DEVELOPMENT AND PERFORMANCE ANALYSIS OF A GREEN HYDROGEN PRODUCTION SYSTEM FOR HYDROGEN DEMAND OF BANGLADESH BY 2040

A thesis submitted in fulfillment of the requirements for the award of the degree of Doctor of Philosophy in Renewable Energy Technology

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April 2023

Originality Statement

We hereby declare that this submission is the own work of **Mr. Gour Chand Mazumder** and to the best of our knowledge it contains no materials previously published or written by any other person, or substantial propositions of the material which have been accepted for the award of any other degree or diploma at the University of Dhaka or any educational institution except where due acknowledgement is made in this thesis. Any contribution to the research by others, with whom **Mr. Gour Chand Mazumder** has worked at the University of Dhaka or elsewhere, is explicitly acknowledged in this thesis. We also declare that the intellectual content of this thesis is the results of **Mr. Gour Chand Mazumder's** research work, except to the assistance from others with due acknowledgement.

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ACKNOWLEDGEMENT

IN THE NAME OF **GOD**, THE MOST KIND AND THE MOST POWERFUL

Thanks to the creator of this wonderful universe for giving me the chance and endurance to complete my thesis. I would also like to thank and acknowledge those individuals and institutions who have come across during my PhD work for their tremendous help, guidance and support to complete this work.

First of all, I would like to express my sincere gratitude to my supervisor **Professor Dr. Saiful Huque** for giving me time, consultation, guidance and encouragement throughout preparation of the whole doctoral dissertation. Then, I would like to express my deepest gratitude towards **Professor Dr. Md. Habibur Rahman**; my co-supervisor. Without his generous guidance, lessons, support and mentorship, this would have not been possible.

I also want to express my heartiest thanks to Dr. S M Nasif Shams, Associate Professor, Institute of Energy, University of Dhaka, for his encouragements, appreciations and pivoting comments throughout the work. I also thank to Dr. Himanghshu Ranjan Ghosh for his care and guidance to improve the thesis and the overall research, Dr. Galib Hashmi and A S M Ibrahim for their valuable advice and suggestions.

I would like to thank Md. Najmul Nahid and Mr. Antar Anwer to help me in data collection and data analysis in a part of this research.

I would like to thank all the office staffs of the Institute of Energy, specially Md. Sah Alam Mia, Md. Bellal Hossain, Mr. Shishir Dutta, Mrs. Sonia Akhter, Mr. Masud Rana, Md. Shaid Mia, Md. Swapan Mia, Md. Shwan Mirza and Md. Afzal Hossain for their enormous support especially in laboratory works.

A part of this work is funded by the Ministry of Science and Technology, Government of People's Republic of Bangladesh which helped me a lot to conduct research in several places in Bangladesh and I express my gratitude to the management of Lumbini Ltd, support staff of Lumbini, Md. Zohir, Section Seven Ltd., Bangladesh Power Development Board and Shinehardy Solar and Power Tech for giving me access to their rooftops for wind data collection. I express my heartiest thanks to the workshop workers of Alpha Engineering who helped me constructing the electrolyzer.

I could not have finished this study without the full support of my family members. Their continuous love and encouragement provided me the courage and patience on completing this doctoral thesis.

Lastly, I would like to extend my deepest appreciation to all the teachers and staffs of the Institute of Energy for their kind support on the technical and the administrative aspects of this study.

Publication List: Total Papers Published (**11**)

Journal Papers (8)

1. Practical Study of Water Electrolysis for Solar Powered Hydrogen Production Using Stainless Steel Electrode and Sodium Hydroxide Solution, **Gour Chand Mazumder**, S M Nasif Shams, Abu Shahadat Md. Ibrahim, Md. Habibur Rahman. *International Journal of New Technology and Research (IJNTR)*, ISSN: 2454-4116, Volume-5, Issue-3, March 2019, Pages: 84-90, IF: 3.953.
2. Assessment of Wind Power Potential at the Chittagong Coastline in Bangladesh, **Gour Chand Mazumder**, Abu Shahadat Md. Ibrahim, S. M. Nasif Shams and Saiful Huque, *Dhaka University Journal of Science*, Volume-67, Issue-1, January 2019, Pages 27-32.
3. Development and Performance Analysis of a Low-Cost Hydrogen Generation System Using Locally Available Materials, Dhaka University Journal of Science, **Gour Chand Mazumder**, S M Nasif Shams, Md. Habibur Rahman and Saiful Huque, *Dhaka University Journal of Science*, Volume-68, Issue-1, January 2020, Pages: 49- 56.
4. Use Of Green Hydrogen In Developed Countries And Prospect In Bangladesh For Sustainable Development In Energy Sector, **Gour Chand Mazumder**, S M Nasif Shams, Md. Habibur Rahman and Saiful Huque, *Elk Asia Pacific Journal Of Project Management And Control*, ISSN: 2394-9376, Volume-6, Issue-1, June 2020, Pages: 1- 14. IF: 1.156.
5. Assessment of Small Wind Turbine Installations at Dhanmondi, Dhaka, Bangladesh, Antar Anwar, **Gour Chand Mazumder**, ASM Shamsul Arefin and Abu Shahadat Md. Ibrahim, *Dhaka University Journal of Applied Science & Engineering*, Volume-6, Issue- 1, January 2021, Pages: 66-73.
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7. Production of Green Hydrogen in Bangladesh and its Levelized Cost, **Gour Chand Mazumder**, S M Nasif Shams, Md. Habibur Rahman and Saiful Huque, *Dhaka University Journal of Applied Science & Engineering*, Volume-6, Issue-2, July 2021, Pages-1-8.
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Conference Papers (3)

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3. Estimation of Hydrogen Demand for a sustainable Energy mix in Bangladesh replacing the traditional fuels by 2040, **Gour Chand Mazumder**, S M Nasif Shams, Md. Habibur Rahman, Saiful Huque, BAPA-BEN Annual Conference-2022, Energy, Climate Change and Sustainable Development in Bangladesh, 11-12 February, 2022, Dhaka. RE-2, PI-03.

ABSTRACT

Nowadays, green hydrogen production through electrolysis of water, using renewable energy sources like solar, wind is increasing worldwide, as it leaves no emission behind. This work is intended to identify the diversified applications of hydrogen in different sectors in Bangladesh like the chemical, food and metal industries, fuel cells, bio-gas, heating applications, etc.

In this research, a green hydrogen production system has been developed using locally available materials and technologies. An electrolyzer is the central part of this system. It has two cells connected in parallel and has bipolar electrode configuration. Each cell has 4 individual electrodes and one shared electrode. Total 9 electrodes have been used. Each electrode is positioned having an equal separation from each other so that each electrode gets equal potential difference across them. Here, 10.6 volt is applied to the assembly, and hence, each pair gets 2.65 volt. NaOH solutions of different molarity are used to optimize the gas production rate. Performance analysis of developed system shows that it can produce 92.5% pure hydrogen with 30.62% efficiency and the production rate is 206 mL/min or 1.104 g/h or 0.0123 Nm^3/h. A practical study on different electrolysis conditions are tested before developing the electrolyzer. The study concludes that the solar photovoltaic panels and wind turbines are technically feasible for water electrolysis.

Wind speed data was collected for one year (July, 2015 to June, 2016 and July, 2016 to June, 2017) at two sites in Chattogram and Dhaka, two busy metropolitan cities in Bangladesh. The Weibull distribution of data shows that the shape factor of the wind data in Dhaka (Lat: 23.7390° N, Long: 90.3831° E) is 1.42 and scale factor is 1.96 ms^{-1} at measured height of 27 meters from sea level. The shape factor for Chattogram (Lat: 22.2877° N, Long: 91.7751° E) site is 1.8 and the scale factor is 2.2 ms^{-1} at the height of 59 meters from sea level. It is found that the scale factor significantly improves with the increase of hub heights. For Chattogram site, scale factor is around 3.68 ms^{-1} at a height of 130 meter, and for the Dhaka site it is nearly 4.17 ms^{-1} at 200 meters.

At measured height the yearly average energy density would be 7800 Whm^{-2} for Dhaka site and for Chattogram site it would be around 12300 Whm^{-2}. The site specific wind characteristics suggest that the turbines having 2 ms^{-1} cut-in-speed and 10 ms^{-1} rated speed would produce energy with 30% capacity factor, from the month of April to September, for both the sites. For the urban building rooftops, lightweight small capacity (~1kW) wind turbines with mentioned characteristics are most suitable. DB 400 and AWM-1500 model turbines have the similar characteristics and were chosen for the further simulation.

The values of the global solar radiation (taken from NASA for July 1983 to June 2005) are 4.59 kWh/m^2/day and 4.76 kWh/m^2/day for Dhaka, and Chattogram, respectively. The average sunshine hour for both the cities are about 4.5 hours/day.

The economic feasibility, especially the Levelized Cost of hydrogen, produced from PV and wind based power options, have been determined. Life-cycle-cost analysis shows that, the production cost of hydrogen of a plant using Solar PV power is about BDT 859.77/Nm^3 or BDT 9.56/g. The electricity consumption of the developed hydrogen plant is 3897.6 kWh/year and the energy requirement for hydrogen production is about 108.72 kWh/kg. The amount of hydrogen yield is 35.85 kg or 398.56 Nm^3 per year. Sensitivity analysis based on different parameters finds that the production cost of hydrogen using solar power varies from BDT 7.99/g to BDT 10.93/g or BDT 718.85/Nm^3 to BDT 982.99/Nm^3. The cost includes lead acid battery cost, replacement cost and maintenance costs. On the other hand, for wind power scheme, the production cost is about BDT 10.30/g or BDT 926.66/Nm^3. For wind-solar hybrid model, the production cost of hydrogen would be BDT 7.47/g or BDT 671.71/Nm^3 with reduced number of battery usage. Sensitivity could impact the cost to vary between BDT 7.28/g or BDT 654.50/Nm^3 to BDT 10.11/g or BDT 909.64/Nm^3. Based on the simulated results, it is found that the solar-wind hybrid model would be the most effective for green hydrogen production in Bangladesh.

Demand potential of hydrogen is estimated to cope with the targets of Bangladesh Government by 2040. The demand potential analysis is based on the methods and criteria adopted by the several international agencies, research institutes and laboratories. Out of several methods and assumptions, three scenarios, each having a specific percentage of different fuel mix are selected, modified and set for Bangladesh. For Scenario-1, the least GDP growth case, Bangladesh would require about 2.98 MTOE of hydrogen in 2040. The Scenario-2, set for the moderate GDP growth case would require about 6.05 MTOE and for Scenario-3 which is the maximum expected GDP growth case, the hydrogen requirement would be 9.12 MTOE. The power sector would consume about 70% whereas industries and transport would consume 23% and 6%, respectively. However, considering the socio-economic conditions of Bangladesh, Scenario-1 could be achieved easily with the projected time period to enter in the world hydrogen economy.

In comparison to the current international cost of hydrogen, the developed electrolyzer shows higher production cost. The developed unit is a small capacity electrolyzer and works properly to produce green hydrogen. Research should be conducted to develop large scale electrolyzer in Bangladesh to evaluate the cost from large scale production unit. Technology transfer may also help to establish green hydrogen economy. Due to the availability of solar and wind resources, solar PV and wind turbine technology would largely contribute to the green hydrogen production in Bangladesh.

TABLE OF CONTENTS

List of Figures

List of Tables

Nomenclature

Full Form	Abbreviation/Symbol/Unit
Photovoltaic	PV
Hybrid Optimization of Multiple Energy Resources	HOMER
Renewable Energy	RE
Separator Membrane Assembly	SMA
Perfluorosulfonic Acid	PFSA
Meter Per Second	ms^{-1}
Wind Power Density	WPD
Fuel Cell Vehicle	FCV
Megawatt	MW
Kilowatt Hour	kWh
Ampere	A
Ampere Hour	Ah
Voltage	V
Million Ton Oil Equivalent	MTOE
Kilogram Oil Equivalent	kgOE
Million Tonne	MT
Gram	g
Normal Meter Cube	Nm^3
Kilo	K
Billion Cubic Feet	Bcf
Million Standard Cubic Feet per Day	MMscfd
Gasoline	Gasol.
Natural Gas	NG
Renewable Energy	RE
South Asian Association for Regional Cooperation	SAARC
Hydrogen	H_2
Compressed Natural Gas	CNG
Liquefied Natural gas	LNG
National Renewable Energy Laboratory	NREL
U.S. Energy Information Administration	EIA
Life Cycle Cost	LCC
Levelized Cost of Electricity	LCOE
Cost of Electricity	COE
Levelized Cost of Hydrogen	LCOH
Economic Research Institute for ASEAN and East Asia	ERIA
East Asia Summit	EAS
Bangladeshi Taka	BDT
Year	y
Hour	h
Minute	min
Taka	tk

Chapter 1
Introduction

1.1 Background

The civilization of today's world is highly dependent on the utilization of fuels and energy. The reserves of world's fossil fuels and energy are depleting very fast. It has been estimated that it would be depleted by 2060 [1]. Fossil fuels are the major contributor to the environment pollution and global warming. Researchers suggest that about 80% of coal, 50% of gas and 30% of world oil reserve cannot be used to limit the global warming within 2 ^{O}C level [2]. To fight global warming, depleting fossil fuel and oil crisis, nuclear disasters and environment deterioration, scientists have been searching for safer renewable energy sources [3].

According to the International Energy Agency, global energy demand will increase up to 30% by 2040 [4]. Also, the world has the decarbonizing planet goal set for 2050. 2% of global carbon dioxide emission occurs from the production process of hydrogen alone [5]. The primary task of this research is to produce hydrogen without emitting carbon dioxide.

Addressing the issues, Hydrogen is one of the most potential candidates for the replacement of fossil fuels. Burning or using hydrogen leaves no emission. Today's most of the supplied hydrogen is produced from coal and gas which are not considered renewable method [6]. Low carbon hydrogen production is costly, but, the cost of hydrogen production from renewable electricity is becoming lesser and competitive day by day [7].

Solar photovoltaic and wind turbine are the most prominent renewable electricity production technologies throughout the world. The global photovoltaic system installation capacity has reached to 633.7 GW. The cumulative data is shown in Fig. 1.1 from 2000 to 2021 [8].

Beside this, the global cumulative wind power capacity has reached up to 743 GW. Among them 93 GW is installed in 2020.

Hydrogen produced by renewable energy is known as Green Hydrogen. The use of Solar Photovoltaic technology and Wind power is becoming popular. The cost is becoming lower day by day as the technologies are being matured and widely used.

In Bangladesh, solar photovoltaic (PV) technology has been proved as environmentally safe and reliable energy technology. It is the most potential and considered the first major RE source in Bangladesh [9]. This happened because, a moderate Global Horizontal Irradiation of 4.5 kWh/m^2 covers the country on daily basis.

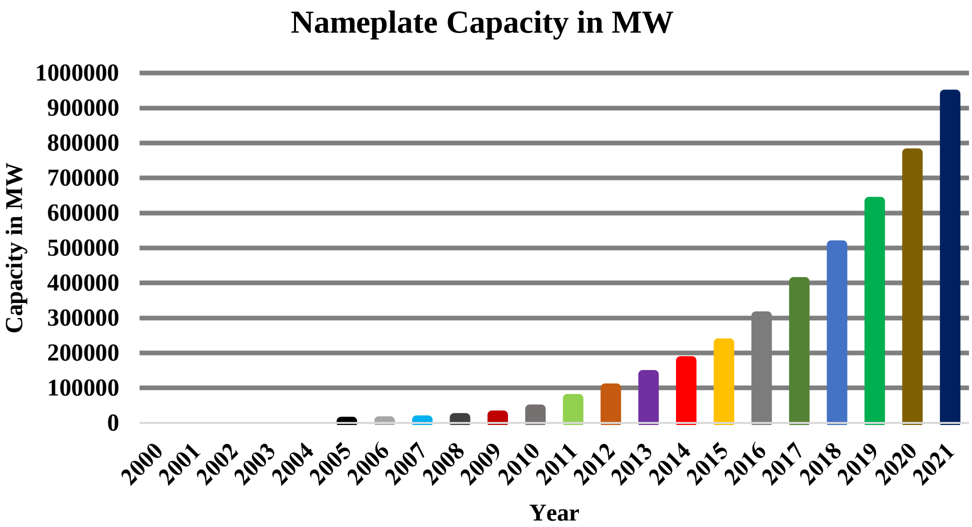


Fig. 1.1. Global cumulative solar PV installation capacity

Taking these advantages, the use of photovoltaic systems in Bangladesh made world record. Nearly 4 million SHSs are being used only in Bangladesh out of 6 million worldwide (till 2016) [9] and already crossed 6 million by 2022 [10].

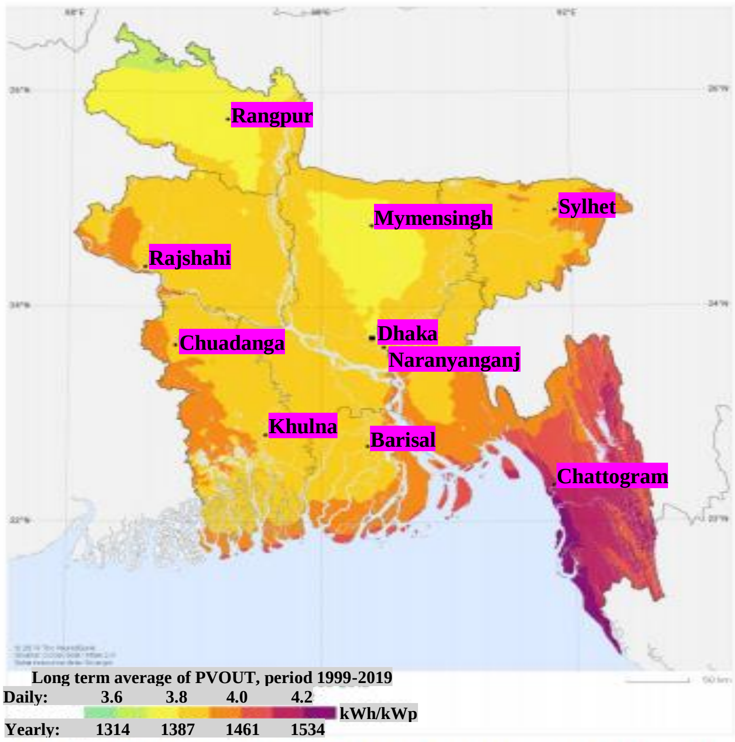


Fig. 1.2. Photovoltaic power potential in Bangladesh, source (ESMAP)

Fig. 1.2 shows that the Chattogram region is exposed to the higher solar energy. Dhaka, Rajshahi, Khulna and Sylhet regions have nearly similar exposure to Sun.

Most of the PV systems are installed in rural off grid areas and commercial owners [12]. The government of Bangladesh is also developing and establishing mega power plants using PV technology [11]. Bangladesh government has already published the feed-in-tariff for Solar PV users.

Wind is the third major RE source in Bangladesh. The resource is required to explore on the basis of site and projects, recommended by various reports and studies. Preliminary study shows that 30,000 MW of power can be produced from an area of 20,000 km^2 having an average wind speed about 5.75 ms^{-1} to 7.75 ms^{-1} in Bangladesh [13].

The Bangladesh government is encouraging people to use any type of renewable energy sources. Government has already completed 130.23 MWp Solar PV installations, 522 MWp under implementation and 1522.77 MWp under planning within various projects in different locations of the country. A total of 2175 MWp Solar PV installations are expected to be completed within 2023. Beside these, government has already developed several wind power projects in coastal areas. The installed capacity is about 2.9 MWp till now. In upcoming years, additional 257 MWp would be installed [14].

1.2 The World on Clean Fuel Technology: Green Hydrogen

In the quest of clean fuel technology the world has chosen hydrogen as a prospective candidate. Burning or using hydrogen emits no harmful greenhouse gases. Hydrogen can be used for many applications starting from food industry to transport vehicle. Approximately 10-11 million metric tons of hydrogen are produced in the US each year [15]. For reference, this is enough to power 20-30 million cars (using 700 to 1,000 gallon energy equivalents per car per year) or about 5-8 million homes. Globally, the production is around 40.5 million tons (about 44.4 million short tons or about 475 billion cubic feet), and is expected to grow 3.5% annually [16]. Major current uses of the commercially produced hydrogen are for oil refining, where hydrogen is used for hydro-treating of crude oil as part of the refining process to improve the hydrogen to carbon ratio of the fuel, food production (e.g., hydrogenation), treating metals, and producing ammonia for fertilizer and other industrial uses.

A growing use of hydrogen is to support emerging applications based on fuel cell technology along with other ways to use hydrogen for electricity production or energy storage. More than 50 types and sizes of commercial fuel cells are being sold worldwide and the value of fuel cell shipments reached $498 million in 2009. Approximately 9,000 stationary fuel cell systems and 6,000 other commercial fuel cell units were shipped that year. The total 15,000 represented 40% growth over the previous year. In addition, 9,000 small educational fuel cells were shipped [17].

Hydrogen is also being used in homes for cooking and other heating applications. A model research project is implemented in France at Cappelle-la-Grande. About 100 homes in this northern France village are using green hydrogen produced from Solar PV and Wind farms. Green hydrogen is being used as a gas mix in the existing pipeline there.

Report states that the production cost of renewable hydrogen is about $3 to $7.50/kg whereas the steam methane reformation which is the industrial and non-renewable method costs about $0.90 to $3.20. [18].

Due to the success and recent developments in RE sectors in Bangladesh, particularly Solar PV and Wind, this research aims to explore the potential of Green Hydrogen production in Bangladesh using Solar PV and Wind power generation technologies.

1.3 Objectives of the Present Work

Hydrogen can be produced via electrolysis of water using any electrical source, including utility grid power, solar photovoltaic (PV), wind power, hydropower, or nuclear power. Electrolysis is currently done at a wide range of scales, from a few kW to 2,000 kW per electrolyzer.

Electrolyzer plays an important role for the production of hydrogen. Most advanced Electrolyzers use very costly metals like platinum and complex chemical compound like Polymer electrolytic membrane. This project designs and develops an alkaline electrolyzer using locally available materials [18]. Electrolysis parameters are studied separately to understand the actual in situ behavior. Studied results are used to design and construct the working samples of the electrolyzer.

The performance of the developed devices and systems is studied for further development. The primary source of the required energy to run the electrolyzer is solar photovoltaic panels or Wind Turbines. The system is developed in such a way that user can power it from any DC source as well [19].

Safety is a primary concern of any system which produces or uses hydrogen gas. Several safety devices are developed and tested for proper functionality. Some locally available safety devices are studied and incorporated in the developed system [19].

This research aims to find the green hydrogen consumers in Bangladesh [19]. Demand projection is a key for the establishment of hydrogen economy. Most of the East Asian Countries and neighboring countries like India, China and Japan has already started establishing the hydrogen economy plans and projects along with the hydrogen economy policy [21]. Bangladesh needs to make the policy to keep pace with the future development goals. This research also prepares a demand potential of hydrogen in Bangladesh within 2040 [21].

This research also aims to evaluate the potential of green hydrogen production using Solar PV and Wind power. This research estimates the levelized cost of green hydrogen production using Solar PV [22], Wind or Solar-Wind hybrid model [23] of electricity input. It also prepares wind power potential analysis on two different sites in Dhaka as an urban site and Chattogram as a coastal site [24-25]. The analysis results are used to calculate the production cost of Green hydrogen using the developed electrolyzers.

1.4 Organization of this Thesis

The content of this thesis has been organized in ten chapters, among which **Chapter 1** gives the general background of photovoltaics (PV), wind power, green hydrogen and the objectives of this work.

This thesis deals with several objectives including the identification of Hydrogen consuming sectors in Bangladesh and prospective use of it, given in **Chapter 2**. The research deals with the construction and performance study of a developed Electrolyzer based on practical study and data analysis.

In **Chapter 3**, Practical Study of water electrolysis for solar powered hydrogen production using stainless steel electrode and sodium hydroxide solution is given.

Chapter 4 deals with the development and performance analysis of a hydrogen production system. In this chapter, the design, construction, operation and advantages of the developed electrolyzer is described.

Chapter 5, describes the production of solar powered green hydrogen production in Bangladesh and its Levelized cost using the locally developed electrolyzer.

Chapter 6, provides the analysis of wind power potential of Dhaka and Chattogram, based on two selected sites where the data were measured within this research activities.

Similar to the **Chapter 5**, in **Chapter 7** and **8,** the Levelized cost of green hydrogen has been estimated for the wind and wind-solar-hybrid model of power production.

In **Chapter 9**, the demand potential of hydrogen in Bangladesh within 2040 has been estimated.

Finally, **Chapter 10** provides further recommendations and an overall conclusion of all the chapters in this thesis.

1.5 Outcome and Contribution of this Research

Hydrogen demand potential scenarios are modified for the Developing and under developed countries like Bangladesh. The model can be used for assessing the similar cases. Sectors are identified, specifically where hydrogen can be used to replace fossil fuels in Bangladesh. Cost Analysis has been conducted for separate geographical locations like sea shore and urban city areas as renewable hydrogen production is a geography dependent venture. Results shows that it is possible to produce green hydrogen in Bangladesh using wind and solar photovoltaic technologies.

A working green hydrogen production system is developed. The developed electrolyzer can produce 92.5% pure hydrogen. The efficiency of the electrolyzer is 30.62%. All the components of the electrolyzer is made using locally available materials.

A macro level Gas separation geometry is introduced to collect hydrogen and oxygen separately. Commonly the geometry is implemented using micro and Nano technologies in advanced alkaline electrolyzers. Due to the implementation of this geometry, the developed electrolyzer is able to produce pure hydrogen. Usually the KOH solution is used for electrolysis, this electrolyzer can use both KOH and NaOH due to its low temperature operation. (60~70^{o}c).

Wind power potential for green hydrogen production is analyzed. **Suitable turbines are identified for comparatively low-wind-speed regions**. These small turbines can be used to produce hydrogen solely or by the co-generation scheme with Solar PV technology.

Lastly, **the overall research approach and outcomes can be utilized or further improved to establish and assess the potential green hydrogen economy for developed and under developed countries like Bangladesh.**

Chapter 2

Worldwide Usage of Green Hydrogen and Prospect in Bangladesh

2.1 Introduction

Being a densely populated country, Bangladesh has many serious issues. Energy crisis is one of them. Per capita energy consumption in Bangladesh is very low, 422 kWh in 2022 [26]. Continuous supply of energy is a must to support business and day to day activities of mass people. On an average, about 77.9% people has access to electricity [27]. Every government faces critical challenges to meet this crucial necessity. For past decades the energy sector of Bangladesh is in a bit stable condition. Installed electricity generation capacity crossed 25000 MW in the year 2022 [28]. However, sustainable growth and infrastructure development is yet in primary stage. To strengthen and stabilize this sector, government has already diversified and de-centralized the resources. Natural gas is the major source to produce electricity and transports. About 75% energy demand is covered by natural gas. Household heating is met largely by biomass in rural areas. Natural gas by central distribution company and private cylinder suppliers operate in urban and sub urban areas in the country. Import of electricity is contributing to the national grid. Coal and nuclear power plants are under construction. Renewable energy resources are also being used in standalone and centrally connected mode [29]. In Bangladesh, number of solar home systems is the highest in the world and fifth in small bio-gas plants. A very few wind turbines are installed in coastal region. Government has planned to increase renewable energy share up to 10% in energy mix within 2030.

In 2014, 0.46 million tonne of carbon-di-oxide emission per capita has been recorded [30]. In contrast to the world picture, this amount is not very significant at all but the increasing rate is alarming. It is moving forward at an average rate of 5.17 % annually. Major emission sources in Bangladesh are various industries, fossil fuel based power plants, transport vehicles and households. Use of natural gas is contributing to reduce emissions but this resource is depleting. Alternative to natural gas must be accommodated before it gets finished. Bangladesh is not importing liquid propane which creates a dependency on external parties and suppliers. Hydrogen can contribute to support the need of natural gas requirements [31]. Some countries are directly feeding hydrogen gas into existing distribution line to support the supply [32]. This type of establishments require state of art safety mechanisms.

Currently, in Bangladesh, hydrogen is produced using non-renewable methods. The industrial non-renewable methods are not environmentally safe. Study shows that the green hydrogen production is becoming more price competitive day by day [33] and so, green hydrogen might be adopted by industries in future. As Bangladesh is a solar abundant country and photovoltaic technology has success stories, proper development and extensive research on green hydrogen might open a new door to a promising energy resource.

