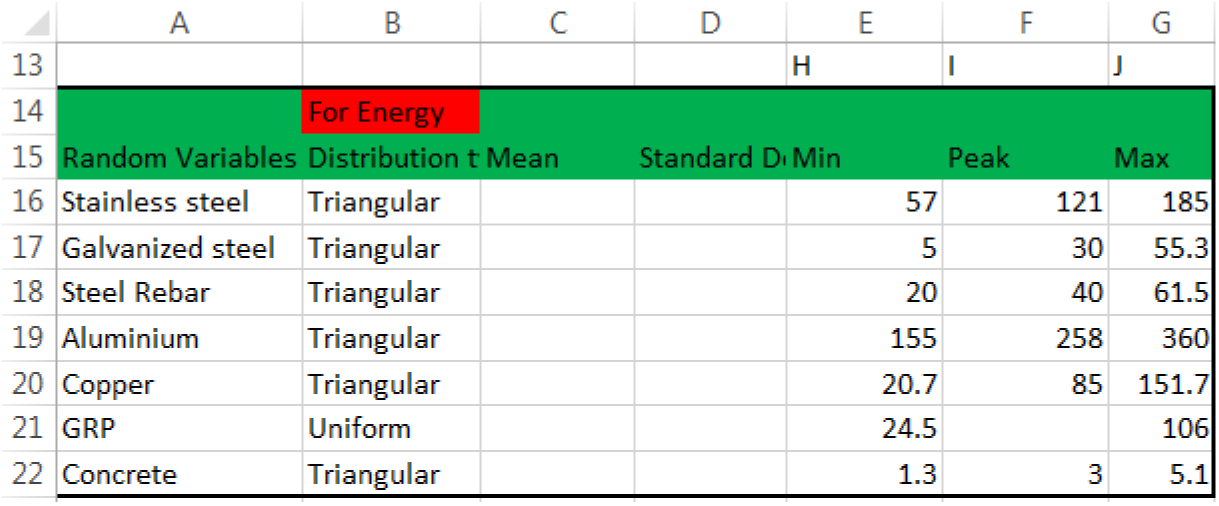
Logic Function used for the GRP energy: =RANDBETWEEN(E21,G21)

Logic Function used for the Concrete energy =IF(I14<=($F$22-$E$22)/($G$22-$E$22),SQRT(I14*($G$22-$E$22)*($F$22-$E$22))+$E$22,$G$22-SQRT((1-I14)*($G$22-$E$22)*($G$22-$F$22)))

Function used for the total energy:
=(B43*B6)+(C43*B7)+(B8*D43)+(E43*B9)+(B10*F43)+(G43*B11)+(B12*H43)+I29

Function used for the Energy Payback time: =I43/I34, where I34 is the output energy of the system, 191468.57 MJ/year

The inputs of these function is given in the following figure:



	A	B	C	D	E	F	G
13					H	I	J
14		For Energy					
15	Random Variables	Distribution t	Mean	Standard D	Min	Peak	Max
16	Stainless steel	Triangular			57	121	185
17	Galvanized steel	Triangular			5	30	55.3
18	Steel Rebar	Triangular			20	40	61.5
19	Aluminium	Triangular			155	258	360
20	Copper	Triangular			20.7	85	151.7
21	GRP	Uniform			24.5		106
22	Concrete	Triangular			1.3	3	5.1

Figure: Inputs to the logic function