In this chapter, worldwide situation of hydrogen exploitation, importance and advancement of its applications are discussed. It identifies difficulties and gaps to promote this scope in Bangladesh with the identification of sectors.

2.2 Green Hydrogen Worldwide

Green hydrogen is a new term in the field of hydrogen technology. Green hydrogen is produced using renewable energy sources and does not emit any harmful greenhouse gases. It is mainly the electrolysis of water.

Electrolysis requires electrical energy to breakdown the water molecules into hydrogen and oxygen. The electricity is supplied from renewable sources like Solar or Wind. A simplified process diagram is shown in Fig. 2.1.

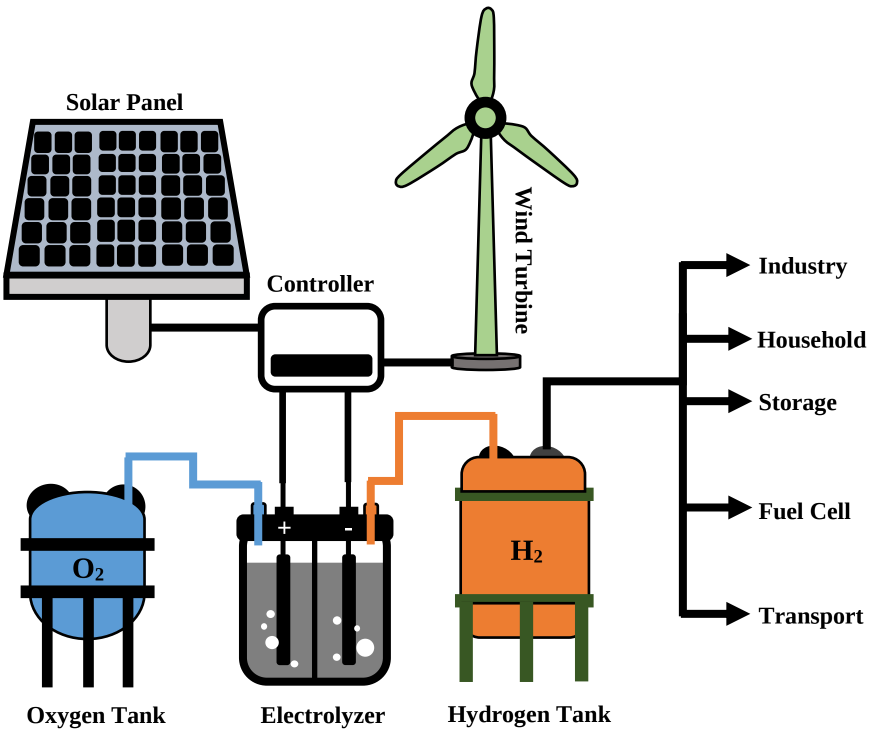


Fig. 2.1. Green hydrogen production and usage

In 2018, several carbon capture and storage projects are announced in Europe. This facilitates 100 MW capacity water electrolyzer for hydrogen production [34]. In Netherlands, a 20 megawatt of electrolyzer is planned to be established for the large scale conversion of sustainable electricity into green hydrogen. The facility will produce 3000 tonnes of hydrogen per year which can run about 300 hydrogen buses [35]. Successful completion of this project would lead the development of a 100 MW capacity installation which will convert and store sustainable energy in the form of hydrogen gas. Netherlands has a 1 MW facility already in operation.

The cost of green hydrogen is expected to be competitive by 2030 in Australia, Germany and Japan [36]. To acquire this phase, these countries need to modify their policy into renewable energy (RE) friendly level. In contrast to that, Bangladesh has already established tolerable RE policy. Investor can be benefitted while running projects in Bangladesh. Analysis shows that by 2025, worldwide green hydrogen production will expand up to 3205 MW and already crossed 250 MW by 2019. So, this is the high time for Bangladesh to put some effort on green hydrogen as other countries have advanced miles ahead.

2.3 Worldwide Scenario of Hydrogen Production and Application

World's highest amount of hydrogen producer is the United States. About 9 million metric tonnes H_2 are produced per year in US. California, Louisiana, and Texas are the three states which are the major producers in this area. About 95% hydrogen is produced from natural gas through Steam Reforming Method [37]. Almost 100% hydrogen is used in refinery, metal and food industry.

The National Aeronautics and Space Administration (NASA) is a mentionable single user of hydrogen in US. In USA, fuel cell based applications are becoming popular day by day. Fuel cells are used to produce electricity from hydrogen [38].

Two types of application of fuel cells are common, in vehicles and electricity production. The number of fuel cell vehicles (FCVs) are increasing. More than 350 FCVs are in operation from 2016 in California [37]. About 50 hydrogen refueling stations are established to support these vehicles. In this state, fuel-cell based distributed power generation crossed over 210 MW using 480 fuel cells. Connecticut has approved a 63.3 MW fuel cell station.

This would be the world's largest installation [39]. Already it has 35 MW and planned to have 20 MW. There are 600 companies in US operates for hydrogen and fuel cell network there. In 2015, about 726 million USD has been accounted in investment and revenue in this field [40].

More new jobs are created resulting an increase labor income and local tax. The list from US includes New York, Colorado, Hawaii, Massachusetts, New Jersey and Ohio for hydrogen and fuel cell endeavors and business. As of 2019, FCVs exceed 6500 in USA. Fig. 2.2 shows the capacity of used fuel cells in USA.

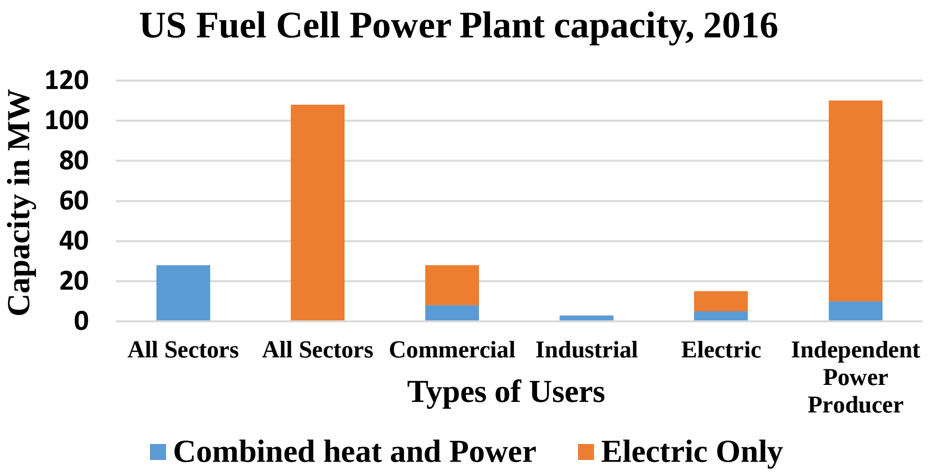


Fig. 2.2. Fuel cell usage in USA

Source: U.S. Energy Information Administration, Form EIA-860, Annual Electric Generator Report

France has announced its aim for the withdrawal of diesel and gasoline vehicles sell, by 2040, to gear up the Paris Climate Agreement [41]. The country decided to invest USD 100 million to achieve the goals in green energy and establish hydrogen energy sector. It also plans to become a leader in hydrogen production for the green transportation plans.

There are ten countries trying to move towards green hydrogen to replace the use of fossil fuels. The countries are Australia, Canada, China, France, Germany, Japan, Norway, South Korea, U.K. and U.S. Australia has already moved forward to green hydrogen economy and aims to establish 5 GW combined solar and wind power plant to produce solely green hydrogen and looks forward to export the hydrogen. Australia's primary focus is on Japan and South Korea as they are the major importers of fuels.

China is speeding up their motivation towards hydrogen economy. They aimed to increase the number of fuel cell vehicles up to million within 2030. By 2025 they would establish 100 hydrogen refueling station for 5000 FCVs. They have already exempted taxes for fuel cell vehicles and targeted to have 100 fuel cell and component manufacturers to support the future demands.

Japan is the global leader for hydrogen fuel cell vehicles. Efforts from Toyota and Honda are remarkable for developing the fuel cell vehicles and further development of this technology.

Being an important application of hydrogen, fuel cell vehicles pivot the demand of green hydrogen. Due to the fact that the country accounts the most liquid natural gas imports; to reduce this, they are trying to shift the need towards renewable hydrogen. They have set a global target for 10,000 hydrogen refueling stations within next ten years [42].

Norway has potential to produce hydrogen using hydro-power. They have already encountered an accident in hydrogen refueling station which is the first in the world. The country is using fuel cells to operate ferries which is a pioneering development [43].

Concerning the safety issues and accident of Norway, South Korea has set a goal for 850000 FCVs within 2030. It has planned to subsidize in the energy sector. About 1.8 billion USD is to be handed to FCV and refueling sector [44].

World's top offshore wind market is in United Kingdom (UK). Taking this advantage into account United Kingdom has planned to invest about 15 billion USD on 4 GW offshore wind power plant for renewable hydrogen production.

Developed and economically stable countries are very much interested for green hydrogen production and applications. It is mainly taken into account as an emission reduction strategy.

It is expected that by 2040, world's energy production and usage scenario would experience a change which will be led by green hydrogen as these countries are investing and creating scopes for renewable hydrogen technologies. Currently, the major demand for hydrogen is not for energy, however these endeavors and developments of applications are creating demands for hydrogen in energy sectors.

2.4 Demand Potential of Hydrogen in Asian Countries

There is no conventional study on demand and supply chain of Hydrogen in Asian region, however, the future demand is estimated using various resources and some studies done by regional organizations. These materials include the Economic Research Institute for ASEAN and East Asia's (ERIA) energy outlook, as well as the latest hydrogen utilization and technology trends, and other demand estimation documents [45].

The analysis identifies three major sectors for hydrogen utilization. These are mainly Electricity generation, Industry, and transport. Table 2.1 shows country-wise future demands. These countries are mainly in ASEAN and East Asian region.

The data is obtained using three scenarios. Percent mix of hydrogen into currently used fuels is categorized as scenarios. Categories are set to have 5%, 10% and 20% mix of hydrogen with fossil fuels. In these countries, electricity generation is mainly done by coal and natural gas. It has been expected that 20% of new coal-fired electricity generation will be converted into natural gas and H_2 mixed fuel fired generation [45]. This will be same for existing natural gas based electricity generation.

Table 2.1. Hydrogen demand potential by country in 2040 (in MTOE)

Country	Electricity	Industry	Transport	Total
China	29.00	10.80	16.80	56.60
India	44.50	4.00	11.10	59.60
Myanmar	0.60	0.20	0.90	1.70
Philippines	1.80	0.00	0.80	2.60
Indonesia	7.70	1.10	7.50	16.30
Malaysia	3.40	1.60	2.50	7.50
Singapore	0.60	0.20	0.00	0.80
Thailand	1.40	1.20	0.60	3.20
Viet Nam	6.40	0.80	1.70	8.90
Cambodia	0.20	0.00	0.20	0.40
Brunei Darussalam	0.20	0.00	0.00	0.20
Japan	12.00	1.80	3.20	17.00
Republic of Korea	9.20	1.30	1.10	11.60
New Zealand	0.20	0.10	0.30	0.60
Australia	4.20	1.00	1.90	7.10
Other than ASEAN	99.20	19.10	34.30	152.60
EAS Region Total	125.40	24.60	48.60	198.60

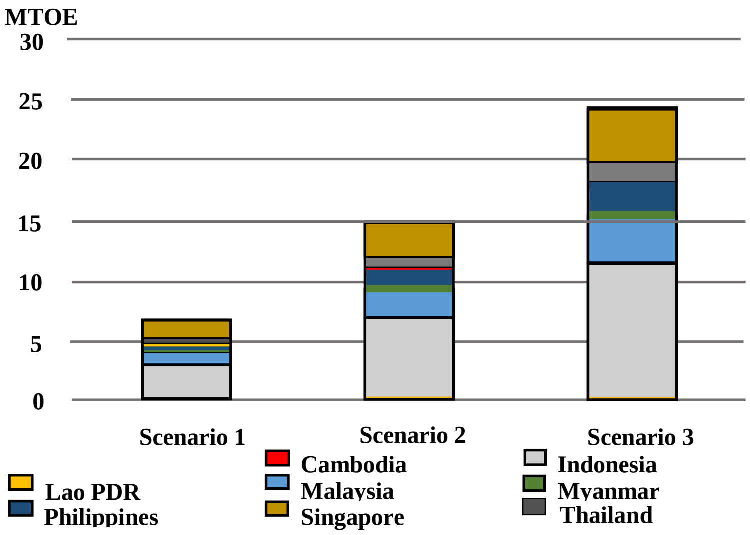


Fig. 2.3. Hydrogen demand potential in 2040, by ASEAN countries

Source: ERIA Research Project Report 201 2018, No. 01 (Report of Economic Research Institute for ASEAN and East Asia to the G20 Energy Transitions)

20% of natural gas consumption for industrial purposes will be replaced by natural gas and H_2 mixed fuel. Transports are mainly using gasoline and diesel. Passenger Fuel Cell Vehicle, Fuel Cell Bus and Fuel Cell Train will replace some portion of Gasoline and diesel demand by H_2.

The data of hydrogen demand for these countries are presented in Table 2.2 and Fig. 2.3. The countries like Myanmar, Cambodia are assessing for hydrogen demand. The similar analysis is unavailable for Bangladesh but the scenario clearly shows the future plans of regional countries toward Hydrogen economy. Bangladesh has to move towards it with other neighboring countries.

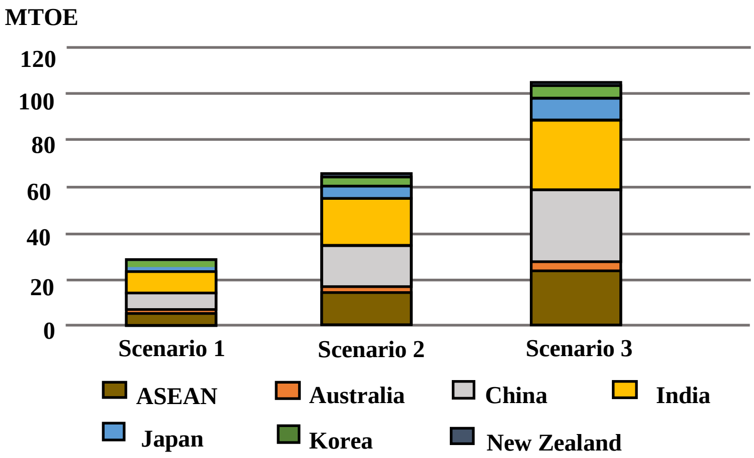


Fig. 2.4. Hydrogen demand potential in 2040, by East Asian countries

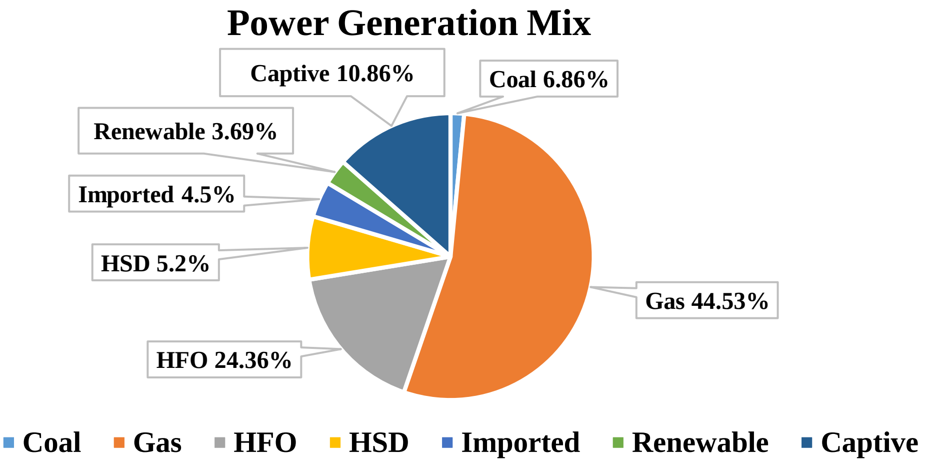
Source: ERIA Research Project Report 201 2018, No. 01 (A report from Economic Research Institute for ASEAN and East Asia to the G20 Energy Transitions Working Group (ETWG))

Table 2.2. Fuel replacement scenario in transport sector.

Fuel to be replaced	Type of Country	H2	Gasoline	Diesel	Scenario
Gasoline by Passenger FCV	OCED	2%	98%	0%	Case1
		10%	90%	0%	Case2
		20%	80%	0%	Case3
	Non OCED	1%	99%	0%	Case1
		5%	95%	0%	Case2
		10%	90%	0%	Case3
Diesel by Fuel Cell Bus	Japan	0.05%	99.50%	0%	Case1
		0.10%	99.90%	0%	Case2
		0.20%	99.80%	0%	Case3
	Other Countries	0.025%	99.975%	0%	Case1
		0.05%	99.95%	0%	Case2
		0.10%	99.90%	0%	Case3
Diesel by Fuel Cell Train	All type	5%	0%	95%	Case1
		10%	0%	90%	Case2
		20%	0%	80%	Case3

2.5 Sectors for Hydrogen Applications in Bangladesh

Like other East Asian countries, Bangladesh is also largely dependent on fossil fuels for her energy production. Starting from the electricity generation to industry, household, and transport sectors, the country is using Kerosene, Diesel, Petrol, Octane and Natural gas. Recently LPG and LNG are imported [46]. In rural areas people are largely dependent on biomass based energy. Study shows that, many countries in this region have potential to use hydrogen as a fuel-mix in future. The main sectors are power generation, transport, and industries. So, in future, there would be an impact on Bangladesh Energy sector also. Bangladesh mostly uses natural gas to produce electricity. It is about 44.53%. This natural resource is depleting quickly. Mixing hydrogen with natural gas can save up to 20% using currently available technologies. This sector is a major concern as most of this gas resource is provided for electricity generation. Hydrogen can be used in transport sector also. Fuel cell passenger vehicles and buses are performing well and have become a matured technology though development is also going on.



Total Power Generation Capacity = 16,288.03 MW (Including OFF-Grid RE)

Fig. 2.5. Bangladesh's electricity generation mix (SREDA, 2022)

Bangladesh has petroleum refinery sector which uses hydrogen in their production process. Eastern Refinery Limited is such a company. It collects light and heavy crude oils, refines and supplies fuel oils to marketing companies. This industry has an installation of Steam Methane Reforming (SMR)-Hydrogen production plant. The production capacity is 790 metric tonne/year. However, due to some technical reasons the plant is inoperative at present. Hydrogen is a crucial element for processing crude oils. Due to the unavailability of ready hydrogen, some categories of refinements are not being done here [46]. There are other 7 government refineries and 14 private refineries which are mainly fractionation plants. These plants do not use hydrogen in their refinement process.

Sulphur content of Bangladeshi fuel is comparatively high. Currently, the upper limit of Sulphur content in diesel used in Bangladesh is 2500ppm. This high Sulphur content is partly responsible for particulate matter which is a major pollutant from diesel-run vehicles. Around 3 million tonnes of diesel is needed annually in Bangladesh. Of them, 15% which is 0.45 million tonnes produced by Eastern Refinery Limited (ERL) per year and the rest 85% is imported from abroad.

The Sulphur in diesel, produced by the ERL, is around 5000ppm while it is 2000ppm in the imported diesel. Thus, when these two are blended the resultant blend has a Sulphur content of around 2500ppm.

In 2012, the World Health Organization declared that diesel pollutants are carcinogenic, which means that the particles could cause cancer. These pollutants can also reduce visibility by creating smog and may be responsible for acid rain. ERL has also proposed setting up a 1.4 million tonnes de-sulphurization unit which will be able to produce 350ppm Sulphur diesel.

2.6 Scopes in Bangladesh

In rural areas, mostly bio-mass is used for cooking and heating applications. Bio-mass creates smokes and it is the main reason for indoor air pollution. Women and female children in rural areas, who uses biomass in kitchen, are in high risk of chronic obstructive pulmonary disease (COPD) [47]. Improved cooking systems might reduce the health risks as well as would improve the environment. Bio-gas plants are playing an important role to reduce kitchen smokes and micro particles. However, bio gas contains 30% to 35% carbon-di-oxide in composition with Sulphur-di-oxide [48]. Hydrogen can be used to improve bio-gas by the help of hydrogenotrophic methanogens. This process can increase the methane percentage nearly 85-89% [49].

Fertilizer industries are using hydrogen gas to produce urea. They are using Steam methane reforming method to produce hydrogen. This process releases vast amount of carbon-di-oxide. Apart from this, hydrogen is used in food industry for hydrogenation of fat and oil, in chemical industry for methanol, hydro alkylation, hydrocracking, hydro-de-sulphurization, hydrochloric acid production, etc. In metal industries, hydrogen is used for reduction of metallic ore. In engineering workshops, hydrogen is used for welding. Each of the above mentioned industries are operating in Bangladesh and day by day the number is increasing. The requirement of hydrogen is also increasing in Bangladesh as rest of the world. So, there is scope of green hydrogen production for local market. As like other developed countries, transport and power generation sectors can also use hydrogen as a primary fuel mix to produce energy.

2.7 Summary

The major parts of a green hydrogen production system are renewable power source and electrolysis. Bangladesh is a solar boon country. Solar panels are readily available in local markets along with other system components like battery, charge controller, inverter etc. This technology is potential for renewable hydrogen production in Bangladesh. Government has subsidies on renewable energy projects and has user friendly policies. However, some important aspects of this particular establishment need to be addressed further. Hydrogen is a very useful element and a potential alternative source in energy sector.

Chapter 3

Practical Study of Water Electrolysis

3.1 Introduction

In search of clean fuel technology, researchers are working on a lot of materials. For the clean environment aspect, hydrogen comes first as a potential choice. This is because hydrogen can be produced very easily from water electrolysis. Hydrogen is a renewable element [50]. Burning hydrogen only emits water. So it is considered safe for environment. Usage of hydrogen requires safety concerns as this gas is highly explosive in a particular range of mixture with oxygen. Water electrolysis is very established method for hydrogen production. Industries are using this method for many years [51]. Advanced technologies have already been emerged for efficient production method.

The context of countries like Bangladesh is a point of interest of this research. Unhealthy cooking method of rural people is costing lives in under developed countries [52]. According to world health organization indoor air pollution causes millions of deaths. Women and children are directly affected [53]. Green hydrogen could be incorporated into household applications to improve lifestyle [54]. Using Solar photovoltaic panels to electrify the working system would add advantages for the off grid people. Locally developed electrolyzers and short term storage systems using local technologies and materials could be researched for such purposes.

3.2 Ideal Characteristics of Electrolysis

Water electrolysis is a simple electrochemical process. The characteristics of Water electrolysis are dependent on various parameters. These are so critical that alteration of any parameter will result in varied performance of the whole system. The molarity of the electrolytic solution, power source, distance between the electrodes and the size of the electrodes are selected as physical parameters [55]. Whereas, applied voltage, current density, resistivity and temperature are observed as indicating parameters. In this research, the physical parameters have been varied to collect the data on indicating parameters. Water electrolysis is an endothermic (heat is absorbed from the surroundings by the system) reaction. Electrical energy is used to split the water into hydrogen and oxygen molecules. Temperature plays an important role on water electrolysis. Pure water electrolysis is not thermodynamically favored as it is a good insulator [56]. In standard condition the reaction is as follows

Anode (oxidation):

$$2H_2O \rightarrow O_2(g) + 4H^+(aq) + 4e^-;\ E_O = +1.23\ V \qquad (3.1)$$

Cathode (reduction):

$$2H^+(aq) + 2e^- \rightarrow H_2(g);\ E_O = 0\ V \quad (3.2)$$

So the required cell voltage becomes

$$E_{Cell} = E_{Cathode} - E_{Anode} = 0\ V - 1.23\ V = -1.23\ V \quad (3.3)$$

(at 25 ^{0}C, pH 0 [H+=1.0 M]) According to the Nernst equation, the cell potential is same for 25 °C with pH 7.

$$[H^+] = 1.0\ X\ 10^{-7}\ M$$

Nernst equation is derived from the change of Gibbs free energy in standard condition.

The Nernst equation for half-cell is

$$E_{red} = E^0_{red} - \frac{RT}{ZF}\ln(Q) \quad (3.4)$$

The full cell equation is similar

$$E_{cell} = E^0_{cell} - \frac{RT}{ZF}\ln(Q_r) \quad (3.5)$$

Here, E_{red} is the half-cell reduction potential at the temperature of interest,
E^0_{red} is the standard half-cell reduction potential,
E^0_{cell} is the cell potential (electromotive force) at the temperature of interest,
E_{cell} is the standard cell potential,
R is the universal gas constant: R = 8.314472 $JK^{-1}mol^{-1}$,
T is the temperature in kelvin.

Gibbs free energy change, ΔG is a function of standard condition free energy change, ΔG^0 by the relation,

$$\Delta G = \Delta G^0 - RT\ \ln(Q) \quad (3.6)$$

Where, $\Delta G = -zFE => -\frac{\Delta G}{ZF}$; hence $E^0 = -\frac{\Delta G^0}{ZF}$

Which implies the Nernst equation. Here, F is the Faraday constant, the number of coulombs per mole of electrons: F = 9.64853399(24)×104 C mol^{-1}, z is the number of electrons transferred in the cell reaction or half-reaction, Q is the reaction quotient of the cell reaction. In practical cases separation of water elements does not simply starts at 1.23 volts. There are a number of handful issues and conditions which, in fact, have influences on electrolysis. Electrolysis starts at a certain voltage level dependent on system's intrinsic and extrinsic conditions [57]. The minimum energy required to start electrolysis is known as Gibbs free energy. The term free energy represents the available energy in a system. This is a very well-known term in thermodynamics. The required voltage to start the separation of hydrogen and oxygen is known as the reversible voltage. Hydrogen generation is not possible within the area between the zero level and reversible potential. Fig. 3.1 shows the operational and non-operational regions for electrolysis.

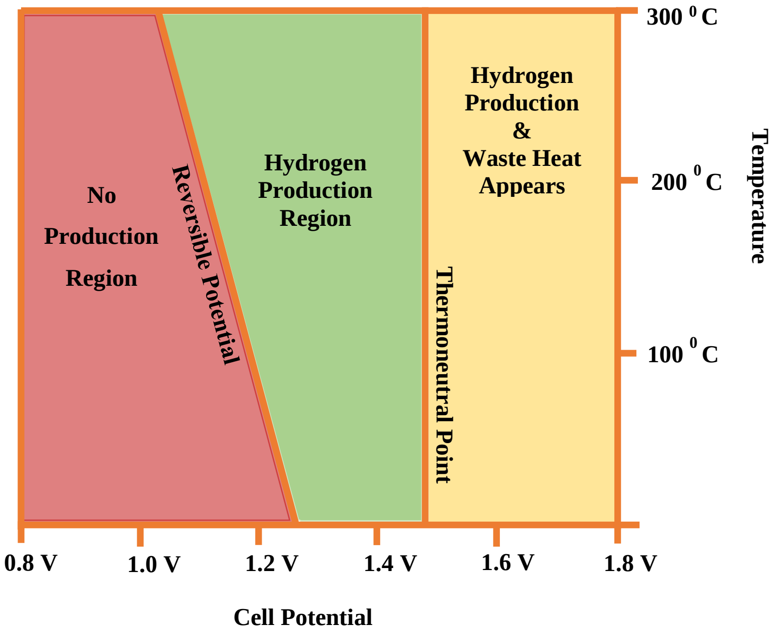


Fig. 3.1. Ideal characteristics of electrolysis

The overall cell voltage is comprised of reversible voltage, anode over-potential, cathode over-potential and inter electrode Ohmic drop [58]. The expression below shows the relationship of these active voltage components of cell voltage. Fig. 3.1 shows ideal conditions for general electrolysis.

$$V_{cell} = V_{rev} + V_{anode} + V_{cathode} + V_{Ohm} \tag{3.7}$$

The reaction enthalpy denotes the minimum energy required for the start of the reaction.

$$V_{Gibbs} = \text{work done} + \text{heat} \tag{3.8}$$

The efficiency of water electrolysis is largely dependent on the supply voltage. Over voltage produces extra heat which does not contribute to the generation of hydrogen gas. This over voltage results in waste of energy [59]. The most efficient voltage point for water electrolysis is known as thermo-neutral point. At which the electricity and heat both contribute to gas generation. Above this condition electricity is wasted as heat. The thermo-neutral voltage is around 1.48V. This voltage might be dependent on system characteristics [60].

Another issue relates the practical condition for electrolyzer is over-potential. This is a difference between the required voltage for half reaction in ideal condition and the voltage required for a practical setup [61]. This occurs both in anode and cathode. Including the resistivity of electrode material, there are other micro components of this deviation, from standard case. Like activation polarization over-voltage and concentration polarization over-voltage which can be seen under the over-potential requirement for electrolysis [62].

The reversible potential may have been altered by changing the system configuration like electrode gap, molarity, system temperature, types of electrode material, geometry of electrode etc. which have been investigated and observed in this research. Along with these, other characteristics and behavior of electrolysis with respect to different conditions have been studied.

3.3 Methodology

To observe performance determining key parameters, some variables are selected. Applied voltage, size of electrodes, and separation gap of electrodes and molarity of sodium hydroxide solutions are considered as variables. Current distribution or consumption by the electrolyzer and gas production rate are the measuring values to determine the key performance for a known setting. Stainless steel of 316L grade have been used to construct the electrodes of different sizes [63]. Standard sodium hydroxide (NaOH) solutions of different molarities were used. Applied voltage have been varied after 3 minutes for a particular setup, Change in current consumption, temperature and gas production was recorded after three minute interval.

Recorded data is tabulated and the performance parameters are compared for each condition. Some key results and tables are presented in this thesis with comments. Considering the use of solar panels or wind turbines as the source of power for the electrolyzer, the effect of voltage deviation has also been observed and discussed.

3.3.1 Testing Instrument and Setup

A dedicated test setup is developed to complete this task. The setup is mainly a glass jar having two compartments. Electrodes can be fixed with two connecting leads. The connecting leads are designed to vary the separation gap between attached electrodes. Two temperature sensors are inserted from the top of the jar. The jar is air tight from all the sides.

A separator frame is deployed at the center which can hold a membrane. The task of membrane is to separate the gases [64]. For smooth gas collection, two gas outlet channels are incorporated in the design. The design of the developed instrument is shown in Fig. 3.2.

3.4 Observation of Parameter Characteristics

Applied voltage is the primary variable against which current distribution and gas production have been observed. A standard variable voltage source was used to feed power to the system. Applied voltage was changed in a predetermined manner. The highest capacity of that voltage source is 18 V and 3.5 A. The other parameters are current distribution, electrode gap and electrode size.

3.4.1 Current Distribution

According to the recorded data it has been found that the increment of voltage results in linear increment of current in a certain molarities solution of NaOH. Size of electrode increases the current consumption.

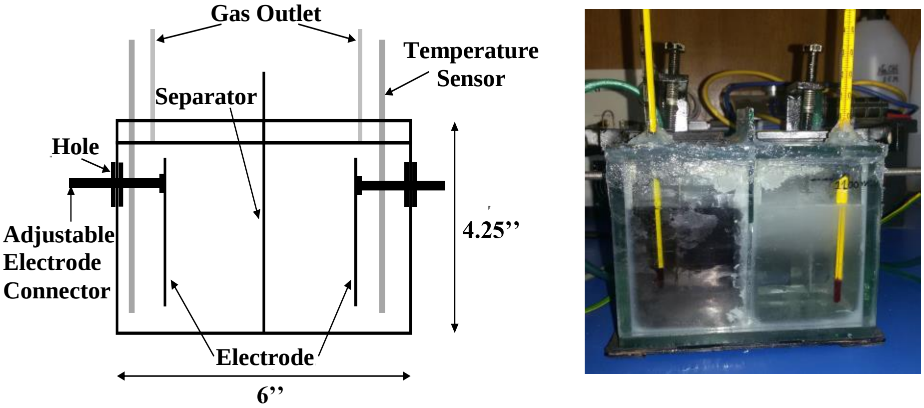


Fig. 3.2. Developed test electrolyzer

3.4.2 Gas Production Behavior

The more the system absorbs current the more gas will be produced. However, there is a limit for this linearity. To a certain voltage stress (or the current distribution) a particular system would use electrical energy to split the water. After that limit the extra energy would increase the temperature of the system and produces inefficiency.

3.4.3 Temperature Change

Temperature, during the reaction, does not change drastically. But there is a certain limit of applied voltage after which temperature gets increased [65]. At this point gas production rate falls down. This result agrees with the theoretical explanations. The temperature increment is proportional to the voltage increment. The testing apparatus was not insulated and hence, it becomes cool with the ambient.

3.4.4 Solution Characteristics

New solutions are the most productive. Because new solutions are free from impurities accumulated during reaction inside the test electrolyzer compartments. In this electrolyzer silicon based adhesive is used to attach the separator membrane. This adhesive is non reactant to NaOH solution once cured properly. However, some small particles of dried silicon might get free inside the compartments once dried. It gives a chance to get mixed with the solution. And each solution gives proper data up to four times of use, and after that it get weaker gradually. This is because of the impurities get mixed with the solution [66]. Most of the impurities are found dust particles, silicon compound, iron and other traces. The sources of iron are the connection lead and adjustable electrode connectors.

3.5 Effect of Molarity Change

Using different molarity NaOH solutions, the molarity effect is examined. During this test all other conditions remain same and several molarity solutions are used one after another. It finds the variation of the performance parameters like current distribution, gas production, etc. Here, other condition means the same electrode size and same separation gap between two electrodes.

3.5.1 Current Distribution on Molarity Change

During this test, current distribution is found decreasing with the decrease of solution molarity. Fig. 3.3 shows the difference between 1.5M and 1.0M which is not very wide. On the other hand, the difference between 0.5M and 0.25M solutions is greater. Table 3.1 present data of current consumptions due to molarity Change.

Table 3.1. Sample data of current on molarity change

Voltage	1.5M(amp)	1.0M (amp)	0.5M (amp)	0.25M (amp)
1.00	0.00	0.00	0.00	0.00
1.30	0.00	0.00		
1.50			0.03	
1.60	0.02	0.02		
1.70				0.03
1.90	0.07	0.07		
2.00			0.09	
2.20	0.29	0.35		
2.40				0.17
2.50	0.71	0.67	0.40	
2.70	1.09			
2.80		1.06		
3.00			0.78	
3.10	1.50	1.46		0.42
3.40	1.87	1.85		
3.50			1.19	
3.70	2.34			
3.80		2.38		0.67
4.00	2.74		1.53	
4.10		2.72		
4.30	3.16			
4.40		3.16		
4.50			1.94	0.90
5.00			2.37	
5.20				1.19
5.50			2.8	
5.90				1.47
6.00			3.16	
6.60				1.79
7.30				2.02
8.00				2.31
8.70				2.58
9.40				2.89
10.00				3.16

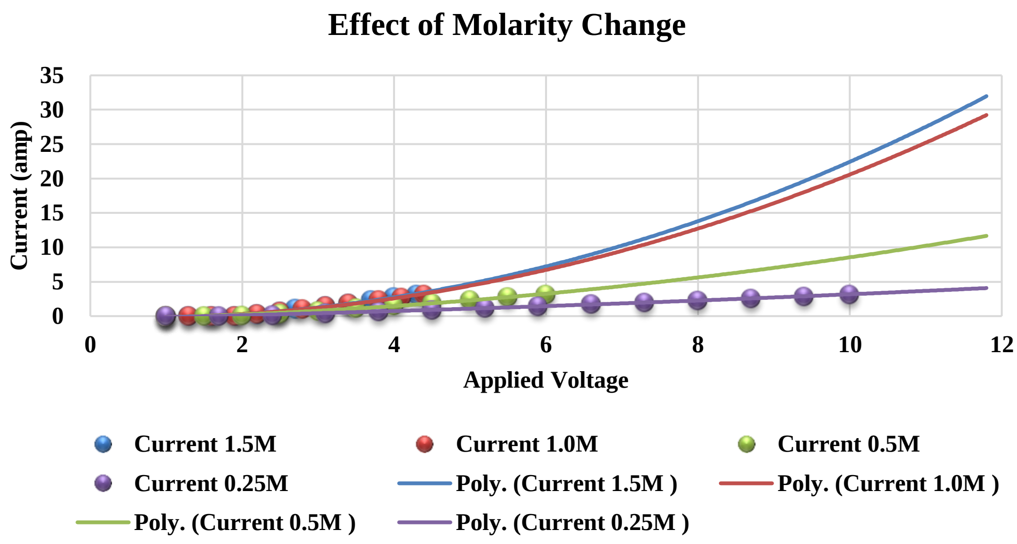


Fig. 3.3. Current distribution on molarity change

3.5.2 Gas Production on Molarity Change

According to recorded data the gas production rate increased with the increase in molarity. Fig. 3.4 shows that the gas production rate for 1.0M solution is higher than 1.5M. The reason is the aging effect of the solution [67]. 1.5M solution, used here, was older than the solution of 1.0M. The 1.5M solution was used for more than 4 times to test the same procedure. Table 3.2 presents Sample Data of gas production rate on molarity change.

Table 3.2. Sample data of gas production on molarity change

Voltage	1.5M (mL/min)	1.0M (mL/min)	0.5M (mL/min)	0.25M (mL/min)
1.00	0.00	0.00	0.00	0.00
1.30	0.00	0.00		
1.50			0.00	
1.60	0.00	0.00		
1.70				0.00
1.90	0.00	0.00		
2.00			0.00	
2.20	0.00	2.67		
2.40				0.00
2.50	0.00	5.67	1.67	
2.70	3.33			
2.80		15.00		
3.00			6.67	
3.10	10.00	20.00		1.67
3.40	15.00	28.33		
3.50			15.00	
3.70	23.33			
3.80		28.33		8.33
4.00	28.33		23.33	
4.10		43.33		
4.30	36.67			
4.40		46.67		
4.50			30.00	10.00
5.00			33.33	

5.20				16.67
5.50			80.00	
5.90				26.67
6.00			126.67	
6.60				23.33
7.30				33.33
8.00				33.33
8.70				46.67
9.40				40.00
10.00				56.67

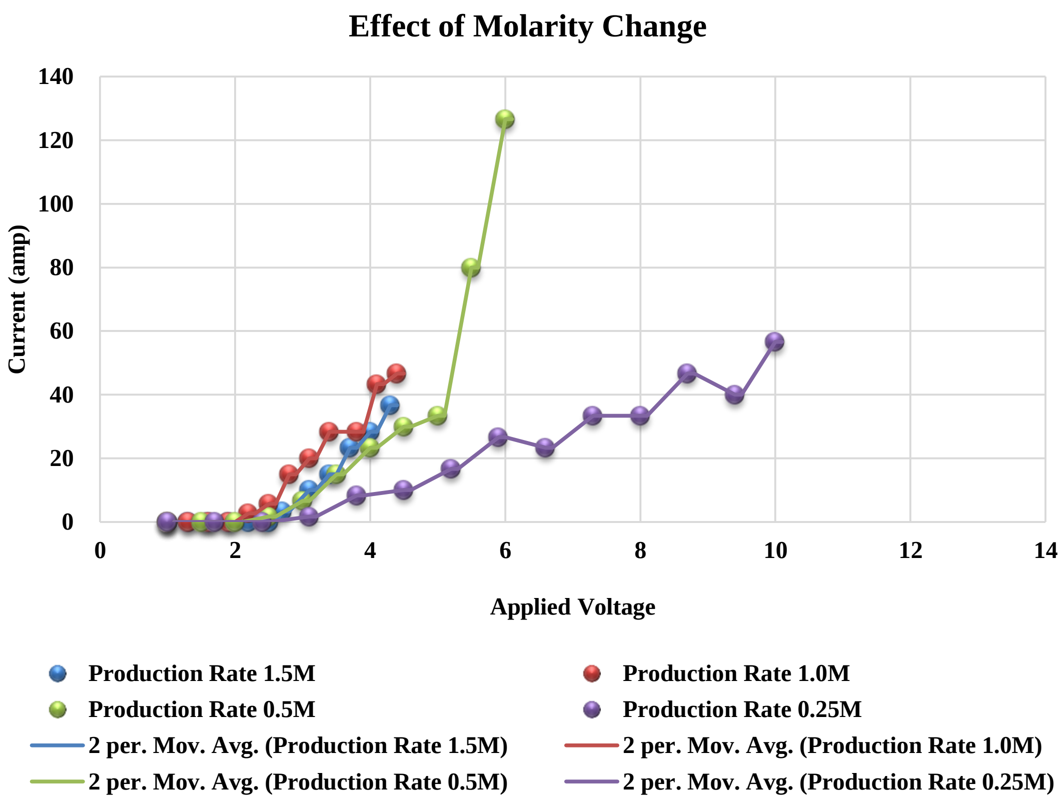


Fig. 3.4. Effect of molarity change on gas production

3.6 Change of Electrode Gap

To observe the change in performance due to the change in gaps between electrodes, this test has been performed. Electrode gap is decreased after each set of tests. The closest separation forms higher current distribution through the solution and electrode surface as shown in Fig. 3.5. It is notable that all other conditions should remain same. Table 3.3 contains the data of current change with electrode separation.

3.6.1 Current Distribution on Gap Change

Current distribution due to the changes in separation is found increasing with the decrement of gap. Fig. 3.5 shows that the current increases as the gap between electrodes are less, keeping the molarity fixed. Table 3.3 present sample data of current consumption due to the change in gap. After each set of tests and data collection, the full setup is opened and the gap between electrodes is changed.

Table 3.3. Sample data of current on gap change

Voltage	10cm(amp)	8cm(amp)	6cm(amp)	4cm(amp)
1.00	0.00	0.00	0.01	0.00
1.30	0.00	0.00	0.00	0.00
1.60	0.00	0.02	0.03	0.03
1.90	0.11	0.07	0.10	0.07
2.20	0.21	0.29	0.43	0.42
2.50	0.53	0.71	1.02	1.04
2.70		1.09		
2.80	0.95		1.53	1.78
3.10	1.32	1.50	2.18	2.43
3.40	1.71	1.87	2.64	3.16
3.60			3.17	
3.70	2.07	2.34		
4.00	2.44	2.74		
4.30	2.83	3.16		
4.50	3.08			
4.60	3.16			

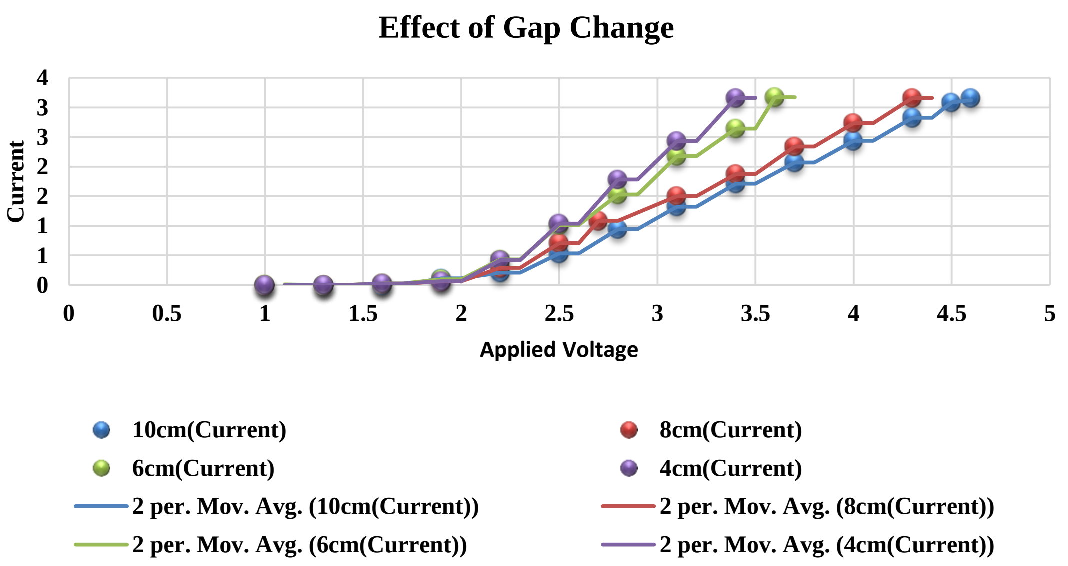


Fig. 3.5. Current distribution on gap change

3.6.2 Gas Production on Gap Change

Change of gas production rate depends with the change in electrode gap. Lower gap between electrodes results higher production rate as shown in Fig. 3.6. Observed data shows linear relationship between the results. Table 3.4 shows sample data of gas production due to gap change. During this test all other conditions remain fixed. Due to the change in gas the ions are subjected to travel a longer path to complete the reaction or the electrical circuit. Due to the longer distance, it requires the longer time to carry the electrons by the ions for the same applied voltage. Hence, the gas production rate gets reduced if the gap is increased between electrodes.

Table 3.4. Sample data of gas production on gap change

Voltage	10cm (mL/min)	8cm (mL/min)	6cm (mL/min)	4cm (mL/min)
1.00	0.00	0.00	0.00	0.00
1.30	0.00	0.00	0.00	0.00
1.60	0.00	0.00	0.00	0.00
1.90	0.00	0.00	0.00	0.00
2.20	0.00	0.00	0.67	1.67
2.50	1.67	0.00	8.67	11.67
2.70		3.33		
2.8	11.00		17.33	26.67
3.1	17.33	10.00	28.33	38.33
3.4	23.33	15.00	32.33	43.33
3.6			42.67	
3.7	26.67	23.33		
4	33.33	28.33		
4.3	36.67	36.67		
4.5	40.00			
4.6	43.33			

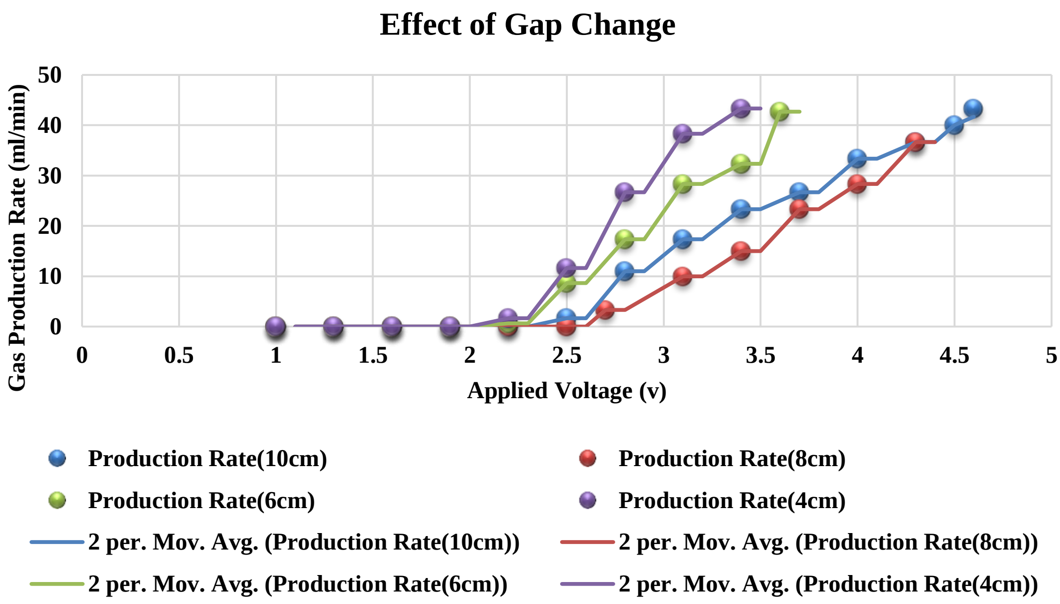


Fig. 3.6. Gas production on gap change

3.7 Size of Electrode

To examine the impact of the size of electrodes in electrolyzer performance, different sizes (Appendix A, Table-A2) of electrodes have been used. It is found that, the current consumption of electrolyzers varies with the size of its electrodes. It is because of the effective surface area of the electrode.

3.7.1 Current Characteristics on Size Change

It is observed that, the larger the size of electrode, higher the current consumption occurs. The change in current is shown in Fig. 3.7. Table 3.5 shows the sample data of current consumption due to electrode size change.

Table 3.5. Sample data of current on electrode size change

Voltage	Type1(amp)	Type3(amp)	Type5(amp)
1.00	0.00	0.00	0.00
1.70	0.02	0.01	0.03
2.40	0.17	0.23	0.31
3.10	0.48	0.61	0.80
3.80	0.83	1.05	1.27
4.50	1.16	1.49	1.76
5.30	1.50	1.91	2.28
6.00	1.90	2.40	2.77
6.50			3.16
6.70	2.27	2.88	
7.10		3.16	
7.40	2.615		
8.10	3.00		
8.30	3.16		

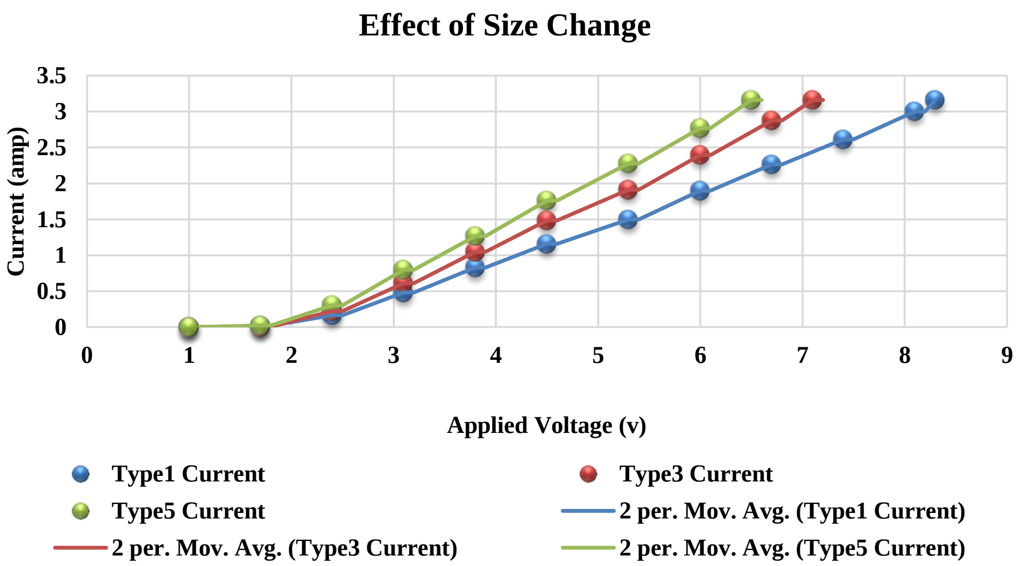


Fig. 3.7. Current distribution on electrode size change

3.7.2 Gas Production on Electrode Size Change

Gas production depends on the effective surface area of the electrode. It is found that the higher the surface area, the higher the production rate. After the completion of a set of tests, the pair of same sized electrodes are changed and new pair of electrodes are set to perform all the tests again.

Table 3.6. Sample data of gas production rate on electrode size change

Voltage	Type 1 (mL/min)	Type 3 (mL/min)	Type 5(mL/min)
1.00	0.00	0.00	0.00
1.70	0.00	0.00	0.00
2.40	0.00	0.00	1.67
3.10	3.33	3.33	1.67
3.80	10.00	13.33	16.67
4.50	16.67	16.67	23.33
5.30	20.00	30.00	20.00

6.00	26.67	33.33	40.00
6.50			33.33
6.70	30.00	36.67	
7.10		45.00	
7.40	33.33		
8.10	46.67		
8.30	46.67		

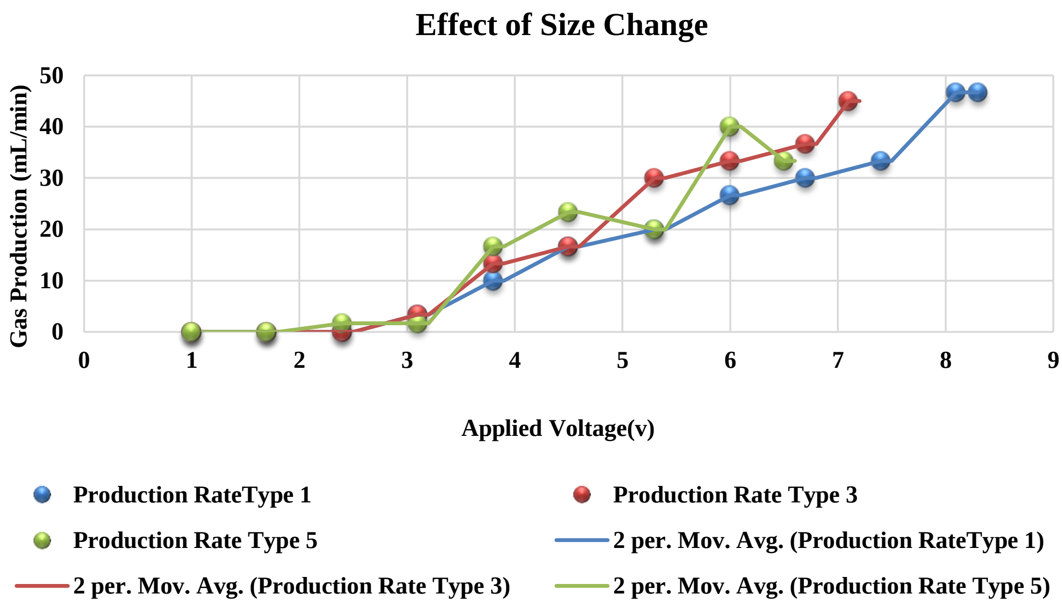


Fig. 3.8. Gas production on electrode size change

3.8 Voltage Swing Test for Solar and Wind Application Assessment

Voltage swing test comments on the systems behavior when the hydrogen generator is powered from solar panels or wind turbines [68]. Naturally the power output from solar panels and wind turbines varies with the weather conditions [69].

Table 3.7. Sample data of swing test

Applied Voltage (V)	Current (Amp)	Gas Production Rate (mL/min)
2.55	1.23	9.75
3.20	2.43	9.75
2.55	1.25	18.75
3.50	3.16	25.00
2.55	1.30	20.00

Sometimes the voltage level goes higher and sometimes it gets lowered with accordance to the solar radiation and wind speed. This happens mostly in rainy season, autumn and summer. So, the output of solar PV panels and wind turbines are very much dependent on weather conditions. The objective of this test is to observe data with a variable power source simulating the natural conditions. Table 3.7 shows sample data of voltage swing test. Here, the applied voltage, consumed current and gas production rate is presented with the respective units of measurement.

3.8.1 Current Characteristics

Voltage level has been increased and decreased step by step so that the change can be identified. It is observed that any sudden increase can boost up the current distribution along with the gas production. It remains at the same distribution at a specific voltage even after having a voltage swing, shown in Fig. 3.9.

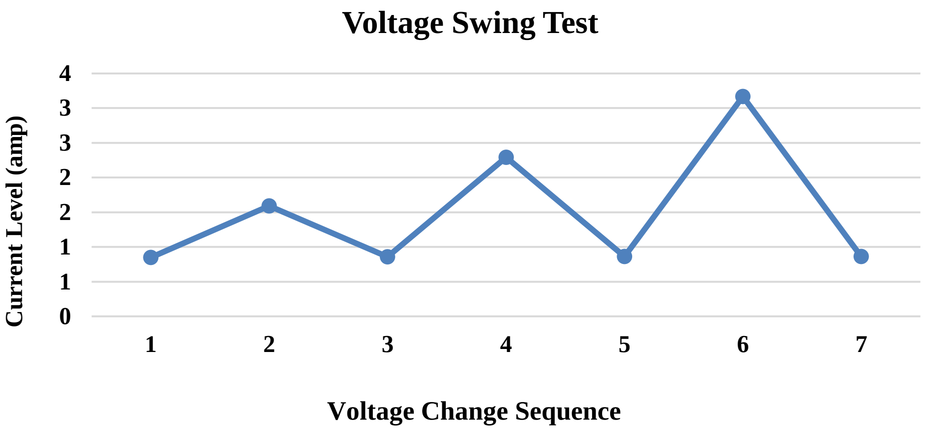


Fig. 3.9. Current distribution on voltage swing

3.8.2 Gas Production Characteristics

However, the production gets some increment which is diminished over a short period of time, shown in Fig. 3.10. This time can be described as the equalizing period of electron for a voltage overshoot.

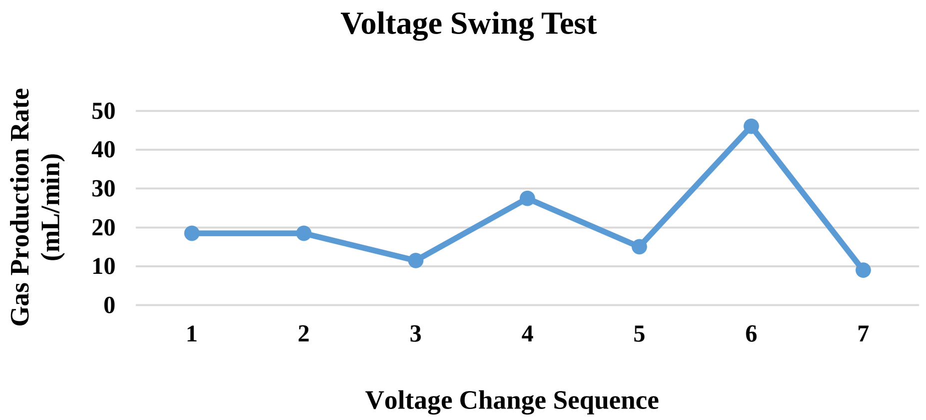


Fig. 3.10. Gas production on voltage swing

3.9 Summary

The overall test is carried out to find several dependencies and characteristics of electrolysis parameters. It is found that the higher molarity can boost the electrolysis speed and gas production. The electrode size can regulate the electrolysis. Less separation gap can accelerate the reaction and current distribution would be higher for closer electrodes. Importantly the scheme is aimed to have solar photovoltaic panels or wind turbines as its main power source. The fluctuation of voltage has no negative impact on the gas production during sodium hydroxide based water electrolysis.

Chapter 4

Development and Analysis of a Hydrogen Production System

4.1 Introduction

Electrolysis is one of the most popular methods for the generation of hydrogen. Advancement in methods has been immerged over time. Among all of these technologies, alkaline and polymer electrolytic membrane (PEM) based electrolyzers are mostly researched.

Alkaline electrolyzers are simple compared to PEM electrolyzers. Both technologies require a direct current source to operate. Mainly two categories of alkaline electrolyzers are available, unipolar and bipolar [70]. In unipolar alkaline electrolyzer, the electrodes are directly connected to power terminals. Anodes and cathodes are connected alternatively. The arrangement is set in a tank and electrodes are suspended one after another. Multiple cell operation can be facilitated in this arrangement by connecting each cell parallel.

Required operating voltage ranges between 1.95 Vdc to 2.5 Vdc. Unipolar electrolyzers are very simple and easy to repair. Any problematic cells can be disconnected without altering the whole system functionality [71]. Unipolar electrolyzers can operate at low temperatures and have a low current density which implies some drawbacks. Hence, the most recent unipolar electrolyzers can operate for high-pressure hydrogen output (6000 psig) [72].

The equations 4.1 and 4.2 represents anode and cathode reactions for Unipolar and Bipolar electrolyzers.

Anode reaction:

$$4OH^-(aq) \rightarrow O_2(g) + 2H_2O(l) \tag{4.1}$$

Cathode reaction:

$$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq) \tag{4.2}$$

In bipolar electrolyzers (often called filter pass), layers of electrodes are placed alternately. It uses a separation membrane or diaphragm [73]. Higher stack voltage is achievable by the series connection of cells [74]. As the cell layer is thin so bipolar electrolyzers are considerably smaller than the unipolar electrolyzers. High-pressure gas output and small size are advantageous for various applications. Bipolar electrolyzers cannot be repaired without disassembling the whole stack. However, servicing is rarely required [75].

In earlier times, asbestos is used as diaphragm but in recent days manufacturers are using polymer materials [76]. Technological advancement for alkaline water electrolysis achieved an efficiency range of 64% to 70% using KOH electrolyte [77]. Some commercial electrolyzer systems achieved 56% to 73% efficiency [78-79]. Advanced alkaline electrolyzers use an aqueous solution of KOH (25–30 wt%), but KOH is very corrosive. In recent days, diaphragms (or membranes) for alkaline electrolyzers are being developed as composite objects [80]. Ceramics or microporous materials are being used. Microporous polymer membranes, glass-reinforced poly-phenylene sulfide (PSS) compounds, or metal oxide composites are among them [81]. Less expensive metals (non-platinum-group metal) are used for electrodes. Porous nickel-based alloys are also used to increase electrode surface area [82].

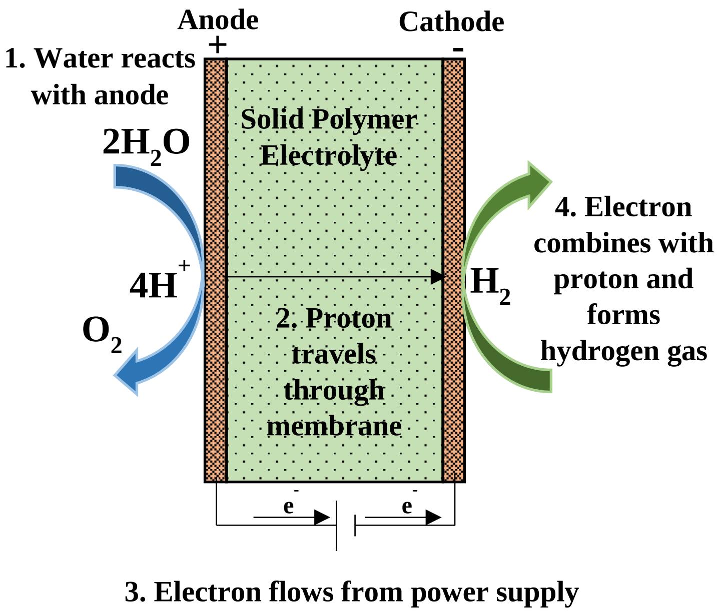


Fig. 4.1. PEM electrolyzer components and reactions

PEM electrolyzers are advanced and costly devices. The efficiency of PEM electrolyzers are higher and use electrodes made of expensive metals like platinum. Polymer membrane serves as both the gas separator and ion conductor [83]. Fig. 4.1 shows a PEM electrolyzer cell and reaction steps [84]. Anode and cathode reactions are given in equations 4.3 and 4.4, respectively. PEM electrolyzers require high purity de-ionized water (1 MΩ-cm) for longer stack life [85]. The most commonly used membrane is Nafion [86]. PEM electrolyzer also works in bipolar electrochemistry for multiple cell stack configuration [87].

Anode reaction:

$$2H_2O \rightarrow 4H^+ + 4e^- + O_2 \tag{4.3}$$

Cathode reaction:

$$4H^{+} + 4e^{-} \rightarrow 2H_2 \quad (4.4)$$

In PEM electrolyzers, oxygen is produced at anode side and hydrogen is produced at the cathode side. High pressure across the membrane can be achieved. The current density is greater [88] than 1600 mA/cm^{-2}.

In recent days, commercial PEM electrolyzers have efficiency [89] ranges from 51% to 83%.

PEM electrolyzers have many advantages over alkaline electrolyzers. Due to increased efficiency, the operating cost is lower. However, many other important factors limit the use of PEM electrolyzers [90]. Platinum and polymer electrolytic membranes are very costly materials. Lifetime is a critical issue of PEM cells. Sudden start-stop affects longevity [91]. PEM electrolyzers have components made of stainless steel. Metallic cations dissolved in water contaminates the membrane by the exchange of proton [92]. It reduces the proton conductivity. Catalyst loading improves the lifetime of the cell, but it increases the cost again [93].

Recent PEM electrolyzers are also having the same configuration as like as 30 years ago [94]. Thick Nafion 115 and 117, black platinum electrodes with a high load of catalysts, and thick graphite made bipolar plates [95].

Polymer electrolytic water electrolyzers (PEWE) have a variety of range of applications. Starting from 100 watts small laboratory scale to 6 MW input power capacity [96]. Low capacity (below 1 kg (H_2)/h) devices are available in the market for decades but not optimized in terms of material cost and the Levelized cost of hydrogen [97]. Short life is also a factor that causes the increased replacement cost of components. The largest PEWE installation is located in Mainz (Germany) which is a 'Power to Gas' plant. The input capacity is about 6 MW [98].

Applicability of PEWE in the energy sector requires more optimization of costs. Durability, materials, operating conditions and economics should be improved [99].

Hydrogen production projects in developing countries would require cost effective methods. Water electrolysis is the most convenient and easiest method for hydrogen production. Commercially available PEM electrolyzers are expensive [100]. A standard PEM electrolyzer costs about 53000 BDT excluding VAT and other charges [101]. Short term storage methods are also very important for the proper use of hydrogen gas along with safety devices [102].

The prospect of green hydrogen production using RE sources is reported to be an effective method of producing alternative fuel. Hence, for Bangladesh, this research aims to develop a green hydrogen production system using indigenous materials and local technology that can be run by using renewable energy (RE) sources. A very common electrolyte, sodium hydroxide (NaOH) is used for electrolysis.

Electricity that is used to produce hydrogen via electrolysis is considered as the storage of that electricity [103]. Now days, hydrogen is considered as a renewable energy storage [104]. Excess electricity is used to produce hydrogen to store energy. Later on, it is used to produce electricity by using fuel cells on a requirement basis. Fuel cell-based power plants are already in existent [105]. The potential of hydrogen, as clean energy, has been assessed and considered very promising [106]. Apart from this, hydrogen is experimented for the use in Biogas up-gradation through methanisation process [107]. Results show that the methane content of biogas can be increased up to 96% by converting carbon dioxide inbounds in reactor [108-110]. In this research, an electrolyzer is developed using locally available materials. Beside this, the performance of the developed system is tested and presented.

4.2 Schematic Diagram of the Developed System

The hydrogen generation system, developed in this research, consists of several parts as shown in Fig. 4.2. Solar photovoltaic and wind energy have been used here as the source of renewable energy.

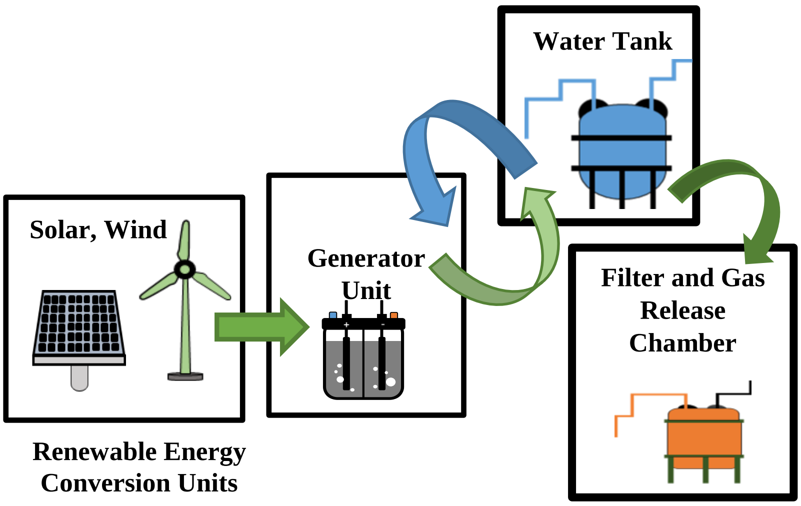


Fig. 4.2. Block diagram of the composite system

The hydrogen generator is built to operate on the NaOH solution. The generator unit which is an alkaline electrolyzer is the central component of the system. Electrolyte mixed water is filled in water tanks that hold the solution and work as primary gas collectors. There are two types of primary gas collectors. As this generator splits water and delivers two gases separately, it requires two different primary gas holders, one for oxygen and another for hydrogen.

The produced hydrogen is collected from one of the primary gas collectors and channeled into a filter. The filter itself works as the gas release chamber. Finally, hydrogen is collected from the gas release outlet. The block diagram shown in Fig. 4.2 presents a high-level description of the overall system components. Detail descriptions are given in the following sections.

4.2.1 Electrolyzer Components

Water is split inside the electrolyzer unit using electricity. The components of the electrolyzer are electrodes, gas channel separators, membranes, inlets, and outlet ports, frame, nut-bolts etc.

4.2.2 Electrode

Two types of electrodes are developed and used to build the electrolyzer. There are total 9 electrodes. Three of them having a connection lead for electrical power input. Other plates or electrodes do not have any lead. Fig. 4.3 shows the electrodes. Electrodes are made of stainless steel. The grade of steel is 316L. The thickness of each plate is 1mm. Fig. 4.3 shows the dimension of each plate. There are three holes on each plate. Upper two are designated for different gas passage and the bottom one is for solution movement.

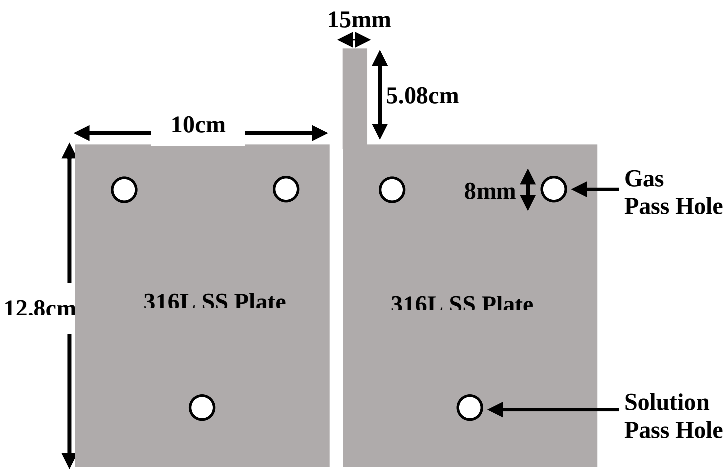


Fig. 4.3. Electrode plates

4.2.3 Gas Channel Separator

Gas channel separator is a unique and new technique for water electrolyzers. In common electrolyzers, separate delivery of hydrogen and oxygen is not facilitated. The developed electrolyzer has an assembly of electrode separator and membrane that keeps continuous separation of hydrogen and oxygen from the very beginning of bubble formation. Fig. 4.4 shows the separator with a specific dimension used for this development.

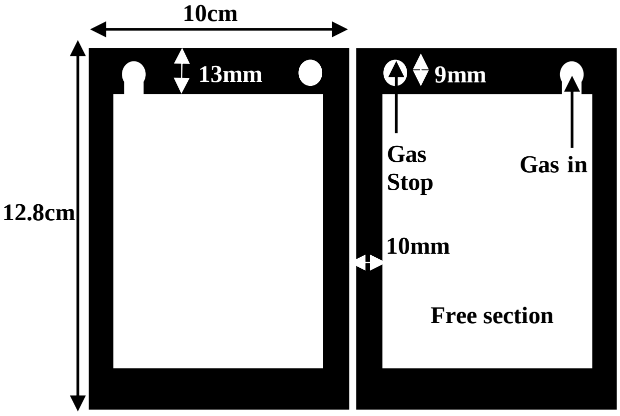


Fig. 4.4. Gas channel separator

On the body, each separator has two distinct holes. One is open vertically so that the gas can move up to the passage denoted as gas in and another hole is used to block gas from the same compartment, marked as the gas stop in Fig. 4.4. The second hole is not opened from any side so that it can restrict any gas passage. The thickness of the separator is about 2 mm.

The function of the gas channel separator is to separate the electrodes from each other thus making a compartment of about 45.72 cm^3 (height 12.7 cm, width 9 cm, thickness 0.4 cm).

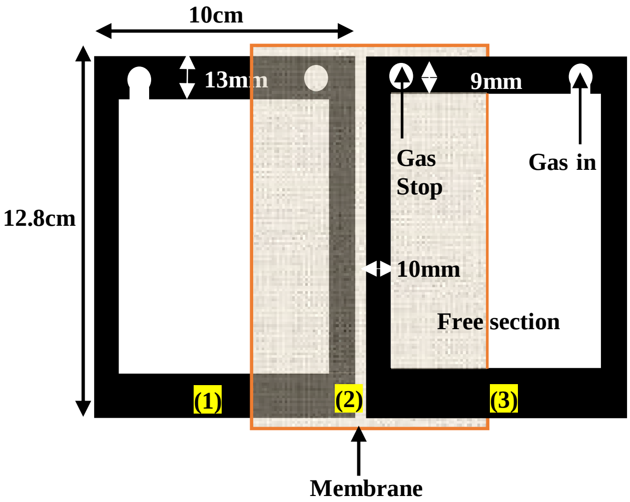


Fig. 4.5. Separator membrane assembly

4.2.4 Separator Membrane Assembly (SMA)

The most important part of this electrolyzer is the electrode separator membrane assembly. The separator membrane assembly (SMA) is placed one after another [111]. The right side separator is in a vertically flipped position from the left side. In between them, the membrane is placed. Fig. 4.5 shows the separator membrane assembly. The membrane is a nylon 120 plain sheet. The membrane allows the electrolyte solution to pass through all the compartments but it restricts any gas bubbles to pass through. This generator is a nine plate module. A total of eight SMAs are used for the configuration. One SMA is placed between two electrodes.

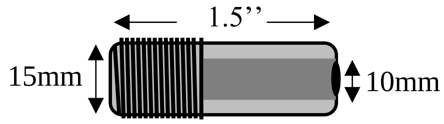


Fig. 4.6. Inlet and outlet ports

This can be compared with the electrode membrane assembly of commercial polymer electrolytic membrane (PEM) electrolyzers.

4.2.5 Inlet and Outlet Ports

There are three inlet and outlet ports on this device as shown in Fig. 4.6. The ports can serve as inlet and outlet at the same time. But the hydrogen outlet and oxygen outlet are deployed separately. All the ports are same in size and design. These are made of PVC fiber having a 10mm channel centered to its body. These are placed in such a way that the holes on the outermost electrode plates can access the port channel.

4.2.6 Frame

Two PVC sheets have been used to frame the device. About 0.9 cm thick sheet is used to construct the frame. The function of the frame is to hold all electrode plates along with separator and membrane. There are drilled holes on both frames periphery as shown in Fig. 4.7. Bolts and nuts are used with metal washers to adjust and match the requirements of the design. This arrangement prevents any leakage. On the front sheet, two holes are made for hydrogen and oxygen passage. The back sheet has one hole for purging electrolyte solution.

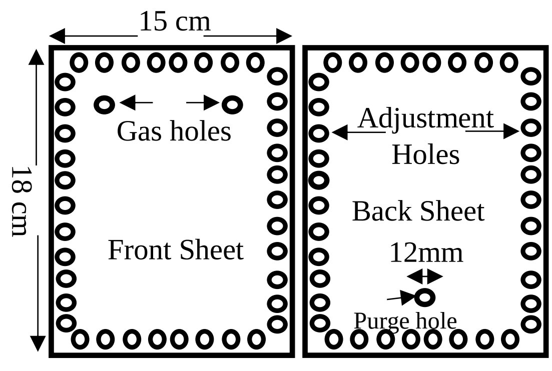


Fig. 4.7. Frame

4.2.7 Solution Tank: Oxygen and Hydrogen Chamber

Two identical 750 mL jars are used as solution tanks for laboratory setup. Two different gases are accumulated into two different chambers. The tanks hold and pour the liquid into the electrolyzer through the drain port, as shown in Fig. 4.8.

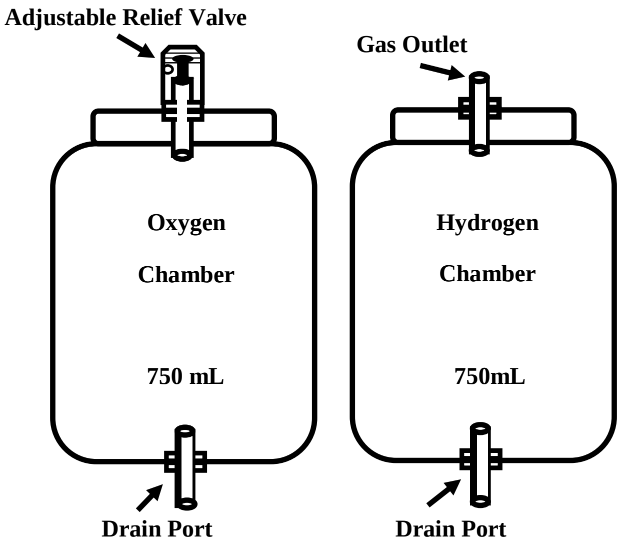


Fig. 4.8. Oxygen and hydrogen chamber

Gases are produced within different compartments of the electrolyzer and travel through the drain port in the form of bubbles to the gas chambers. In the oxygen chamber, one adjustable pressure relief valve is used. The adjustment is slightly higher than the working pressure. The system collects only hydrogen gas and releases oxygen into ambient after a certain pressure is built in the oxygen chamber. Hydrogen is directly collected from the upper portion of the hydrogen chamber, shown as accumulation space in Fig. 4.9.

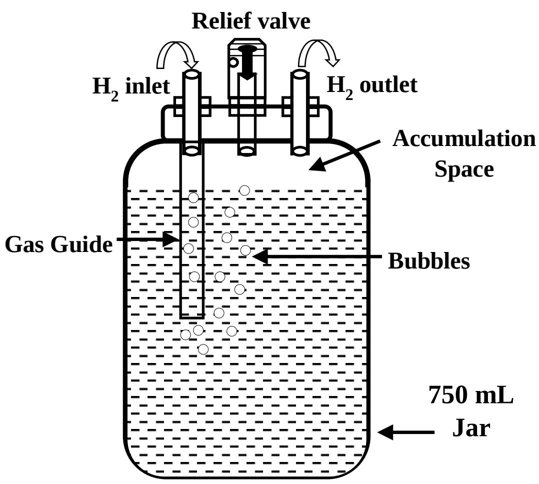


Fig. 4.9. Gas release chamber

4.2.8 Filter and Release Chamber

Hydrogen from the primary gas chamber is transferred to the filter. The filter is about 95% filled with clean water. The gas inlet of the filter is attached with a guide pipe submerged into the water. Hydrogen gas travels into the water and forms bubbles before accumulation on the top of the filter/ release chamber (Fig. 4.9). This filter provides safety for operation. If the gas is directly used for burning, flashback may occur. There are a handful of reasons for flashbacks occurring in a pipeline [112].

This arrangement restricts flash from traveling back to the electrolyzer. One pressure relief valve is attached to it as an extra safety measure. Raw hydrogen is cleaned by the water and release as a final output.

4.3 Electrochemical Operation

The developed electrolyzer is a single package having two sets of same cell stacks connected in parallel. The voltage requirement thus remains lower for double output. Current consumption is higher for such a combination.

4.3.1 Electrode Types and Bipolar Electrochemistry

In this arrangement, there are two categories of electrodes according to their functionality. The first category is the drive electrode [113] shown in Fig. 4.10. In Fig. 4.11 it is shown that there are 3 electrodes which are having direct connection to the power source (+/- sign marked). Drive electrodes have a direct connection to the power terminal either positive or negative terminal biased [114]. Here, the device has 2 negative and 1 positive drive electrodes. The other type is floating electrode [115]. Floating means that these electrodes are not having any physical connection to the power source [116]. It is only submerged into the electrolyte. These floating electrodes experience an interfacial potential difference along with the electrolyte solution. The electrode becomes equipotential conductor [117]. This phenomenon is called bipolar electrochemistry. In electrolytic solution, polarization happens to any conducting material in an electric field [118]. This polarization creates a potential difference between the material surfaces. The potential is equal to the electric field multiplied by the size of the object.

$$P = \frac{E_a - E_c}{d} \tag{4.5}$$

$$g^{+} = P(S_1 - S_0) \tag{4.6}$$

$$g^{-} = P(S_2 - S_0) \tag{4.7}$$

In equation 4.5, P denotes the electric field value, E_a and E_c stands for anode and cathode potential of the source or drive electrode. Where d is the distance between two electrodes [119].

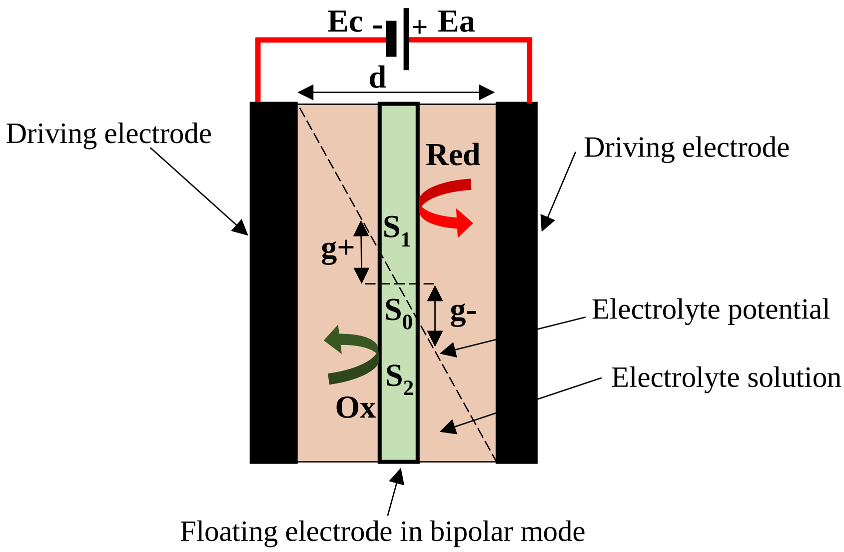


Fig. 4.10. Bipolar electrochemistry

In equation 4.6, g^+ is the potential driven by the anode, S_1 is the potential point, distant from S_0, the center of the object. Similarly in equation 4.7, g^- is the potential induced by cathode at S_2 point, distant from S_0. Here, S_0 is the center of the object [120].

The potential difference depends on the position of the electrodes [121] in the electric field created by the drive electrodes. When this potential difference becomes equal to electrolysis voltage [122] then reduction and oxidation reactions start at the surfaces. If the oxidation reaction occurs at one side, the reduction is coupled simultaneously at the other surface [123-124].

In this device, each electrode is positioned having an equal separation from each other hence each electrode has equal potential difference across them. Here, 10.6 volts are applied so each pair gets 2.65 volt which is sufficient for electrolysis [125].

In this developed electrolyzer, there are 8 compartments where a positive surface and a negative surface are formed face to face. Each compartments are divided by a membrane. The negative surface (cathode) attracts positive ions (cations) (H^+). Here, cations (H^+) receive electrons (e^-) and form H_2 gas. Here, the reduction reaction is shown in (eq. 4.8).

The reaction in Cathode:

$$2\,H^+(aq) + 2e^- \rightarrow H_2 \qquad (4.8)$$

On the other hand, in the positive surface (anode) oxidation reaction occurs. Oxygen gas is produced by splitting the water molecules by collecting electrons to complete the circuit (eq. 4.9)

The reaction in Anode:

$$2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^- \qquad (4.9)$$

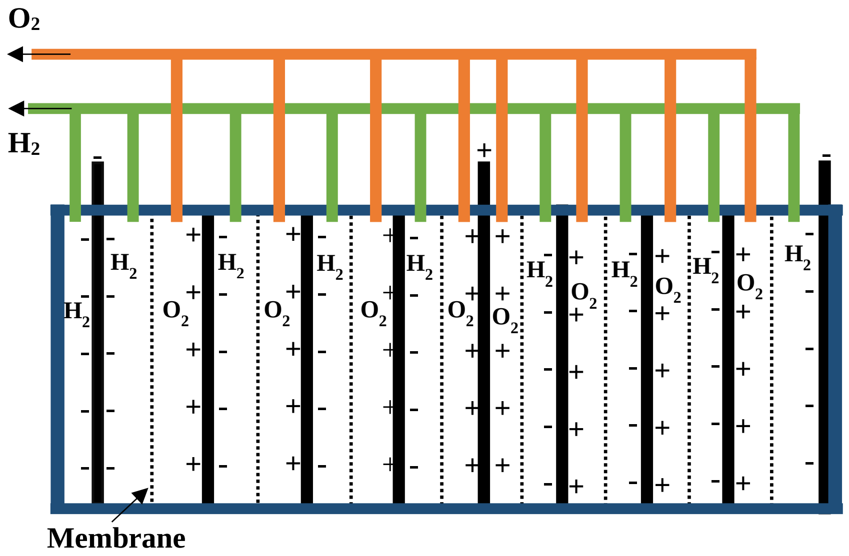


Fig. 4.11. Internal operating condition

The production of hydrogen and oxygen occurs at two distinct surfaces separated by a membrane, and thus, forms two different gas columns in the same compartment. Bubbles cannot pass through the membrane thus stays separated. All hydrogen columns and all oxygen columns are connected separately through SMA which forms separate hydrogen and oxygen channel. This arrangement enables the feature of pure hydrogen production.

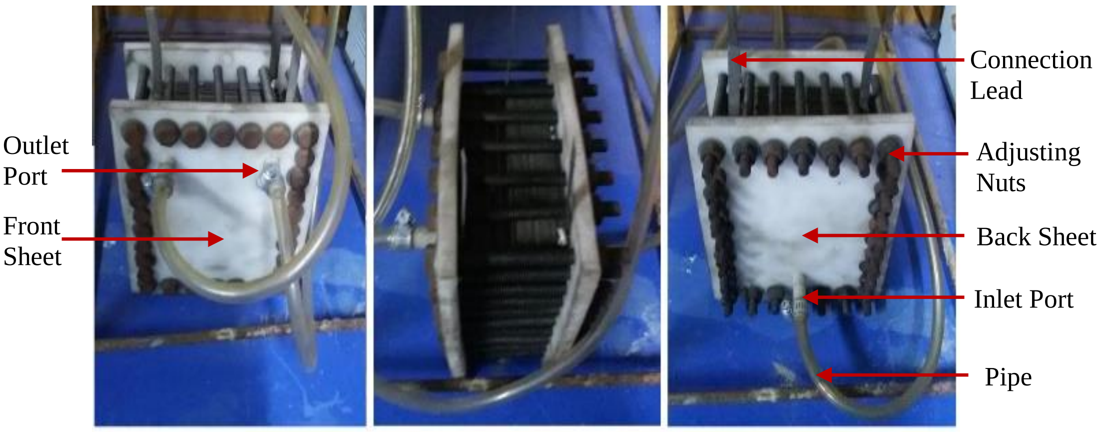


Fig. 4.12. Developed electrolyzer

4.4 The Complete System

The complete hydrogen production system shown in Fig. 4.13 is comprised of an electrolyzer (Fig. 4.12), a solution tank, and a gas release chamber. Tanks are placed above the electrolyzer. All components are connected by using poly pipes PE 100. The chance of hydrogen leakage by poly pipe is negligible other than metal piping unless physical damage occurs [126].

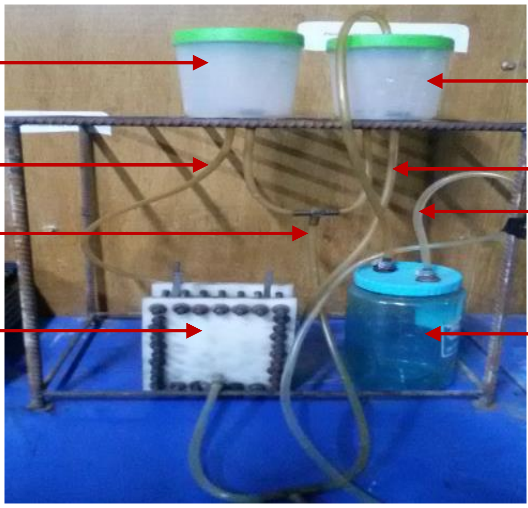


Fig. 4.13. Overall system for laboratory test

In the laboratory, a switched-mode power supply (SMPS) is used to operate the system and data collection. Produced gas is collected in jar and volume is measured with time intervals. Table 4.1 shows the actual development cost of the electrolyzer.

Table 4.1. Actual cost of locally available materials for 1 unit electrolyzer

Item Name	Price in BDT	Units
Steel Plate	400	9 plates
Nut and Bolts	200	38 pcs
PVC Sheet	250	4 mm Sheet
Diaphragm	50	5 Gauge Nylon Sheet
Gasket	150	1.5 mm 40 sq feet
Washer	100	50 pcs
Nozzle	150	3 pcs
Pipes	100	20 feet
Ring	100	6 pcs
Jars	300	3 pcs
Ports	200	3 pcs
Workmanship	500	Plate sizing
Total	2500	

4.5 Performance Study of the Developed System

The developed system is studied for six months. Gas production performance is tested for several molarity solutions. Solid sodium hydroxide pellets [127] are used to prepare a solution. A laboratory-standard scale is used to weigh the pellets. De-mineralized water [128] is used to make the solution. Laboratory standard de-mineralized water is collected from scientific stores. 5-liter solutions are made for each molarity by adding the required amount of NaOH pellets. Data are presented in Table 4.2, 4.3, 4.4, 4.5 and 4.6.

Table 4.2. Sample data for 1.5 M NaOH solution

Voltage (volts)	Current (amp)	Wattage (watt)	Production (mL)	Production rate (mL/min)
10.24	10.66	109.16	0	0.00
10.27	10.65	109.38	500	500.00
10.25	10.64	109.06	125	125.00
10.26	10.63	109.06	125	41.67
10.24	10.63	108.85	125	41.67
10.25	10.62	108.86	375	125.00
10.26	10.62	108.96	375	125.00
10.27	10.61	108.96	375	125.00
10.22	10.61	108.43	250	83.33
10.23	10.6	108.44	250	83.33
10.22	10.6	108.33	500	166.67
10.13	10.6	107.38	375	125.00
10.15	10.6	107.59	375	125.00
10.15	10.6	107.59	500	166.67

The performance of the system and device is evaluated based on the practically gathered data sets. Electricity consumption is also measured and presented here. The quality of produced gas is tested using a standard gas analyzer.

Gas is produced up to 5000 mL and each data element is recorded after three minutes of interval. For a 1.5 M solution, the electrolyzer's electricity consumption rate is about 108.58 watt on an average, where voltage and current are respectively 10.22 volts and 10.62 amps (Table 4.2).

The data collection period is about 35 minutes. A total of 4250 mL hydrogen is produced within this time. This implies the overall production rate about 121 mL/minute. The three minutes' average is found to be 141 mL/minute.

Table 4.3. Sample data for 1.0 M NaOH solution

Voltage (volts)	Current (amp)	Wattage (watt)	Production (mL)	Production rate (mL/min)
12.15	10.67	129.60	0.000	0.00
12.14	10.66	129.40	480.00	160.00
12.05	10.65	128.30	395.00	131.67
12.06	10.64	128.30	500.00	166.67
12.02	10.63	127.80	475.00	158.33
11.97	10.62	127.10	400.00	133.33
11.95	10.62	126.90	500.00	166.67
11.93	10.62	126.70	750.00	250.00
11.88	10.62	126.20	500.00	166.67
11.85	10.61	125.70	750.00	250.00
11.81	10.61	125.30	250.00	83.33

Table 4.3 presents similar data for 1.0 M solution. Data is taken for 28 minutes for this solution. 5 L gas is produced within this period, which results in a production rate of about 178.57 mL/min. Three minutes' average rate to be 166.67 mL/min. In this run, the electricity consumption rate is found to be 127.43 watts.

Table 4.4 shows data for 0.5 M solution. About 22 minutes were required for 5 L gas production that indicates a higher production rate for this solution.

Table 4.4. Sample data for 0.5 M NaOH solution

Voltage (volts)	Current (amp)	Wattage (watt)	Production (mL)	Production rate (mL/min)
11.31	10.63	120.23	0.00	0.00
11.28	10.63	119.91	875.00	291.67
11.28	10.62	119.79	1125.00	375.00
11.24	10.62	119.37	750.00	250.00
11.23	10.62	119.26	550.00	183.33
11.20	10.62	118.94	450.00	150.00
11.18	10.62	118.73	500.00	166.67
11.16	10.62	118.52	625.00	208.33
11.16	10.62	118.52	125.00	125.00

The electrolyzer consumes electricity at the rate of 119.28 watts and the production rate is about 227.27 mL/min. Three minutes' average rate to be 194.44 mL/min. All measurements are taken in natural ambient condition (around 28^0c and 1 ATM pressure). The STP volume of the produced gas is about 206 mL/min [Appendix-F, Table 1 and 2].

Table 4.5. Sample data for 0.25 M NaOH solution

Voltage (volts)	Current (amp)	Wattage (watt)	Production (mL)	Production rate (mL/min)
13.07	10.67	139.50	0.00	0.00
13.16	10.65	140.20	460.00	153.33
13.14	10.64	139.80	575.00	191.67
13.08	10.63	139.00	625.00	208.33
13.04	10.62	138.50	500.00	166.67
13.00	10.62	138.10	450.00	150.00
12.95	10.61	137.40	400.00	133.33
12.92	10.60	137.00	525.00	175.00
12.88	10.60	136.50	375.00	125.00
12.84	10.60	136.10	500.00	166.67
12.80	10.60	135.70	500.00	250.00

Table 4.5 shows data for a 0.25 M solution. About 29 minutes have been required for 4910 mL gas production. The power consumption average is found to be 137.95 watts and the production rate is about 172.41 mL/min. Three minutes' average rate to be 156.36 mL/min. Table 4.6 shows the calculated values that are used to find the operational efficiency of the electrolyzer. The lower heating value of 1 gram hydrogen is about 120 kJ [129]. The hourly flow rate is 12.36 liter/hour in STP condition which gives about 1.104 grams of H_2 per hour. The STP condition flow rate of the developed electrolyzer is about 0.0123 Nm^3/h [Appendix F, Table 3 and 4].

Table 4.6. Calculated values for operational efficiency

Molarity	Electricity consumption in Jules	Gas production in Jules	Efficiency in %
1.50M	228165.00	41363.00	18.13
1.00M	214093.00	48543.48	22.67
0.50M	157461.33	48222.00	30.62
0.25M	240040.91	48543.48	20.22

In STP, One liter of hydrogen gas weighs about 0.0893 grams. These values are used to calculate the calorific value of produced hydrogen over the operation time period. The highest efficiency is found to be 30.62% for 0.5 M solution and the lowest efficiency is found for 1.5 M solution. A higher molarity solution can reduce operational efficiency. The gas passage is an important factor for the higher gas production rate. 1.0 M and 0.5 M solutions are moderate for longer operation.

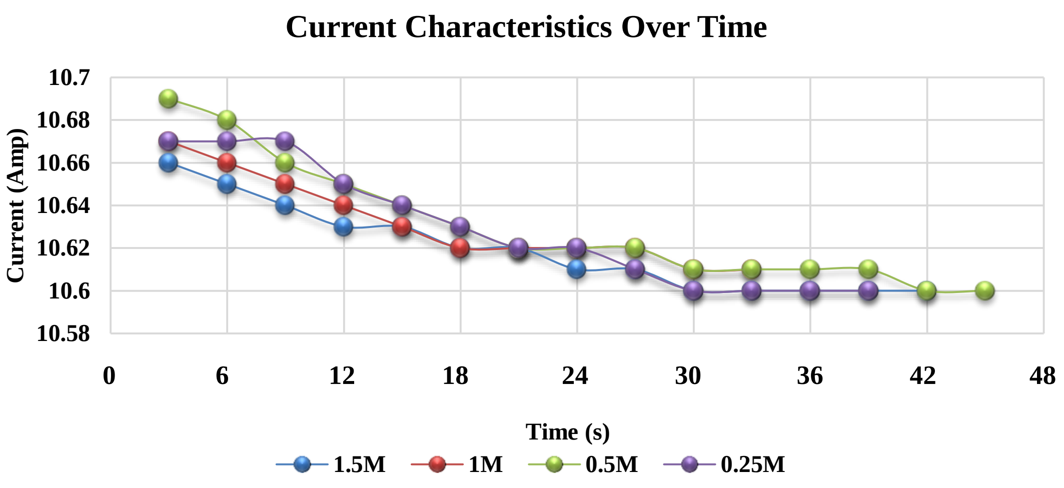


Fig. 4.14. Current characteristics

During the electrolyzer operation, it is observed that, with the increase of operational time, the current consumption is decreased for all molarities solutions shown in Fig. 4.14. This happens due to the formation of bubble cloud, near the electrode surface [130]. Bubble cloud or stand-in gas-bubbles may occur if the gas release rate is lower than the production rate. This implies an increase in internal resistivity [131]. The gas production characteristics for different molarity solution are shown in Fig. 4.15. The data is graphed according to the data collection sequence that is named as time sequence where bars in the graph show cumulative production values found in an instant.

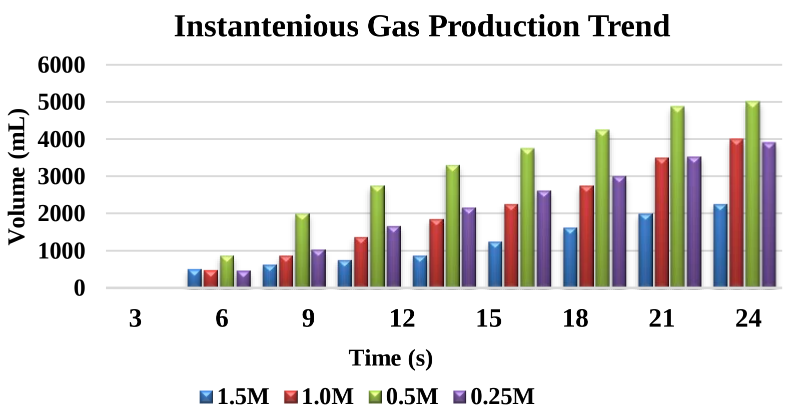


Fig. 4.15. Instantaneous gas production trend

The quality of produced gas is measured by using a standard (ATEX Certified, Model: GEOTEC-5000) gas analyzer [132]. It is found that about 92.5%

pure hydrogen is produced by the electrolyzer. Here, Carbon dioxide and oxygen are found in the mix because of the initial accumulation of ambient gases in the purge pipe of the analyzer. The gas quality is also examined through burn test. Produced hydrogen is pure enough for continuous burn without any explosion. The mix of oxygen in the produced gas would result in an explosion. During burn test the flame color is brown due to the used burner is made of brass metal.

4.6 Comparison with Commercial PEM Electrolyzer

The price of commercially available PEM electrolyzers is higher than the developed electrolyzer. The developed device has higher electricity consumption that results in lower efficiency. The reduced efficiency might occur due to the resistivity of electrode plates and separator membranes [133]. Stand in bubbles (or bubble cloud) near electrodes can also increase resistance [134]. Impurity in solution has an impact on performance [135]. Fouling may occur on membrane surface [136] which significantly reduces the conductivity [137]. During the test, the same solution is used several times. The test environment was not dust free and the components of the system were not kept in an enclosed dust-free compartment. So the dust particles might have got mixed with the solution. These could be the major reasons for having a lower efficiency. Increasing the thickness or size of steel plates could reduce the resistance [138]. The external pumps can be used to prevent the formation of the stand-in bubbles and thus could improve the performance. Table 4.7 shows the comparison against a commercial electrolyzer. The production rate and electricity consumption of the developed electrolyzer are higher compared to the commercial PEM electrolyzer. Due to the lower efficiency of the developed device the operating cost would be higher. But for log run applications like projects, having 25 years' life cycle, replacement cost is an important cost element which would be higher for imported electrolyzers for components and initial investment [139-140]. Any component replacement of PEM electrolyzers can increase the cost. At present the best PEM electrolyzers can run for 40000 hours which is equivalent to 4.5 years [141].

Table 4.7. Comparison values and comments

Features	Locally Developed Electrolyzer	Commercial Model (QLC-120 PEM Electrolyzer)
Price	BDT 2500	BDT 53805 (without port tax and other fares)
No Of Cell	2	2
H_2 Flow Rate	206 mL/min or 0.0123 Nm^3/h	109 mL/min [19] or 0.0065 Nm^3/h
Power Supply	DC	DC
Wattage	120 Watt	36 Watt
Plate Size	128 cm^2	56.75 cm^2
Membrane	Nylon 140	Nafion PFSA
Metal	SS316L	Titanium Sintering carpet and precious metal electrode
Water	Distilled water and NaOH	deionized or re-distilled water
Efficiency	30.62%	54.07%

This run time requires higher catalyst loadings, thicker membranes and high-performance separator plates which results in more costs. Any project having a lifetime of 25 years, the electrolyzers are to be replaced minimum 6 times.

4.7 Summary

Due to the use of platinum and polymer electrolytic membrane, PEM electrolyzers are costly. A high price is a barrier to popularize the use of hydrogen. The use of hydrogen for small scale energy requirements is being increased worldwide, whereas it is yet to explore in Bangladesh. Extensive research is required to develop electrolyzers locally and accomplish optimal design for small and large scale applications. The developed electrolyzer can deliver hydrogen at a rate of 227.27 mL/min at room temperature or 206 mL/min in STP condition. However, the efficiency is about 30.62% which is half of the advanced PEM electrolyzers. The quality of hydrogen produced by the developed device is reliable for energy conversion applications.

Chapter 5

Solar Powered Hydrogen Production Cost in Bangladesh

5.1 Introduction

Green hydrogen production cost is directly related to the renewable energy (RE) production cost and hence, it is supposed to be lower as the RE fuels are free natural resources [142]. Bangladesh is a solar boon country hence using solar power to produce green hydrogen might become a prospective venture. In this chapter, the economic analysis of a solar-powered hydrogen production plant is presented.

Economic analysis is a method of evaluating the costs and benefits of a decision, project, or policy using economic principles and techniques. It involves the application of economic theory and quantitative methods to analyze and evaluate different options and to identify the most effective solution. It can also include evaluating the potential risks and uncertainties associated with the project or decision, as well as any external factors that may impact its success or failure. In this research, life-cycle-cost (LCC) method is used for the analysis.

A hydrogen production plant using solar photo-voltaic (PV) powered water electrolyzers has been developed at the Institute of Energy in Dhaka University (Lat: 23.73 ^{O} N, Long: 90.40 ^{O} E) [143]. The site has an 11.6 kWp PV power plant. The solar PV plant is connected with a 3 kW AC load which is a compressor and 3.5 kW DC load of water electrolyzers. Electrolyzers use DC power which is found directly from solar PV array to produce hydrogen from water electrolysis. Production yield is about 1433.76 liters (STP) or 128.03 grams of hydrogen in a four hours of operation (10 AM to 2:00 PM) period in a single day sun exposure to PV panels.

The lifetime of the developed electrolyzer is considered about 5 years [144-145]. However, the operational lifetime of the electrolyzer unit would be much longer as the electrodes of the developed electrolyzer is made from 316L grade stainless steel. 316L grade stainless steel is resistant to a wide range of NaOH concentration and temperature. It is considered resistant to any molarity solution of NaOH up to 80^{o}C of operating temperature [146].

The operating temperature of the system is around 55 ^{o}C. Due to this, the life time of the developed electrolyzer is expected for a longer period of time. The replacement cost of electrolyzer components like electrode, membrane, gaskets etc. are considered throughout the lifetime of the project [147-148]. The holidays and system maintenance works will shut off the production during a business year. So, this non-operational days are provisioned in this plan. Within a business year, about 85 days are considered for maintenance and the working day off. It is assumed that the project lifetime is 25 years. The discount rate is considered to be 12%.

Table 5.1 shows the general assumptions of the project.

Table 5.1. List of assumptions for the project

Assumptions	Assumption value	Reason
Project Lifetime	25 Years	Similar to most wind and PV projects [149-150]
Number Production Off days	85	Holidays and maintenance works
Discount rate	12%	Bangladesh Government Gazette [151]
Solar panel lifetime	25 years	Warranty and lifetime [152]
Battery Lifetime	5 years	Warranty and lifetime [153]
Electrolyzer replacement time	5 years	Expected lifetime [154]
Inverter replacement time	10 Years	Expected lifetime, warranty [155]

5.2 Methodology

Water electrolysis for hydrogen is expensive because of high initial investment of solar and wind systems and operational cost of electrolysis. So it is essential to perform an economic assessment of similar systems. The Life Cycle Cost (LCC) analysis has been performed [156-159]. The input of LCC, the Levelized cost of electricity is obtained by HOMER ENERGY software considering the design for the project. Fig. 5.1 shows the flow of the performed analysis.

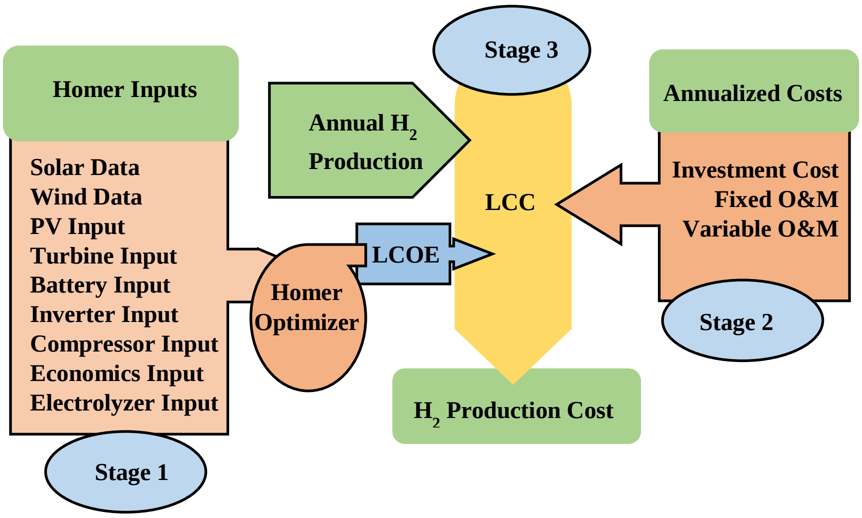


Fig. 5.1. Stage wise calculation flow

5.2.1 Life Cycle Cost (LCC) Analysis

The LCC has several approaches to fit practical scenarios for specific applications [160-162]. LLC defines the cost elements, the cost structure and relationships between various costs. LCC analysis adopts the Levelized cost of energy (LCOE) method. LCOE is a well-known and widely used tool in renewable energy sectors. Here, the numerical value of LCC presents the cost per unit (kg, gram or Nm^3) output [163]. The presented cost shows the cost per unit mass of hydrogen [148,164].

The adapted LCC structure was taken from the well-developed existing methods and papers [148,157-158,164-165].

Equation 2 presents investment cost, C_{inv}.

$$C_{inv} = C_{we} + C_c + C_s + C_{misc} \quad (5.1)$$

Here,
C_{we} is the water electrolysis cost,
C_c is the compressor cost,
C_s is the storage unit cost, and
C_{misc} is the miscellaneous costs.
In the LCC method, all costs are annualized by multiplying a factor called capital recovery factor (CRF), shown in equation 5.2.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (5.2)$$

Here,
i is the nominal discount rate,
n is the lifetime of the project.
The annualized investment cost is calculated using the following equation.

$$C_{inv,a} = CRF \text{ X } C_{inv} \quad (5.3)$$

The cost of operation and maintenance (O&M) has fixed cost and variable expenditures.

$C_{vom,a}$, presents annual variable operation and maintenance costs in equation 5.4.

$$C_{vom,a} = C_{mc} + C_{elec} + C_{sal} + C_{rep,a} \quad (5.4)$$

In equation 5.4,
C_{mc} stands for the compressor maintenance cost,
C_{elec} is electrical wiring and related maintenance cost,
C_{sal} is the salary expenditure of personnel, and
$C_{rep,a}$ annualized replacement cost.
In equation (5.5), the annualized replacement cost is calculated. Here, C_{rep} is the present value of a system auxiliary to be replaced.

$$C_{rep,a} = CRF \text{ X } \frac{C_{rep}}{(1+i)^t} \quad (5.5)$$

Here,
t, is the number of year after which a component will be replaced.

In the same manner, the fixed operation and maintenance cost (O&M) is represented as,

$$C_{fom,a} = C_e + C_w + C_{che} \quad (5.6)$$

The annual electricity cost is C_e, C_w stands for the annual water cost, and C_{che} stands for the annual chemical cost.

All the annualized cost is taken into account, and the annualized LCC equation is formed as,

$$C_{LLC,a} = C_{inv,a} + C_{vom,a} + C_{fom,a} \quad (5.7)$$

After having the $C_{LCC,a}$, the LCOH can be obtained by dividing $C_{LCC,a}$, by the annual yield of hydrogen in a particular unit. Annual hydrogen production is denoted as $E_{H_2,a}$ in equation 5.8.

$$LCOH = \frac{C_{LCC,a}}{E_{H_2,a}} \quad (5.8)$$

To perform LCOH analysis, we need to have per unit cost of electricity for this particular case and the yearly production of hydrogen in a particular unit. The production cost is presented for multiple units like liter (STP), grams, meter-cube (m^3), normal meter-cube (Nm^3).

5.3 Analysis of Electricity Cost

Hybrid Optimization of Multiple Energy Resources (HOMER Energy) is a leading optimization and analyzing tool for renewable energy systems (RES). HOMER compares complexities to find out the cost-effective system requirements and optimizes solar photovoltaic panels, storage, and more to reduce energy costs. The software also calculates the Levelized cost of electricity from a system configuration. Users need to set the required parameters and values to the respective module interface [166].

5.3.1 Components and Parameter Setup in HOMER

Solar radiation data for Dhaka and Chattogram sites are presented in Table 5.2. The HOMER software fetches this data from the NASA Surface meteorology and Solar Energy database for July, 1983 to June, 2005.

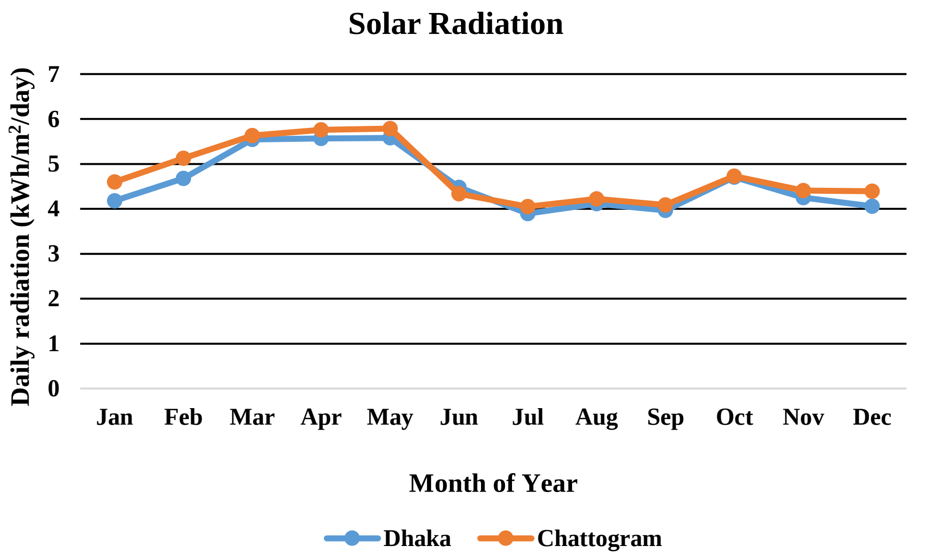


Fig. 5.2. Monthly solar radiation of the selected sites

The annual average solar radiation is 4.59 $kWh/m^2/day$ for sites in Dhaka and 4.76 $kWh/m^2/day$ for Chattogram. Both the cities have 4.5 hours/day sunshine periods. Fig. 5.2 shows the variation of solar global horizontal irradiance (GHI) of the selected sites.

Table 5.2. Solar GHI data for selected sites

Month	Dhaka	Chattogram
	Daily Radiation (kWh/m2/day)	Daily Radiation (kWh/m2/day)
Jan	4.182	4.597
Feb	4.677	5.126
Mar	5.546	5.634
Apr	5.564	5.76
May	5.578	5.786
Jun	4.475	4.335
Jul	3.895	4.048
Aug	4.117	4.224
Sep	3.964	4.083
Oct	4.704	4.725
Nov	4.25	4.409
Dec	4.058	4.391

The project lifetime is assumed to be 25 years. The discount rate for Bangladesh for 2018 according to Bangladesh gadget is 12%, and the Inflation rate for 2019 is 5.48% [167]. As the total energy requirement would be met by renewable energy, PV, for this case, the annual capacity shortage is considered zero. The investment detail cost for 25 years is present in Table 5.3.

In the power source module, solar PV parameters are set. Generic Flat-plate PV has been selected. The cost of per kW solar PV is considered including wires, civil work etc. costs.

Table 5.3. Investment detail

Cost Items	Component Names	Cost in 25 Years (BDT)	Reference
Investment	Solar System (10.4 kW)	901742	[168]
	Battery (25 kW)	312500	[171]
	Safety gears	5000	[172-174]
	Compressor unit	15000	[175]
	Inverter (3.49 kW)	59330	[176]
	Electrolyzer (3.48 kW)	72500	[Ch-4]
	Storage	15000	[177]
	Total	**1381072**	
Maintenance Cost	Solar system	261000	[169]
	Battery	94000	[171]
	Inverter	87000	[176]
	Compressor	12500	[175]
	Electrolyzer	12500	[Ch-4]
	Water	210000	[178]
	Chemical	168570	[179]
	Total	**845570**	

Twenty-five years have been considered for the lifetime of the panel. So the replacement cost of PV panels has no impact on the cost analysis and system design unless it lasts less than the expected lifetime. Fig. 5.3 shows the schematic diagram of the system. It consists of solar PV module as power source, charge controller and inverter as power controller units, battery bank as power storage. Electrolyzer unit as the load with a compressor provisioned for storage of gas in cylinders.

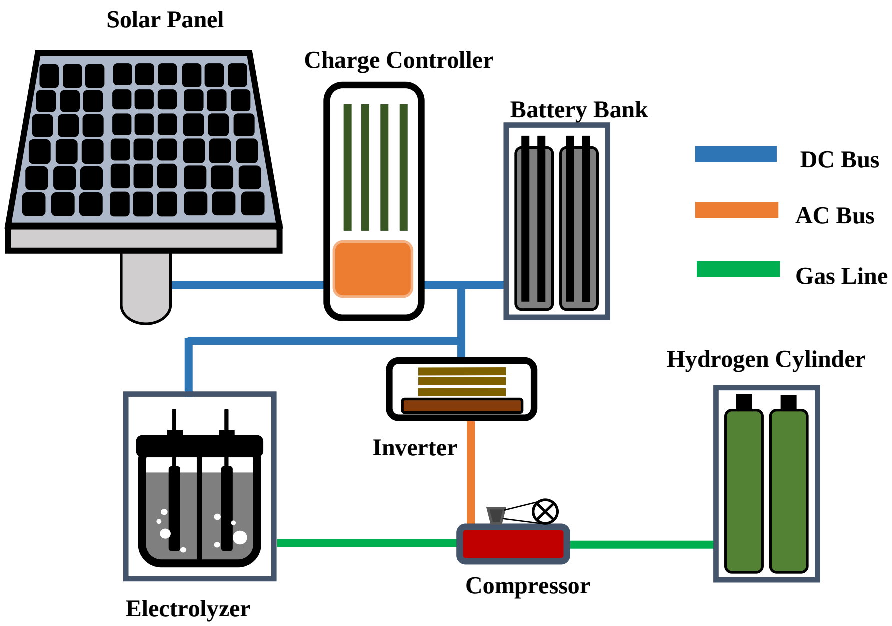


Fig. 5.3. Schematic of solar powered hydrogen production system

To include less performing scenario of system components, sensitivity analysis is performed to evaluate possible scenario and relationship with the electricity cost. Here, per watt-peak module cost is about BDT 56 taka [168]. Per kilo-watt cost input of PV module has been given 86706 BDT. This cost includes cost of wires, installation, metal frame and civil works for per kilo watt PV panels. Operation and Maintenance cost is 2000 BDT/year [169-170]. The derating factor is 80%.

The required number of batteries for the proposed system has been obtained from the HOMER optimizer. The input battery parameters are given as nominal capacity 1 kWh (90 AH, 12V), per unit battery cost is 12500 BDT, Lifetime 5 years, Voltage 12 V, Throughput 2016 kWh and maintenance cost is about 300 BDT per year[171]. HOMER optimizes the number of batteries required.

The DC power needs to be converted into AC power to operate a 3 kW compressor. The inverter parameters are set in HOMER. HOMER optimizes the capacity like the battery. The efficiency of the inverter is 98%, Capital cost 17000/kW, replacement cost 17000 BDT and maintenance cost is about 2000 BDT per year. Lifetime of the inverter is 15 years.

The electrolyzer unit which is DC load, produces hydrogen using electricity. The produced gas would be stored by using a compressor. HOMER software requires to configure these load with operating hours. A 3.5 kW capacity electrolyzer unit is considered for the system. The unit has 29 electrolyzers in it. Each electrolyzer is about 120 watt and the total unit can produce 358.44 liters or 32 grams hydrogen per hour [143]. Each day it is planned to operate electrolyzers for 4 hours. The detail about the developed electrolyzer is given in chapter 4. Per unit electrolyzer development cost is about BDT 2500. The breakdown of actual development cost of the electrolyzer is presented in Chapter 4, Table 4.1. The price of the electrolyzer is not the actual development cost. In this analysis, development cost of electrolyzer is considered. The scaled annual average energy requirement for electrolyzer is about 14 kWh/day. A 3 kW compressor has been selected for the project. The compressor is an AC load. The operational hour is set to be 3 hours per day from 1:00 PM to 4:00 PM. It has been assumed that the produced gas will first be stored in a chamber which is an air tight flexible bag container at atmospheric pressure. Then this initially produced gas will be pumped to the cylinders with the help of compressor. However, the development of this mechanism is out of the scope of this research.

The lifetime of the compressor is 10 years. The scaled annual average energy to be 6 kWh/day. The cost of the compressor is about 15000 BDT [175]. Per year maintenance is about 2000 BDT.

After setting all the parameters, the simulation is processed through the software. The automated calculation returns that about 634 solutions were analyzed from 1964 systems. The optimized system configuration has been simulated and found to have the lowest net present cost hence, returned as the optimized configuration by HOMER. The recommended system architecture is shown in Fig. 5.4. It is found that the system would require 10.4 kW of PV unit, 25 lead-acid batteries, and an inverter of 3.49 kW capacity.

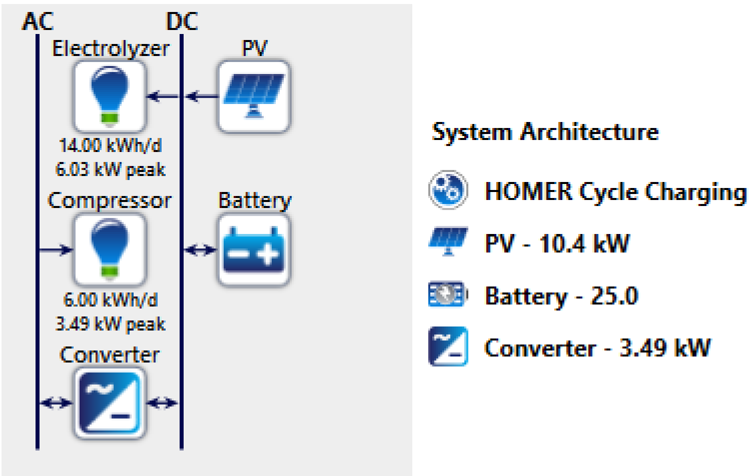


Fig. 5.4. Schematic of the optimized system architecture

The analysis uses the cycle charging mode of HOMER operation to evaluate the cases to find the optimized system architecture. In cycle charging, it charges and discharges batteries in such a way that it maximizes their lifespan and performance. The cycle charging is a useful tool to evaluate a hybrid power system.

5.3.2 Cost Analysis Summary and Electricity Cost

From the Table 5.4, the system's total capital cost is found to be about 12.73 lacs BDT with the replacement cost of components for 25 years' time to be 6.5 lacs BDT.

Table 5.4. Component wise categorical cost summary (in Lac BDT)

Component	Capital	Replacement Cost	O&M	Total
Battery	3.13	6.24	0.94	10.31
PV	9.02	0.00	2.61	11.63
Inverter	0.59	0.24	0.87	1.66
Total	12.73	6.49	4.43	23.62

The Levelized Cost of electricity is found to be 54.64 taka. The cost of electricity is found to be higher because of the requirement for significant amount of lead acid batteries. The cost also counts the replacement costs for each batteries for every 5 years of the project lifetime with its annual maintenance cost. This cost of electricity is carried forward into the next stages of the analysis.

5.4 Calculation of Hydrogen Production Cost

Here, LCC is the used method of finding the per-unit production cost of the product. LCC is based on the annualized costs and requires investment cost, Maintenance cost, Electricity cost, production yield in terms of mass unit etc. In the next section, all these input parameters are discussed.

5.4.1 Investment Cost

The parameter is calculated separately for each system component like Solar PV system, Battery, Compressor, Electrolyzer etc.

The investment of solar PV includes panel cost, power controller, cables, maintenance, and civil works. Table 5.3 shows the investment cost for all necessary system components like PV, Battery, Safety and Control Unit, Compressor unit, Inverter, Electrolyzer, Cylinder and Pipes. The total investment cost for the total plant is about 1381072 taka.

Table 5.5. Summary detail of power generation unit

Cost	NPC(BDT)	2.9M
	Cost of Electricity (BDT)	54.64
	Operating Cost (BDT/y)	443768
	Capital (BDT)	1.27M
PV	Capital Cost (BDT)	901979
	Production(kWh/Year)	15388
Battery	Autonomy (Hour)	31.1
	Annual throughput (kWh/y)	271
	Nominal capacity (kWh)	25
	Usable Nominal Capacity(kWh)	15
Converter	Inverter Mean Output (kW)	3.49

5.4.2 Maintenance Cost

De-mineralized water and chemicals are essential ingredients to produce hydrogen by the developed electrolyzer. The cost of the chemical and water is included in this section. Along with this other maintenance costs are given in the Table 5.3. Each item is expressed as required for 25 years of the project lifetime.

5.4.3 Yearly Hydrogen Production

The electrolyzer unit can produce about 1579.9 liter or 141.09 grams of hydrogen in 4 hours of operation per day. Hence, the yearly production becomes 401452.8 liter or 401.45 m^3 or 35849.74 grams or 398.56 Nm^3. [1000 L = 1 m^3], [1 liter H_2 = 0.0893 gram in STP condition]

5.4.4 Levelized Cost of Hydrogen (LCOH)

The life cycle cost method requires all the expenses and investments converted to per annum values. Annualized values are obtained by multiplying a factor called capital recovery factor (CRF), which is given in equation 5.2. Here, in this analysis, CRF is found to be 0.13.

5.4.5 Annualized Investment Cost

The total investment cost includes the cost of electrolyzer, compressor, safety gears, storage unit and miscellaneous cost given in the Table 5.6.

Table 5.6. Annualized investment detail

Cost Items	Amount
(Cwe) Electrolyzer cost	72500
(Cc) compressor cost	15000
(Cs) storage unit	15000
(Cp) Safety Gears	5000
(Cmisc) miscellaneous costs	5000
Total	112500
Annualized	14625

Here, the annual investment cost is obtained by multiplying the total investment cost with CRF. The value is found to be BDT 14625.

5.4.6 Annual Operation and Maintenance Costs

In the LCC method, operation and maintenance costs are divided. Fixed operation and maintenance costs include mainly the component-wise maintenance costs, replacement costs and salaries.

Table 5.7. Variable cost detail

Cost Items	Amount
(Cmc) maintenance cost for the compressor	500
(Cele) the maintenance cost of electrolyzer	500
(Csal) Salary	96000
(Crep,a) annualized replacement cost.	2929.64
Total	99929.64

Table 5.7 presents the component-wise variable costs for this project. Here, the annualized replacement cost is calculated using equation 5.5. There are only five components (or items) which are to be replaced over different periods throughout the lifecycle of the system. These are given in Table 5.8 in detail. Each component's annualized replacement-cost is obtained, and the total amount is found to be BDT 2929.64. Safety gears include helmets, protective goggles, shoes, gloves etc.

Table 5.8. Annualized replacement cost detail

Items	**Replacement Cost**	**Year of Replacement**	**Crep,a= CRFX{(Crep)/ $(1+i)^t$}**
Compressor	15000	10	615.77
Wires, Pipes	1500	15	34.94
Safety Gears	2000	5	144.69
Electrolyzer	14500	5	1049.03
Storage	15000	5	1085.20
Total			2929.64

5.4.7 Annualized Fixed Operation and Maintenance Cost

Fixed cost is identified as the usable commodity required for hydrogen production, which are electricity, water and chemicals. The simulation shows that the yearly consumption of electricity by the loads which are actually involved in hydrogen production process is about 3897.6 kWh. The Levelized Cost of electricity is about BDT 54.64. It gives the yearly cost of electricity is about BDT 212964.86. The yearly requirement of water is about 350 liters, and the per liter water price is about 24 taka. Similarly, 15 kg of chemical (NaOH) is required, which costs about 6750 taka at a rate kg 450tk/kg. Table 5.9 shows the fixed cost detail.

Table 5.9. Fixed cost detail

Cost Items	**Amount**
(Ce) annual electricity cost	212964.86
(Cw) annual water cost	8400
(Cche) annual chemical cost	6750
Total	228114.86

5.4.8 Annualized Life Cycle Cost

The summation of annualized investment, fixed cost and variable cost gives the annualized life cycle cost (LCC), which is used in equation 5.7. The amount is found to be BDT 342669.51. The annualized hydrogen production is 35849.74 grams or 398.56 Nm^3. Dividing the annualized LCC by annual hydrogen production gives the LCOH about 859.77 tk/Nm^3 or 9.56 tk/grams of hydrogen.

HOMER cannot return any system configuration data for charge controller. Hence, the cost associated with this component is not included in above analysis. As the system is dependent to lead acid battery there is a requirement of charge controller for battery charging. If the system is considered for 96 volt then per hour ampere would become less than the 48 volt system. Considering the 25 kWh battery bank and 96 volt system voltage, the total ampere hour would become 260 Ah. Considering the charging time for 5 hours, the charge controller current capacity becomes 43 ampere. For this rating, at least 3 charge controller might require having 96 volt, 40 ampere rating. Charge controller of this rating has a variety in price range. However, a moderate quality can be found within a price range of BDT 50000 [-170,180]. Considering this component, the hydrogen production cost would increase. The replacement cost is about 50000 per unit in 5 years [181-182] and maintenance cost of BDT 1500 per year that could increase the production cost up to BDT 79/Nm^3 for 3 units of charge controllers.

Here, in calculation we considered the consumption by hydrogen producing loads in electricity consumption but if we consider the cost of full plant capacity the hydrogen production cost will be nearly BDT 2435.31/Nm^3 taka. However, in practical scenario the excess electricity may support other external loads.

5.5 Comparison of Energy to Gas Estimation with Measured Data

In the Institute of Energy the total installed PV capacity is about 14.5 kW. One unit is about 8.9 kW in the energy Park and another 5.6 kW unit is available on canteen rooftop. HOMER Result shows that 10.4 kW PV Power Plant is required to run the designed load. The load is designed to be less than 40% of the required capacity at any time of the given operation. 40% of the required capacity is 4.45 kW. The electrolyzer and compressor will not operate together in the system, hence the system will always face load that is less than 40% of its required capacity. At actual, the load is about 33.46% of the total capacity, 4 hours are selected because in Bangladesh the average sunshine hour is about 4.5 h in a day, so the load would be handled by the system properly. The electrolyzer unit (3.48 kW) will operate for 4 hours per day (8:01 AM to 12:01 PM). The compressor (3 kW) will operate for 3 hours (12:01 PM to 3:01 PM). This compressor has been considered as a probation of the system to store the produced gas primarily in a locally developed large bag.

5.5.1 Energy to Gas Production Estimation

According to HOMER, The plants total yearly energy production is about 15388 kWh per year. For 80% efficient PEM/Alkaline electrolyzer, 50 kWh electrical energy is required to produce 1 kg H_2, so 15388 kWh energy has capability to produce total 307.76 kg/year if not used in any other loads except electrolyzer.

The developed Electrolyzer is about 30.62% efficient. So, this electrolyzer would require nearly double the energy than that of an 80% efficient electrolyzer needs to produce same amount of H_2. For the developed 30.62% efficient electrolyzer the required energy would be about 130.64 kWh/kg H_2 [183-186]. The total energy consumption of the developed electrolyzer, in a year, is about 3897.6 kWh, considering 4 hours of operation per day and 280 days operations in a year. So, the possible production yield is to be 29.83 kg/year or 328.13 m^3/year or 331.63 Nm^3.

5.5.2 Gas Production Calculation by Measured Data

The flow rate of the developed electrolyzer is about 206 mL/min (STP) as mentioned in the chapter 4. The power Consumption is about 120 watt. The designed system needs 29 electrolyzers to comply with the less than 40% load of installed capacity as mentioned in previous section. The operational hour is 4 hours and 280 days for a year, so the yearly yield of hydrogen is about 401452800 mL/year or 401452.8 liter/year or 35849.74 grams or 35.85 kg/year or 394.35 m^3/year or 398.56 Nm^3/yr. [1000 Liter = 1 m^3; 1kg H_2 = 11 m^3 H_2; 1 liter H_2 = 0.0893 gram].

The result is obtained using energy to gas production approach is similar to the result obtained by using the actual measured data. The difference between two results is about 16%. This may occur due to the use of converted data for 30.62% efficient electrolyzer in energy to gas calculation and measured data of gas fluid, STP condition conversions.

5.6 A Brief Comparison with a Similar Imported Electrolyzer

A similar capacity imported electrolyzer is manufactured by HUNAN MORESHINE [187]. The country of origin of this electrolyzer is China, Hunan province. Per unit electrolyzer costs about BDT 53500 if ordered more than 20 pieces. To have 3.48 kW electrolyzer unit as designed for the developed electrolyzer it requires 29 electrolyzers of HUNANA MORESHINE. Production rate is 300 mL/min at ambient condition [187].

Table 5.10. Specification of imported electrolyzer

Hydrogen purity	99.999%
Production rate	272 mL/min or 0.0162 Nm^3/h (STP)
Electricity Consumption	120w
Dimensions	420x210x365(mm)
weight	13kg
Environmental conditions	Ambient and dust free

5.6.1 Actual Cost of an Electrolyzer Imported to Bangladesh

To evaluate an imported electrolyzer, the shipment cost is a key factor for cost analysis. The package weight of the subjected electrolyzer is about 13 kg per unit. The total weight of 29 units would be 377 kg. It has been investigated that a 70 kg package's air shipping cost is around BDT 181500 and additional per kg costs about BDT 2590. So, the total shipment cost would be around BDT 976450 for package weighs about 377 kg [188]. Additional to this, custom clearance fee, value added tax, import duty or custom duty, warehouse storage fee etc. is required additionally. In Bangladesh, custom clearance fee is 1% of the value of goods [189]. The buying price of 29 electrolyzers will be BDT 1551500. The clearance fee would be BDT 15515. At the rate of 15%, value added tax [190] would be BDT 232725. Custom duty for final product in Bangladesh is 25% [191] hence, it would be nearly BDT 387875. Along with other cost shown in table the total cost for the imported electrolyzers would be BDT 3180065.

Table 5.11. Total cost of electrolyzer including other associated costs

Itemized cost of Imported Goods	Rate	No. of Unit	Cost (BDT)
Price of goods	53500 per unit	29	1551500
Freight cost	Total	Total	976450
Clearance Fee	1%	Total	15515
Value added tax	15%	Total	232725
Custom duty	25%	Total	387875
Warehouse storage fee	200 per day	30 days	6000
Miscellaneous			10000
Total			3180065

5.6.2 LCC Cost Components for Imported Electrolyzer

Considering all other annualized investment as same as the developed electrolyzer except the cost of electrolyzer itself, the total annualized investment is found to be BDT 418608.45. The total variable cost is BDT 203783.63. It includes the total replacement cost given in table 5.13.

Table 5.12. Annualized investment detail for imported electrolyzer

Cost Items	Amount
(Cwe) Electrolyzer cost	3180065
(Cc) Compressor cost	15000
(Cs) Storage	15000
(Cp) Safety Gears	5000
(Cmisc) Miscellaneous costs	5000
Total	3220065
Annualised	418608.45

Table 5.13. Variable cost detail for imported electrolyzer

Cost Items	Amount
(Cmc) maintenance cost for the compressor	500
(Cele) the maintenance cost of electrolyzer	500
(Csal) Salary	96000
(Crep,a) annualised replacement cost.	106783.63
Total	203783.63

Table 5.14. Annualized replacement cost detail for imported electrolyzer

Items	Replacement Cost	Year of Replacement	Crep,a= CRFX{(Crep)/ $(1+i)^{t}$}
Compressor	15000	10	615.77
Wires, Pipes	1500	15	34.94
Safety Gears	2000	5	144.69
Electrolyzer	1450000	5	104903.02
Storage	15000	5	1085.20
Total			106783.63

Table 5.15. Fixed cost detail for imported electrolyzer

Cost Items	Amount
(Ce) annual electricity cost	212964.86
(Cw) annual water cost	8400
(Cche) annual chemical cost	8750
Total	230114.86

The electrolyzer unit would consume 3897.6 kWh energy per year. The electricity cost is about BDT 212964 at the rate of 54.64 per kWh. For the imported electrolyzer KOH solution is required. The price for KOH is higher than the NaOH [192]. The total fixed cost is BDT 230114.

5.6.3 Production Cost by Imported Electrolyzer

The total annualized life cycle cost is about BDT 852506.94 found by adding up all LCC components from previous section. The yearly hydrogen production yield of this electrolyzer is about 47335.57 grams or 526.19 Nm^3, considering per unit electrolyzer's production rate to be 272 mL/min (STP). Every day it would operate for 4 hours and 280 days in a year. The hydrogen production cost by a similar imported electrolyzer would be 18.01 tk/gram or 1620.15 tk/Nm^3. A brief comparison between the developed electrolyzer and a similar imported electrolyzer is given in Table 5.16.

Table 5.16. Comparison between developed and imported electrolyzer

Parameters of Comparison	Developed Electrolyzer	Imported Electrolyzer
Yearly Energy Consumption	3897.60 kWh	3897.60 kWh
Yearly Hydrogen Production	35.85 kg	47.34 kg
Wattage for per unit	120 W	120 W
Production Rate	206 mL/min or 0.0123 Nm^3/h	272 mL/min or 0.0162 Nm^3/h
Energy Required for per kg H_2	108.72 kWh/kg	82.33 kWh/kg
Total Cost in a year	342669.51 Taka	852506.94 Taka
Production Cost (tk/kg)	9558.49 tk/kg	18008.17 tk/kg
Production Cost (tk/g)	9.56 tk/g	18.01 tk/g

5.7 Sensitivity Analysis

To perform sensitivity analysis in HOMER, several parameters are selected. These parameters have direct impact on the cost of electricity. Hence, the levelized cost of hydrogen depends on the changes on sensitivity parameters. The parameters can be categorized into two groups. One is the system component and another is the economic factor. The system components parameters are life time of solar panel, derating factor, Time (years), Throughput (kWh), Initial State of Charge (%), Minimum State of Charge (%), Inverter's Lifetime (years), Efficiency (%). In economics Nominal Discount Rate (%), Expected Inflation Rate (%) and Project Lifetime (years) parameters are considered. In this section, every parameter sensitivity case is checked individually as well as linking within the all other parameters of a single system component. For the economic sensitivity analysis, the approach is also maintained.

5.7.1 Sensitivity of System Components

5.7.1.1 Solar Module

For solar panel there are two sensitivity parameters. The sensitivity parameter values are presented in Table 5.17. Linking these two parameters, we have found 9 cases analyzed by HOMER. Where the least COE is found for the 25, 22 and 28 years of PV lifetime with 82%, 80% and 78% derating factor. Simulation results are shown in Table 5.18 to 5.20.

Table 5.17. Solar panel sensitivity parameters

PV Sensitivity parameter Inputs	
PV Derating factor (%)	Time (years)
80	25
75	20
70	15

Table 5.18. Solar panel linked parameters sensitivity cases (Architecture)

Case No	PV time (years)	PV Derating (%)	PV (kW)	Battery (Nos)	Converter (kW)
1	22	78	10.98	24	3.52
2	25	78	11.19	25	3.58
3	28	78	12.51	20	3.41
4	22	80	10.40	25	3.49
5	25	80	10.40	25	3.49
6	28	80	10.40	25	3.49
7	22	82	9.61	27	3.59
8	25	82	10.16	25	3.45
9	28	82	9.86	26	3.49

Table 5.19. Solar panel linked parameters sensitivity cases (Cost)

Case No	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	PV Capital Cost (BDT)
1	2995928	56.44	109349.90	1621826	951904.0
2	2957778	54.31	105384.70	1633503	970082.5
3	2899888	54.62	95268.73	1702732	1084843.0
4	2967550	55.90	110112.60	1583864	901979.1
5	2900393	54.64	104768.20	1583864	901979.1
6	2878817	54.23	103051.30	1583864	901979.1
7	2960831	55.78	112926.50	1541784	833300.8
8	2870934	54.08	104179.10	1561809	880588.3
9	2860670	53.89	104339.40	1549531	855211.4

Table 5.20. Solar panel linked parameters sensitivity cases (Production)

Case No	PV Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)	Battery Nominal Capacity (kWh)
1	15833.44	29.87	260.63	24.02
2	16135.81	30.33	271.34	25.02
3	18044.67	24.89	216.75	20.02
4	15387.71	31.11	271.42	25.02
5	15387.71	31.11	271.42	25.02
6	15387.71	31.11	271.42	25.02
7	14571.47	33.60	293.12	27.02
8	15398.36	31.11	271.16	25.02
9	14954.61	32.36	282.62	26.02

Table 5.18 shows the architecture related changes due to solar panel linked parameters sensitivity. Here, PV derating and PV lifetime impacts the system architecture to be changed. The average PV capacity is about 10.61 kW for all the cases of this sensitivity. The average number of battery is 24 and the average capacity of converter is about 3.5 kW. In Table 5.19 cost related sensitivity cases are presented. The average net present cost is about 29 lacs. The average cost of

electricity is about 54.88 for all 9 cases. The average operating cost is about 1 lac.

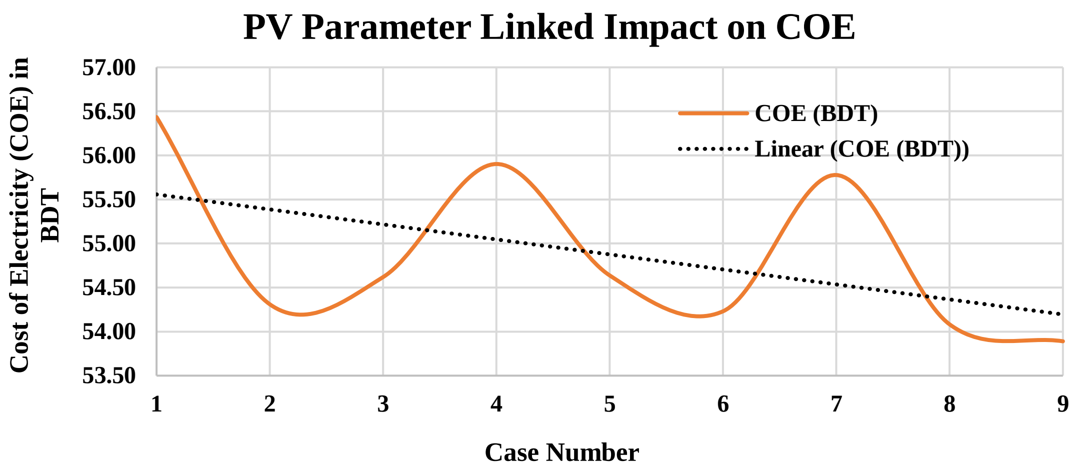


Fig. 5.5. Cost of electricity changing with solar panel linked sensitivity

For solar panel sensitivity cases it has been found that the cost of electricity varies between BDT 53.89 to BDT 55.90. The impact is found to be linear on the cost of electricity. For the lowest derating factor with the lowest lifetime the COE found to be the highest and for the highest derating factor with highest lifetime the COE is the lowest. For the same lifetime, the increase in derating factor, HOMER reduces the PV size and makes a significant increase in battery numbers to optimize the initial capital cost. As the PV size gets reduced significantly for higher derating factor the COE gets decreased.

For the next phase, analysis for all other components, the approach is maintained but here, only the linked parameter results are discussed. The linked parameter analysis includes all different cases altogether which reflects all individual case results also.

5.7.1.2 Battery

There are four parameters in battery components that are linked all together with different values in sensitivity cases give in following tables. Initial state of charge, minimum state of charge, lifetime and throughput are taken as the input.

Table 5.21. Battery sensitivity parameters

Battery Sensitivity Inputs			
Initial State of Charge (%)	**Minimum State of Charge (%)**	**Time (years)**	**Throughput (kWh)**
100	40	5	2016
90	50	4	1612.8
80	60	3	1209.6

The analysis result derived from all linked parameters of battery is presented in Table 5.22 to 5.24. Here, the lowest COE is found to be BDT 54.42 and the highest is BDT 70.11. There are total 81 cases are analyzed by HOMER. Among them 10 case results are presented here as sample. Detail case summary is presented in appendix E, Table E-1, 2 and 3.

Table 5.22. Battery linked parameters sensitivity cases (Architecture)

Case No	Battery time (years)	Battery throughput (kWh)	Initial State Of Charge (%)	Minimum State Of Charge (%)	PV (kW)	Battery	Converter (kW)
1	3	1209	100	40	14.58	15	3.58
2	3	1612	100	40	14.58	15	3.58
3	3	2016	100	40	14.58	15	3.58
4	4	1209	100	40	12.51	19	3.82
5	4	1612	100	40	12.51	19	3.82
6	4	2016	100	40	12.51	19	3.82
7	5	1209	100	40	11.42	22	3.47
8	5	1612	100	40	11.42	22	3.47
9	5	2016	100	40	11.42	22	3.47
10	3	1209	100	50	17.00	14	3.79

Table 5.23. Battery linked parameters sensitivity cases (Cost)

Case No	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	PV Capital Cost (BDT)
1	3282761	61.82	116176.60	1822874	1264582
2	3282761	61.82	116176.60	1822874	1264582
3	3282761	61.82	116176.60	1822874	1264582
4	3058588	57.61	108316.80	1697467	1085094
5	3058588	57.61	108316.80	1697467	1085094
6	3058588	57.61	108316.80	1697467	1085094
7	2888967	54.42	99876.59	1633908	989926.1
8	2888967	54.42	99876.59	1633908	989926.1
9	2888967	54.42	99876.59	1633908	989926.1
10	3500164	65.93	117531.00	2023258	1473783

From Table 5.22 to Table 5.24 battery linked parameter sensitivity results are shown. These table show some samples of all cases which are given in Appendix as mentioned earlier. The presented data average for battery throughput is about 1572 kWh.

Table 5.24. Battery linked parameters sensitivity cases (Production)

Case No	PV Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)	Nominal Capacity (kWh)
1	21573.69	18.67	168.32	15.01
2	21573.69	18.67	168.32	15.01
3	21573.69	18.67	168.32	15.01
4	18511.64	23.65	208.69	19.02
5	18511.64	23.65	208.69	19.02
6	18511.64	23.65	208.69	19.02
7	16888.08	27.38	238.16	22.02
8	16888.08	27.38	238.16	22.02
9	16888.08	27.38	238.16	22.02
10	25142.66	14.52	132.74	14.01

Battery throughput refers to the total amount of energy that can be charged and discharged from a battery over its lifetime. It is typically measured in cycles, with each cycle representing one complete charge and discharge cycle of the battery. The battery throughput is affected by various factors such as the type of battery, the charging and discharging rates, the temperature, and the depth of discharge. The higher the battery throughput, the longer the battery can be used before it needs to be replaced.

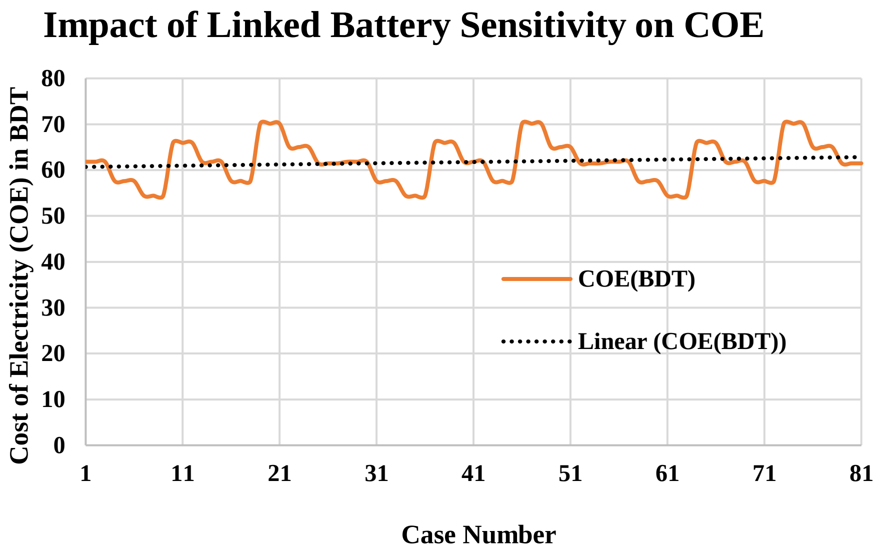


Fig. 5.6. Cost of electricity changing with battery sensitivity cases

Fig. 5.6 shows the variation of COE between cases due to battery sensitivity.

5.7.1.3 Inverter

The converter or the inverter has two sensitivity parameters. Which is life time and efficiency. The linked parameter sensitivity cases are given in Table 5.26 to 5.28. There are 9 of them among which the lowest (BDT 54.11) COE is found in case no. 6. The highest COE is found in case no. 1. Which is about BDT 55.79.

Table 5.25. Converter sensitivity parameters

Inverter input	
Efficiency (%)	**Lifetime (years)**
98	15
96	12
95	10

Table 5.26. Inverter linked parameters sensitivity cases (Architecture)

Case No.	Converter Inverter Efficiency (%)	Converter Lifetime (years)	PV (kW)	Battery	Converter (kW)
1	95	10	10.32	26	3.59
2	95	12	10.63	25	3.67
3	95	15	11.19	25	3.58
4	96	10	11.08	25	3.64
5	96	12	11.06	25	3.72
6	96	15	11.05	25	3.68
7	98	10	10.40	25	3.49
8	98	12	10.40	25	3.49
9	98	15	10.40	25	3.49

Table 5.27. Inverter linked parameters sensitivity cases (Cost)

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	PV Capital Cost (BDT)
1	2961532	55.79	109105.8	1590498	894383.3
2	2945544	55.49	106575.9	1606300	921424.2
3	2957778	54.31	105384.7	1633503	970082.5
4	2973431	54.60	107299.7	1625092	960764.8
5	2961352	54.38	106390.7	1624435	958743.6
6	2946726	54.11	105339.2	1623022	957980.1
7	2924524	55.09	106688.6	1583864	901979.1
8	2911498	54.85	105652.0	1583864	901979.1
9	2900393	54.64	104768.2	1583864	901979.1

Table 5.28. Inverter linked parameters sensitivity cases (Production)

Case No.	PV/Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)	Battery Nominal Capacity (kWh)
1	15258.13	32.36	285.78	26.02
2	15719.44	31.11	273.96	25.02
3	16549.55	30.33	273.14	25.02
4	16390.59	30.33	272.87	25.02
5	16356.11	30.33	273.63	25.02
6	16343.08	30.33	273.92	25.02
7	15387.71	31.11	271.42	25.02
8	15387.71	31.11	271.42	25.02
9	15387.71	31.11	271.42	25.02

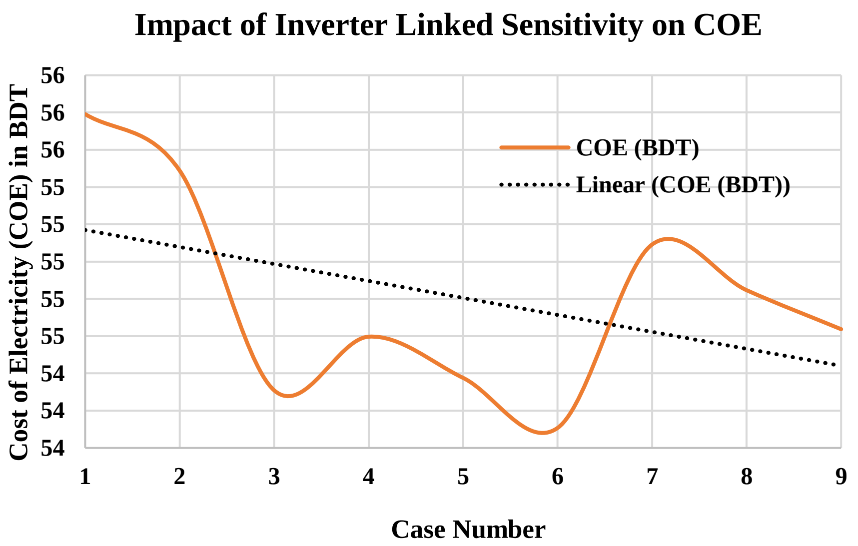


Fig. 5.7. Cost of electricity changing with inverter sensitivity cases

Fig. 5.7 presents the variation of COE between cases of inverter sensitivity. The COE has a steep drop from case number to case number 3. Then it reaches a smaller peak to case number 4. It drops again from here up to case number 6 and takes a straight rise to case number 7 and has a fall again to case number 9.

5.7.2 Economics

In economics aspect, there are three sensitivity parameters. In this analysis these are all linked together and the obtained sample data set is presented in Table 5.30 to 5.32. There are 60 cases found by HOMER for economic sensitivity.

Table 5.29. Economics linked parameters

Economics Input		
Expected Inflation Rate (%)	**Nominal Discount Rate (%)**	**Project Lifetime (years)**
5.48	5	25
6.00	8	20
6.50	12	15

Detail case results are given in appendix E, Table E- 4, 5 and 6. Among all these cases, the highest COE found for case no. 10. The COE is about 67.24. The lowest COE between the cases is BDT 40.23 for case no. 60.

Table 5.30. Economics linked parameters sensitivity cases (Architecture)

Case no.	Nominal Discount Rate (%)	Expected Inflation Rate (%)	Project Lifetime (years)	PV (kW)	Battery	Converter (kW)
1	10	5.48	15	10.40	25	3.49
2	10	5.48	20	10.40	25	3.49
3	10	5.48	25	10.40	25	3.49
4	12	5.48	15	10.40	25	3.49
5	12	5.48	20	10.40	25	3.49
6	12	5.48	25	10.40	25	3.49
7	14	5.48	15	10.40	25	3.49
8	14	5.48	20	10.40	25	3.49
9	14	5.48	25	10.40	25	3.49
10	16	5.48	15	10.40	25	3.49

Table 5.31. Economics linked parameters sensitivity cases (Cost)

Case no.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)
1	2356208	51.17	70857.66	1583864
2	2817282	50.32	93063.53	1583864
3	3187403	49.76	105762.70	1583864
4	2286073	56.38	73160.11	1583864
5	2640974	55.31	93524.48	1583864
6	2900393	54.64	104768.20	1583864
7	2221865	61.74	74889.70	1583864
8	2496038	60.53	93442.39	1583864
9	2678893	59.80	103259.70	1583864
10	2163634	67.24	76109.00	1583864

From Table 5.30 to 5.32, the impact of economics parameters are presented. It is observed that with the increase of discount rate and inflation rate, the cost of electricity increases.

Table 5.32. Economics linked parameters sensitivity cases (Production)

Case no.	PV Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)	Battery Nominal Capacity (kWh)
1	15387.71	31.11	271.42	25.02
2	15387.71	31.11	271.42	25.02
3	15387.71	31.11	271.42	25.02
4	15387.71	31.11	271.42	25.02
5	15387.71	31.11	271.42	25.02
6	15387.71	31.11	271.42	25.02
7	15387.71	31.11	271.42	25.02
8	15387.71	31.11	271.42	25.02
9	15387.71	31.11	271.42	25.02
10	15387.71	31.11	271.42	25.02

The variation of inflation rate is considered 5.48% to 6.5%. Similarly, the discount rate is between 5% and 12%. Bangladesh government has issued a circular by a gadget stating that the rate is to be considered 12% for planning and economic evaluation of projects. The reference is given in earlier section. The inflation rate 5.48% is for the year of 2019. However, the sensitivity input covers up to February 2022, according to the Bangladesh Bank data. Due, to the war between Russia and Ukraine the inflation of country like Bangladesh has been impacted.

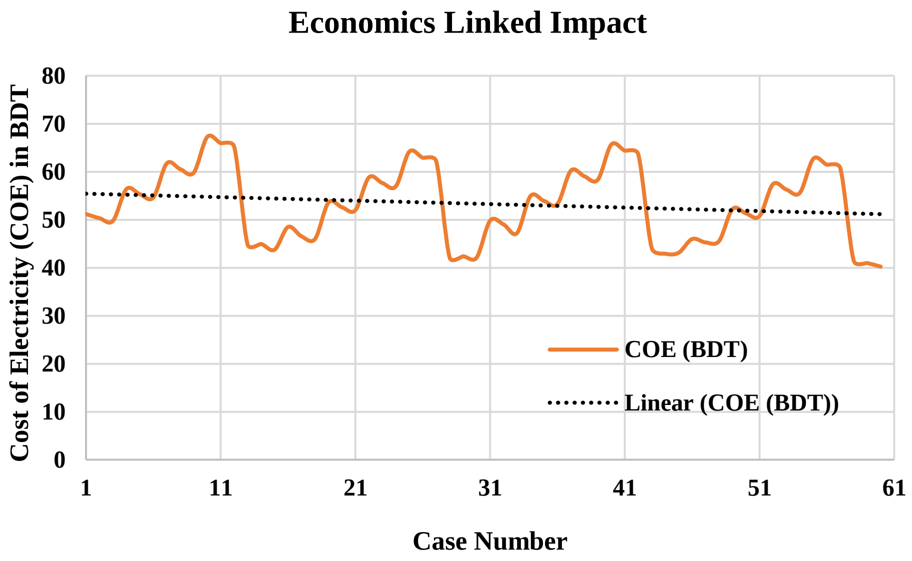


Fig. 5.8. Cost of electricity changing with economics sensitivity cases

Fig. 5.8 shows the variation of cost due to the changes in sensitivity parameters. The change is found to be linear. Observing all these results, it can be concluded that the different economic and system components parameter’s variation can change the cost of electricity. For the selected parameters, it has been found that the COE varies between BDT 40.23 to BDT 67.24. The range includes the changes for all discount rates starting from 10% to 16%. For the highest discount rate and lowest project lifetime, the COE is the highest and for the lowest discount rate and highest project lifetime, the COE is the lowest. It indicates that if this type of RE projects gets subsidies from government the hydrogen production cost will be reduced. At present the discount rate is 12% for Bangladesh, if these RE projects gets 2% reduction in discount rate then the COE will be around BDT 40. Considering all other materials and costs fixed, the levelized cost of hydrogen is directly dependent on the cost of electricity, hence, due to the change in sensitivity parameters, the cost of hydrogen will change. The electricity cost acts as the pivoting parameter in LCC analysis. There have been three economic sensitivity parameters which have impact on the LCC cost of hydrogen presented in Table 5.33. Discount rates, inflations and lifetimes are taken for the COE determination like previous analysis. The analysis shows the highest and lowest results among system sensitivity cases. The obtained cost varies between BDT 718.85 to BDT 982.99 for per Nm^3 of Hydrogen production.

Table 5.33. Economics linked parameters for LCC

Case Number	Electricity Cost	Discount Rate	Lifetime	LCC of H_2 (tk/g)	LCC of H_2 (tk/Nm^3)
10 (Highest COE)	40.23	8	25	7.99	718.85
60 (Lowest COE)	67.24	16	15	10.93	982.99

5.8 International Cost of Hydrogen Production

United States of America and European Union is the central point for the pricing trend of hydrogen. The hydrogen costs from last 7 years show the decreasing trend worldwide. Starting from 2015 the common hydrogen price was in the range of $12.85 to $16 per kg whereas the renewable hydrogen price was $3.23 in Germany and $3.53 in Texas [193]. At that period most common hydrogen price was about $13.99/kg [193]. Starting from there, study shows that the current hydrogen price ranges between US$2.6 to US$12.3 per kg [194]. This range includes all types of hydrogen. The study concluded to reduce the price using dynamic tariff rate exampling 81 utility rates for 20 states of USA which accelerated the price reduction. On those state average price is USD 4.0 per kg [194]. Another report reveals the current price of hydrogen in USA and Europe. It divides the price in three sub-categories based on the mode of production. From grid connection production, the maximum price was $8.81 and lowest price was $6.06 in 2020 [194]. For the same year it was maximum $13.11 and lowest $4.83 in EU [194]. For direct connection and curtailed electricity scenario the max price was in the limit of $11 and lowest was for $6 in USA and EU [195]. It has been indicated that the renewable hydrogen price is largely dependent on the geographic location. Much competitive price can be achieved from the favorable locations and resources. The minimum price for renewable hydrogen was in the limit of 4.5$ in USA and EU in 2020 [195].

Table 5.34. Country wise Production cost of Green Hydrogen with expected value for 2030 and 2050 (in euros per kilogram; Source: Statista.com) [196]

Country Name	2020 Lowest	2020 Highest	2030 Lowest	2030 Highest	2050 Lowest	2050 Highest
Argentina	4.25	4.5	2.25	2.5	1.25	1.5
Australia	4.5	4.75	2.5	2.75	1	1.25
Brazil	4.5	4.75	2.25	2.5	1	1.25
Canada	3.75	4	2.5	2.75	1.25	1.5
Chile	3.5	3.75	2	2.25	1	1.25
China	4	4.25	2	2.25	1	1.25
France	4.25	4.5	3	3.25	1.75	2
Germany	4.75	5	3	3.25	2	2.25
India	4.25	4.5	2.5	2.75	1	1.25
Japan	6.25	6.5	3.75	4	2.5	2.75
Morocco	4.25	4.5	2.5	2.75	1	1.25
Poland	5	5.25	3.25	3.5	2.25	2.5
Russia	3.75	4	2.25	2.5	1.25	1.5

In contrast to USA and Europe, Asian countries are yet to step forward for green hydrogen economy. These countries are mostly involved in policy making, demand projection and production cost analysis. Among them Japan imports hydrogen from Brunei (Blue hydrogen), Australia (Blue), Malaysia (Blue/Green), Saudi Arabia (Blue), Indonesia (Blue) [197]. Study shows that the East Asian countries are targeting $2/kg price for 2030 and $1 for 2050 [197].

The production cost by the proposed models are around 90$ per kg which is very high compared to the international market of green hydrogen. Since, the analysis is based on a 3.48 kW electrolyzer unit, internationally the production units utilize MW scale electrolyzers and hence, the international cost is lower. MW scale electrolyzers have higher annual yield, this is one of the main reasons for the cost effectiveness. Other than that, many countries have curtailed the electricity tariff to lower the production cost of hydrogen provided with other subsidiary facilities.

Since, the developed electrolyzer can produce above 90% pure hydrogen and functions properly, the similar research and development needs to be continued in Bangladesh for MW scale development and installations in near future. In most research, it is concluded that the geographic locations plays a vital role on the cost of green hydrogen. Bangladesh might get advantage due to its geography. As Bangladesh is a solar boon country with the prospect of wind energy in higher heights, renewables like solar and wind based hydrogen production scheme might be prospective in Bangladesh.

5.9 Summary

The production cost of hydrogen by the developed electrolyzer is about BDT 859.77 tk/Nm^3 or 9.56 tk/grams. Through the sensitivity analysis it has been found that due to several changes in discount rate, lifetime and inflation rate the electricity cost is impacted and hence the overall production cost also altered where the life time and discount rate has individual impact. On the sensitivity cases the cost of hydrogen could vary between BDT 0.71/L to 0.98/L or 7.99/g to BDT 10.93/g or BDT 718.85/Nm^3 to BDT 982.99/Nm^3.

Due to non-operational days, there would be 85 days excess electricity along with the non-operational time in any particular day. The excess electricity can be used in other purposes which can benefit the user financially.

The source of water is also a key to produce green hydrogen. Bangladesh has abundant sources of sweet water which can be treated by water treatment plants to make de-mineralized water for larger hydrogen production projects. In Bangladesh, water is comparatively less costly than many developed countries, so hydrogen production projects may exploit to get benefit from this resource. In this project there is no scope for water treatment plant rather the de-mineralized water is assumed to be sourced from local suppliers.

Being the major industrial city, In Dhaka and Chittagong, the supply of demineralized water is abundant because this readymade product is used by the transport sector and it is one of the major sectors for lead acid battery usage. Some other industries like garments and chemical industries use de mineralized water also. There are more than 10 producers of de mineralized water in local market of Bangladesh, hence, assumed to be sourced from the local producers.

In Bangladesh, power generation from wind is comparatively challenging, but solar photovoltaic is being extensively used for the last ten years. Now green hydrogen has come into the global interest. Bangladesh can take part by producing it using its renewable energy resources along with other available raw materials.

Chapter 6

Analysis of Wind and Turbine Selection for Chattogram and Dhaka

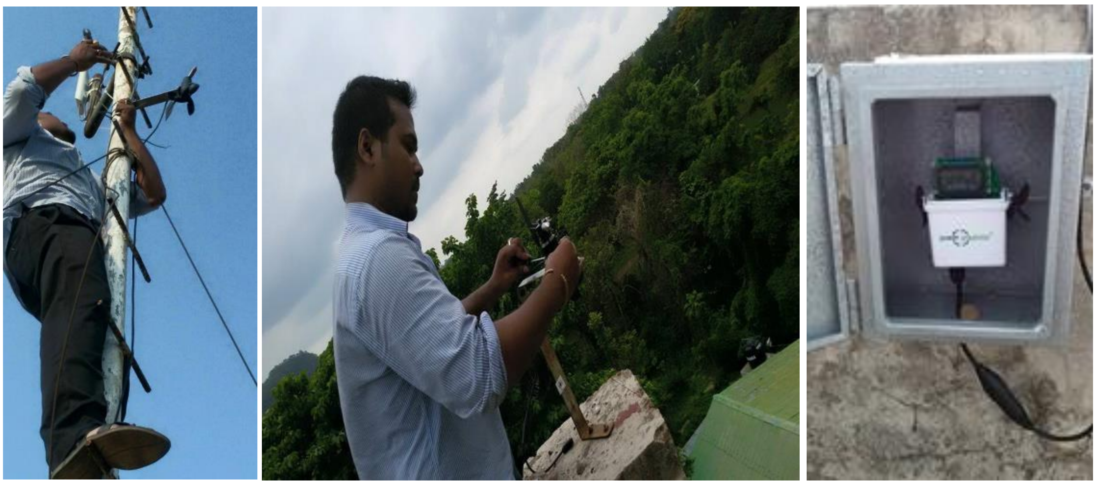
6.1 Introduction

Wind speed at the roof top of the multistoried buildings in the Chattogram coastline could be a good source of wind power. A site (Lat: 22.2877° N, Long: 91.7751° E in Chattogram Export Processing Zone (CEPZ)) was selected for wind speed measurement. This site is selected because it is within the 2 km radius of the coastline. A wind data logger unit is installed in a multistoried building which is a garment factory. The building is only about 1.5 km distant from the coastline. There is no other taller buildings around 2 km periphery of the said building. So there was no physical obstacle for wind flow. Wind speed data are recorded from July, 2015 to June, 2016. The power predictor data logger and 3 cup anemometer were used to record data. The sampling time of data collection was 10 seconds. The data were measured above 30 meter from the ground or 59 meter from the sea level. Statistical methods are used to predict the characteristics of wind speed at the site [198-199]. Also a probable wind power production calculation is performed to portray the site performance [200]. Fig. 6.1 shows the Chattogram site (a) and south side view (b) of the site

(a) **(b)**

Fig. 6.1. (a) Chattogram site (b) Chattogram site South view

Weibull shape and scale parameters are determined using three methods which are given in following sections. Energy and power production analysis are done based on these parameters. Another similar assessment has been conducted to analyze the wind power potential at building rooftops in Dhaka city. For this research, a six storied commercial building in Dhanmondi Thana located at lat: 23.7390° N, long: 90.3831° E has been selected to install a wind data logger on its rooftop. The building is used as a shopping complex and within its 1 km periphery, there are no taller buildings on the South and East sides of the building. Wind speed data have been recorded from April 2017 to March 2018 which have been taken from a height of approximately 23 meters above the ground or 27 meter from the sea level.



(a) **(b)** **(c)**

Fig. 6.2. (a) (b) Site maintenance (c) Data logger central unit

Statistical methods are applied to predict and characterize the site. Weibull Shape and scale parameters are determined using three different methods. Based on the obtained parameters, power and energy production analysis are done. A probable wind power production capacity is calculated to forecast the site performance as like as Chattogram site.

(a) **(b)**

Fig. 6.3. (a) Dhaka site South view (b) Dhaka site East view

The used data logger measures wind speed, wind direction, and solar radiation at regular intervals, which has 10 seconds sampling rate. The data is then recorded by the data logger and stored on a memory storage then transferred to a computer for analysis using specialized software provided in data logger package.

(a) **(b)**

Fig. 6.4. (a) (b) Installed data logger and sensor at Dhaka site

6.1.1 Wind Rose and distribution characteristics

Wind Rose diagram of distribution based on wind directions of the Chattogram site is shown in Fig. 6.5. Distribution shows that the stronger wind flows from the E, and ESE corner of Chattogram site. However impactful wind samples are found from SSW, W, NNW corner here. For Dhaka site most significant wind samples are found from S, SW and SE directions.

Wind Rose Diagram of Chattogram Site

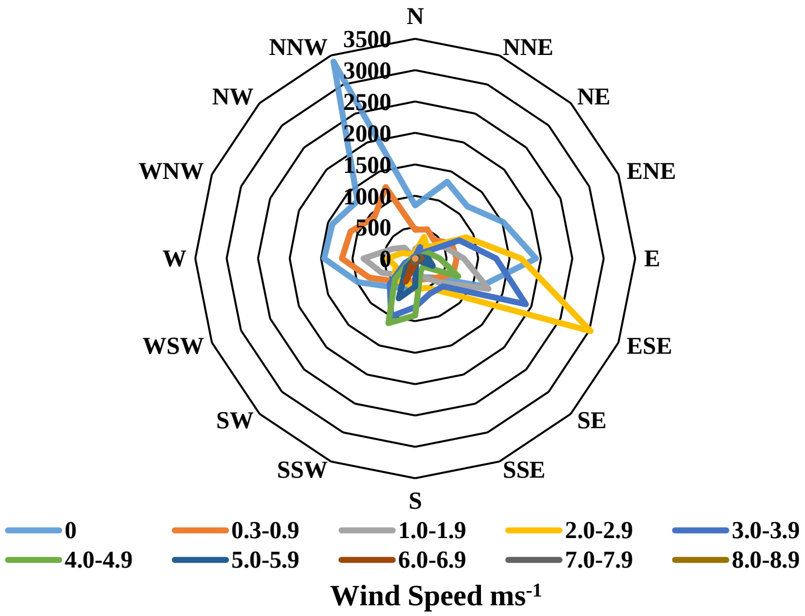


Fig. 6.5. Wind Rose diagram for Chattogram site

There are other mentionable wind samples found from S, SSW, SW, WSW, WNW and NW sides but the samples are comparatively lower wind speeds in

Chattogram. Fig. 6.7 shows the wind rose for the Dhaka site. The Fig. 6.7 shows that there are wind flow available from all the sides of the site however, some area expose lower speed. To capture all the samples, 360 degree vane rotating turbine is best suitable however, vane lock angle can be chosen from NNW corner to E corner through Northern side to shed off the low speeds. Like Chattogram site, 360 degree vane rotation turbine can be installed in Dhaka site. Similarly, vane lock can be imposed for WNW corner to ESE corner through Northern side. Fig. 6.6 and 6.8 are presenting the wind power density with bar diagram. It shows the category wise wind power distribution in a particular direction of the site.

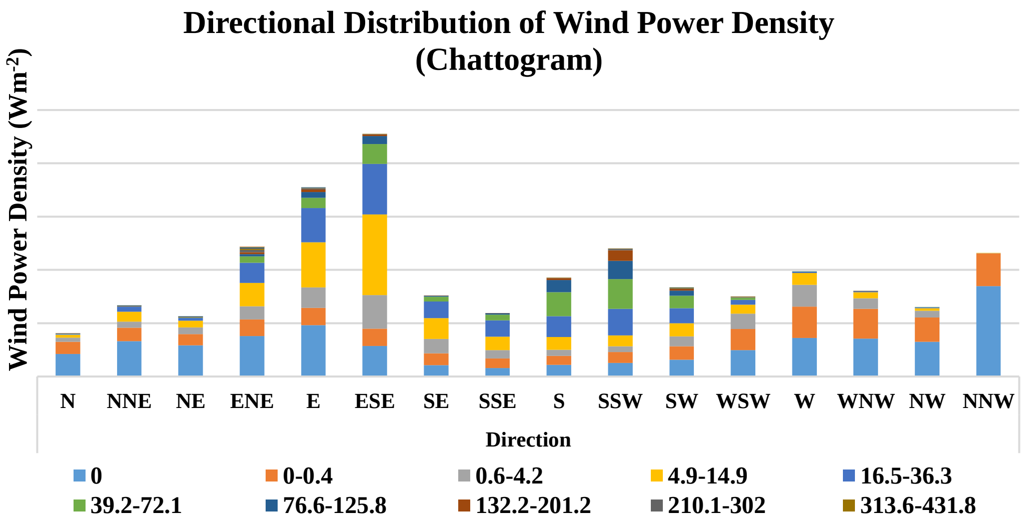


Fig. 6.6. Distribution of wind power density of Chattogram site

6.1.2 Time Segmented Wind Speed Characteristics

Time-segmented wind speed refers to the process of dividing wind speed data into segments or time periods for analysis. This technique involves breaking down the wind speed data into smaller intervals, such as hourly or daily periods, and analyzing the data separately for each time segment. By segmenting wind speed data in this way, it is possible to identify patterns or trends in wind speed that may not be evident when looking at the data as a whole.

Fig. 6.9 and 6.10 show the semi diurnal wind speed characteristics for Chattogram and Dhaka site. Four segments of timeframes with six hours' interval i.e. 00:00- 06:00, 06:01- 12:00, 12:01-18:00, and 18:01- 23:59 are taken for the simplicity of data analysis. From midday to late afternoon or early evening. It is also evident that in April, May, June, July, and August exhibits higher and stable wind speed. On the other hand, other months show lower wind speeds. Time segmented speed distribution for Chattogram site shows that April to august, stronger wind flows between 12 PM to 6 PM. For other moths of the year most significant wind samples are recorded between 6 AM to 12 PM.

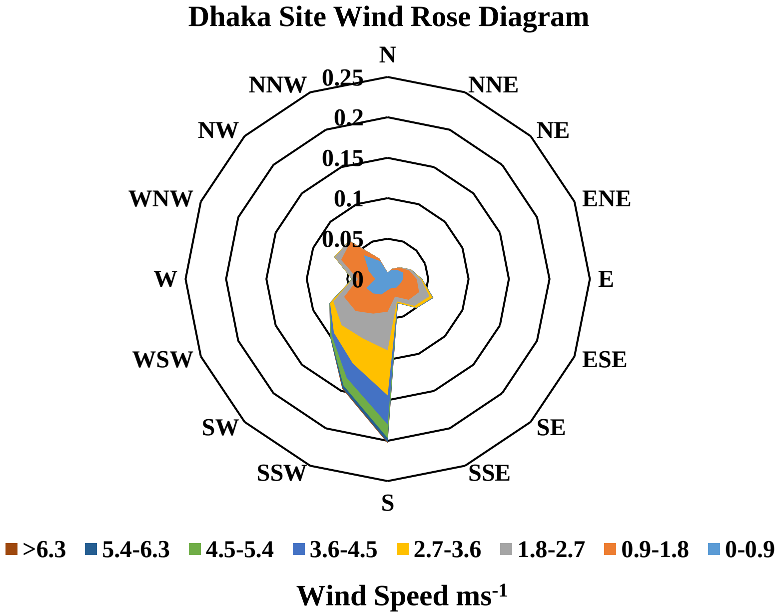


Fig. 6.7. Wind Rose diagram for Dhaka site

The lowest speeds occurs between 6 PM to 12 PM. The stronger wind for this site is at the bin of 3.5 ms^{-1} to 4 ms^{-1} and the weaker bin is for 0.5 ms^{-1} to 1 ms^{-1} speed range. The same category figure for the Dhaka site exhibits a different character.

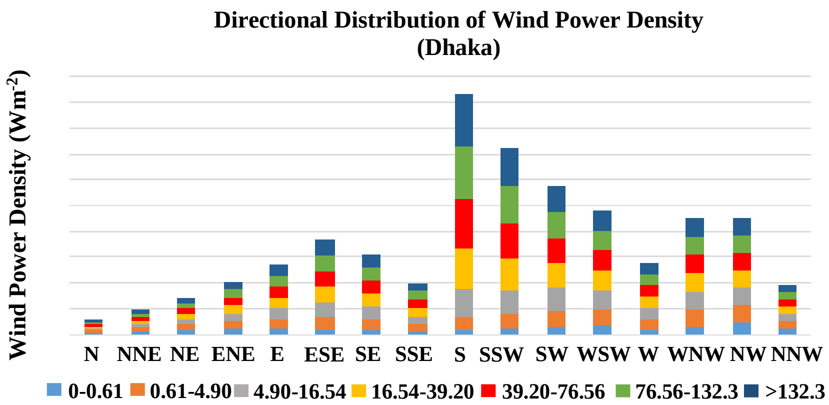


Fig. 6.8. Wind power density of Dhaka site

Stronger wind samples are found between 6 AM to 12 PM throughout the year. The lower speeds start from the mid night and last until 6 AM throughout the year. In this site stronger wind bin is in the range of 2.5 ms^{-1} to 3 ms^{-1} speeds.

Time-segmented wind speed analysis can also be used to identify wind speed fluctuations and gusts, which can be important for assessing the potential impact of wind on structures or for identifying potential safety risks. Hence, it has been carried for data collected from both the sites.

Overall, time-segmented wind speed analysis is a useful technique for analyzing wind speed data and can provide valuable insights into wind patterns and behavior over time. Fig. 6.9 and Fig. 6.10 are such images produced using recorded data from Dhaka and Chattogram.

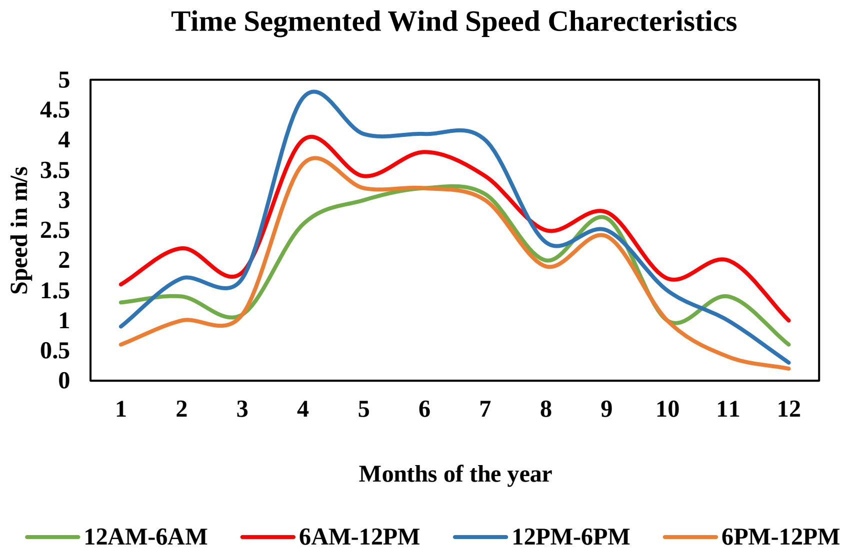


Fig. 6.9. Semi diurnal speed characteristics of Chattogram site

From the time segmented characteristics for both the site it is observed that both the sites have available wind speed samples of 2 ms^{-1} to 3 ms^{-1} range. This means, the wind turbines can be used to continue the power production after or before the sunshine hours if used with the solar PV.

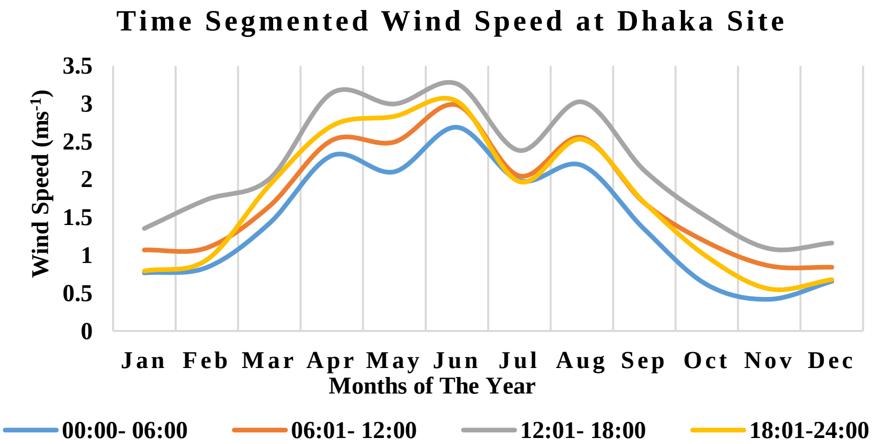


Fig. 6.10. Time segmented wind speed characteristics of Dhaka site

Table 6.1 shows mean wind speed for each months of the year. Observed data is obtained considering all recorded data. The yearly average mean for Chattogram site is found to be 2.23 ms^{-1} and 1.75 ms^{-1} at measured height 30 meter or 59 meter above sea level.

Table 6.1. Mean wind speed at measured height

Months	Mean Wind Speed Chattogram(30 m)	Mean Wind Speed Dhaka (23 m)
January	1.1	1
February	1.5	1.15
March	1.4	1.75
April	3.7	2.7
May	3.4	2.61
June	3.5	2.99
July	3.4	2.1
August	2.1	2.57
September	2.6	1.71
October	1.3	1.07
November	1.2	0.74
December	1.5	0.85
Yearly	2.23	1.75

6.2 Methodology

For wind data analysis the three parameter Weibull distribution function can be expressed by two parameters [201]. The two parameter Weibull distribution is widely used to analyze wind data characteristics [200]. This distribution is distinct and is actually a generalized gamma distribution. It gives better curve fitting and accuracy for month wise probability density distributions of measured wind speed [202]. The Weibull probability density function is expressed as,

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{6.1}$$

Where,

v is the wind speed.

c is the scale parameter. c is the characteristic wind speed of the distribution. It shows how windy is the site [203].

k is the shape factor. The parameter k identifies the shape or breadth of a wind speed distribution [201,204].

Cumulative distribution function of Weibull distribution is an additional part of the probability density function [205] (PDF), and it is stated as, equation 6.2.

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{6.2}$$

Weibull shape factor k and scale factor c can be determined using a number of methods [202]. Curve fitting with probability density function, Method of moments (MOM) and Empirical methods are mostly used to determine the k and c parameters [202]. The empirical methods are useful and used to optimize wind energy systems and predict wind conditions for various applications.

6.2.1 Graphical Method

The graphical method of curve fitting equations can be derived using the logarithm transformation of CDF equation given in eq. 6.2. The derivation needs two times use of logarithms. The steps are given below.

$$ln[1 - \mathrm{F(v)}] = ln[e^{-\left(\frac{v}{c}\right)^k}] \tag{6.3}$$

$$=> ln[1 - \mathrm{F(v)}] = -\left(\frac{v}{c}\right)^k$$

$$=> -ln\{1 - \mathrm{F(v)}\} = \left(\frac{v}{c}\right)^k$$

$$=> ln[- ln\{1 - \mathrm{F(v)}\}] = ln \left(\frac{v}{c}\right)^k$$

$$=> ln[-ln\{1 - \mathrm{F(v)}\}] = \mathrm{k}\, ln(v) - k ln(c) \tag{6.4}$$

Equation 6.4 can be expressed as a straight line as shown in equation 6.5.

$$Y = mx + a \tag{6.5}$$

Where,

$$Y = ln[-ln\{1 - F(v)\}]$$

$$m = k$$

$$x = ln(v)$$

$$a = -k\, ln(c)$$

The slope of the equation 6.5 is denoted by m and it is the parameter k for the Weibull distribution. The parameter c can be found from the intercepts between the slope and y curve expressed in equation 6.6 or 6.7.

$$\frac{a}{m} = \frac{-k ln(c)}{k} \tag{6.6}$$

or,

$$c = e^{-\left(\frac{a}{m}\right)} \tag{6.7}$$

Now, to calculate the values of a and m the regression equation 6.8 and 6.9 is used. These statistical formulas can be used to calculate n pairs of (x, y) values [206].

$$M = \frac{n \sum_1^n xy - \sum_1^n x \sum_1^n y}{n \sum_1^n x^2 - (\sum_1^n x)^2} \tag{6.8}$$

$$a = \frac{\sum_1^n y \sum_1^n x^2 - \sum_1^n x \sum_1^n xy}{n \sum_1^n x^2 - (\sum_1^n x)^2} \tag{6.9}$$

This regression method is also knows as the least square regression method [206, 207].

6.2.2 Method of Moment

The method of moment provides similar result as of maximum likelihood method. First two moments of the Weibull density function are used to find the parameters k and c. The formula uses standard deviation σ , mean wind velocity v and gamma Γ function. Gamma function, given as equation 6.14 which is calculated on (1+1/k). The two moments are given in equations 6.10 and 6.11.

$$v = c\Gamma\left(1 + \frac{1}{k}\right) \tag{6.10}$$

$$k = \left(\frac{0.9874}{\frac{\sigma}{\bar{v}}}\right)^{1.0983} \tag{6.11}$$

Where,

σ is the standard deviation

$\bar{v}$ is the mean wind speed

6.2.3 Empirical Method (Method of Justus)

Similar to that of MOM, Empirical method uses standard deviation and mean wind speed. These are given in equation 6.12 and 6.13. Equation 6.13 uses gamma function given in equation 6.14.

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \tag{6.12}$$

$$c = \frac{\bar{v}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{6.13}$$

$$\Gamma(x) = \int_0^\infty t^{x-1} e^t dt \tag{6.14}$$

6.2.4 Most Probable and Maximum Energy Carrying Wind Speed

To estimate wind energy, there are two most important wind speeds required. These are, the most probable wind speed and the maximum energy carrying wind speed [208-209]. The highest peak of the probability density function represents the most probable wind speed. And the speed having the most energy is the other parameter. The maximum energy carrying speed and most probable wind speeds are used to calculate turbine related speeds for a particular site. Study shows that if the maximum energy carrying speed is close to the rated wind speed of the turbine, the site performs well in terms of energy production [210]. In practical, the condition might not always be met due to seasonal variation of wind speed where the wind distribution has a variety range of speeds. However, during the selection of turbines the turbine related speeds are observed for better selection. Turbine related speeds are cut-in speed, rated speed, cut-out speed, etc.

Here, most probable wind speed (v_p) and maximum energy carrying wind speed (v_m) are calculated using equation 6.15 and 6.16. Result is derived for each month and presented in Table 6.4. Again it is evident that at this height three to five months of a year could be productive for these particular sites.

$$v_p = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \tag{6.15}$$

$$v_m = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \tag{6.16}$$

6.2.5 Wind Turbine Related Speeds and Turbine Selection

Three characteristics speeds of a turbine is very important for the turbine selection. These three are cut in speed, rated speed and cut off speed. These parameters can be determined using equation 6.17, 6.18 and 6.19 [211]

$$V_m \leq V_f \leq (2 \text{ to } 4)\ V_m \tag{6.17}$$

$$(1.5 \text{ to } 3)\ V_m \leq V_r \leq V_f \tag{6.18}$$

$$0.3\ V_p \leq V_c \leq 0.8\ V_f \tag{6.19}$$

Where,

V_f is the cut off or braking speed (ms^{-1}) for the turbine. It is also known as the furling velocity.

V_r is the rated velocity at which turbine produces its rated power output

V_c is the speed at which the turbine starts moving to produce power.

6.2.6 Power and Energy Measurement

Based on Weibull parameters, Power density and Energy density are calculated using equations 6.23 and 6.24. Table 6.6 contains month wise k, c, power (Pd) and energy density (Ed) for a given period of time are presented in Table 6.4. Air density ρ is calculated against the pressure and temperature data of this site using equation 6.20. [212]. Air density depends on various factors like humidity, temperature and air pressure. The air density constantly changes over time as temperature and other dependencies changes.

$$\rho = 1000\left(\frac{287.05P}{t+273.15}\right) \tag{6.20}$$

$$p_d = \frac{1}{2n}\rho \sum_{i=1}^{n} v_i^3 f_i \tag{6.21}$$

$$p_d = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{6.22}$$

$$E_d = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) T \tag{6.23}$$

Here, in equation 6.23,

T is the time period of wind flow.

There are several methods to calculate wind power density. There is an average kinetic energy method, equation 6.21, which uses n number of wind streams for a particular period and speed v with the number of occurrence f between different intervals. It calculates the wind power for per unit area of the turbine blade plane. This equation is later used to find the error between measured wind data and Weibull parameters from different methods to choose for the best matched method of Weibull parameters.

In this research, the wind speed data are acquired at 23-meter height, however, wind speed can be estimated at different heights from the following equation: [213]

$$V_n = V_o \left(\frac{H_n}{H_o}\right)^{\alpha} \tag{6.24}$$

Where,

V_n the new speed at a new height,

V_o is the measured speed at measuring height,

α is the Hellmann exponent or shear exponent.

The value of which is generally considered to be 1/7. The location is a human-inhabited area. There are no other taller buildings within its 1 km periphery. Thus neutral airflow can be found.

6.2.7 Output Power and Capacity

The capacity factor is the measure of how much energy a wind turbine actually produces relative to the amount of energy it could potentially produce if it ran at full capacity all the time. It depends on various factors such as wind speeds, turbine design, maintenance, and environmental conditions. Average power output and capacity factor (CF), denotes the prospect of a wind power generation site. On the basis of Weibull parameter equation 6.25 are used to determine the probable performance of a wind turbine.

$$c_f = \left(\frac{e^{-\left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_{rated}}{c}\right)^k}}{\left(\frac{v_{rated}}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_f}{c}\right)^k} \right) \tag{6.25}$$

6.3 Determination of Weibull Parameters

Three methods have been selected to characterize wind shape factor and scale factor. The graphical method of curve fitting, method of moment and empirical method (Method of Justus) are used for two different sites, one at Dhaka (Dhanmondi) another at Chattogram (CEPZ).

6.3.1 Graphical Method of Curve Fitting

Frequency distribution is matched with the Weibull probability density function (PDF) from which the parameters are determined and shown in Fig. 6.11. Cumulative distribution function, CDF curve is determined, shown in Fig. 6.12. At first, the frequency distribution of recorded data is constructed using Microsoft excel program. For this, wind speed data is stratified and classed into different groups. The sample data of the same class is counted and the number of occurrence is taken as the input data for that class. Then the percentage sample from each group is determined to plot a histogram [214]. A graphical interpretation tool is used to obtain the Weibull PDF curve shown in Fig. 6.11. It uses the measured wind speed frequency distribution to interpolate the approximate Weibull distribution curve and finds the closest fit value of k and c of the distribution using solver algorithm [215]. Here, the "SWISS Wind Power Data Analyzing Tool" is used as it uses the least square regression method [216]. The percentage of sample frequency of classed sample is given as input to this software [217]. It has been used to analyze and fit frequency distribution to the corresponding PDF.

The same procedure is also followed for determining the parameters for each month of the year. Parameters are also calculated using MOM and Empirical method and presented in Table 6.2. It shows shape and scale parameter of the Weibull distribution for the monthly recorded data. Fig. 6.11 shows the frequency distribution and Weibull PDF curve for the Chattogram site.

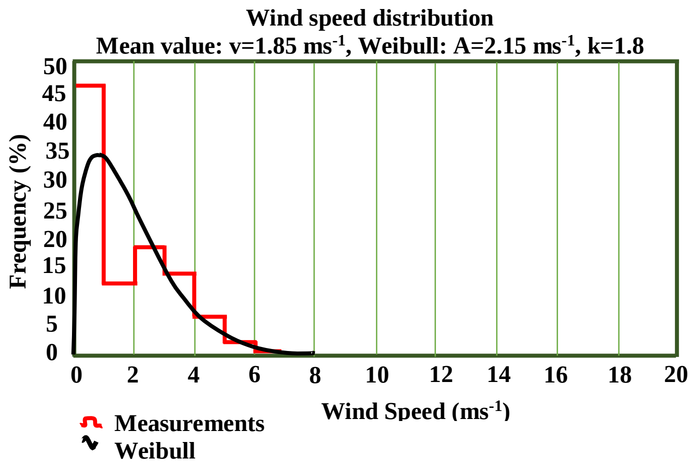


Fig. 6.11. Frequency distribution of Chattogram site

From PDF graph it is evident that the most probable wind speed at 30 meter height for this site is about 1.85 ms^{-1}. It is found to be 1.8 as yearly average value. The characteristics wind speed for this site is 2.2 m/s.

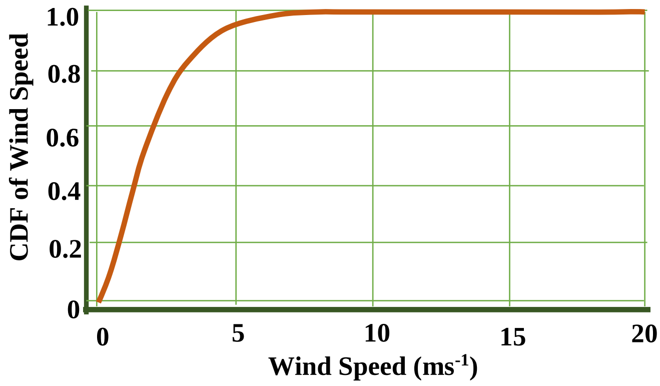


Fig. 6.12. CDF of Chattogram site

This used tool first generates a frequency distribution curve for given input then it compares for the best fit between the frequency distribution curve and the PDF from which the Weibull parameters are determined. First, the parameters have been obtained by using the year-long data. Later, similarly, the parameters have been determined for each month of the year. Fig. 6.13 shows the Weibull Distribution for the data obtained over the year for Dhaka site.

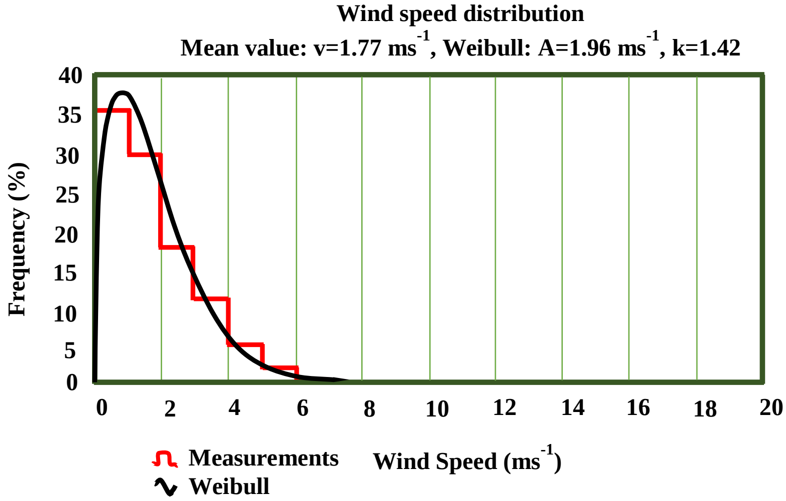


Fig. 6.13. Frequency distribution and Weibull PDF for Dhaka site

The cumulative distribution curve (also known as a cumulative frequency curve or an ogive) is a graphical representation of a cumulative distribution function (CDF) that shows the cumulative probability of a random variable taking a value less than or equal to a given value on the horizontal axis. The cumulative distribution curve is obtained by using the scale and shape factor found from the graphical interpretation of the Probability Density Function (PDF).

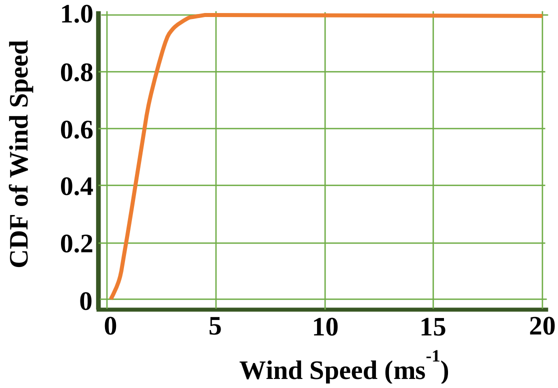


Fig. 6.14. CDF of Dhaka site

For both The sites a stable trend of wind flow is observed from the month of April to September. The value of k ranges between 2.78 to 3 and c between 3.56 m/s and 3.98 ms^{-1} for Chattogram site. Form Dhaka site it has been between 1.7 to 2.53 for k and 1.99 ms^{-1} to 3.38 ms^{-1} for c. Monthly values of k and c found by Method of Moment and Empirical Method have deviation from values found by calculated PDF (Table 6.2). Deviations are between ±0.1. Regression analysis is carried out for all months to test the goodness of fitting provided by the graphical method. Most of the months it shows a 60% to 70% variance that means the curve obtained from the graphical method is 70% closer to the measured data points. For yearly data, R^2 is found to be 72% where the average is 66%. The standard deviation between all months' scale factor is within 0.9 to 0.93 and for the shape factor it is within 0.42 to 0.45. The standard deviation for R^2 value for the months is about 0.13.

Table 6.2. k and c for Chattogram and Dhaka site at measured height

Month	**Chattogram (30 Meter)**							**Dhaka (23 Meter)**					
	Goodness of fit (R^2)	**Graphical Method**		**Method of Moment**		**Justus Method**		**Calculated PDF**		**Method of Moment**		**Justus Method**	
		k	**c**	**k**	**c**	**k**	**c**	**k**	**c**	**k**	**c**	**k**	**c**
Jan'16	0.64	1.28	1.33	0.93	1.06	0.95	1.07	1.76	1.18	1.62	1.11	1.64	1.11
Feb'16	0.57	1.01	1.07	1.26	1.61	1.27	1.61	1.11	1.21	1.11	1.2	1.12	1.2
Mar'16	0.72	1.06	1.23	1.08	1.44	1.09	1.45	1.45	1.95	1.41	1.92	1.43	1.92
Apr'16	0.6	2.93	3.98	3.13	4.14	3.08	4.14	1.93	3.05	1.92	3.04	1.95	3.04
May'16	0.51	3.00	3.95	2.89	3.81	2.84	3.82	2.09	2.98	2.02	2.94	2.04	2.94
Jun'16	0.28	2.78	3.56	3	3.92	2.95	3.92	2.53	3.38	2.58	3.37	2.6	3.37
Jul'15	0.58	1.43	3.07	1.97	3.84	1.96	3.83	1.96	2.41	1.93	2.36	1.96	2.37
Aug'15	0.38	1.88	2.55	1.24	2.25	1.25	2.26	2.32	2.92	2.35	2.9	2.37	2.9
Sep'15	0.69	2.01	3.07	1.57	2.84	1.57	2.84	1.70	1.99	1.56	1.9	1.58	1.91
Oct'15	0.68	1.01	1.01	0.87	1.21	0.89	1.23	1.37	1.23	1.29	1.15	1.31	1.15
Nov'15	0.65	1.07	0.72	1.65	1.34	1.65	1.34	1.39	0.87	1.29	0.8	1.31	0.80
Dec'15	0.65	1.48	0.68	0.99	0.5	1.01	0.5	1.68	1.00	1.62	0.95	1.64	0.95
Yearly	0.73	1.8	2.2	1.7	2.3	1.7	2.3	1.42	1.96	1.35	1.9	1.38	1.91

To choose the best matching results of k and c, the WPD of measured wind speed obtained by equation 6.21 is compared with the WPD obtained using equation 6.22. For both the sites the percentage error with the measured data is found to be around 10% with graphical method and 12% for method of moment and Justus method. Hence, graphical method data is used for the further analysis.

6.3.2 Most Probable and Most Energy Carrying Wind Speed

Power and energy production potential of a site can be determined in various ways. Energy and power density indicate the availability of producible power in every square meter [218]. Most probable wind speed is also a key point to summarize a site character. These two parameters are also used to determine the turbine. Statistical method is used to measure all these values. Generalized equations are modified as functions of Weibull parameters. Weibull Parameters, k and c determined in section 6.3 are used here to find most probable and maximum energy carrying wind speed. Equation 6.15 and 6.16 is used to calculate V_p and V_m, respectively and presented in Table 6.3.

Table 6.3. Most probable and most energy carrying speed at measured height

Months	Chattogram		Dhaka	
	Vp (ms^{-1})	Vm (ms^{-1})	Vp (ms^{-1})	Vm (ms^{-1})
January	0.41	2.77	0.73	1.82
February	0.01	3.15	0.15	3.06
March	0.08	3.34	0.87	3.55
April	3.45	4.75	2.09	4.41
May	3.45	4.68	2.18	4.1
June	3.03	4.33	2.77	4.26
July	1.32	5.66	1.67	3.45
August	1.70	3.75	2.29	3.82
September	2.18	4.33	1.18	3.14
October	0.01	2.98	0.47	2.37
November	0.06	1.93	0.35	1.65
December	0.32	1.21	0.58	1.59

6.3.3 Power and Energy Density at Measured Height

The air density is a highly changing parameter in terms of its measurements. Because it depends on the temperature, air pressure and relative humidity. Hence, the standard air density for 15°C temperature, at average sea level on 1 ATM atmospheric pressure is considered by most of the researchers for analysis and calculation.

Table 6.4. Power and Energy Density at measured heights

Months	Dhaka Site		Chattogram Site	
	P_d (Wm^{-2})	E_d ($W\text{-}hm^{-2}$)	P_d (Wm^{-2})	E_d ($W\text{-}hm^{-2}$)
January	1.56	1160.75	4.05	3011.16
February	4.54	3050.74	4.34	2914.93
March	9.69	7208.68	5.55	4127.77
April	24.02	17294.20	39.01	28090.15
May	20.61	15335.14	37.75	28084.73
June	25.86	18618.90	28.63	20614.94
July	11.65	8665.91	38.87	28918.19
August	17.72	13182.56	14.47	10768.01
September	7.86	5657.59	23.44	16873.96
October	2.73	2034.68	3.65	2714.22
November	0.94	675.40	1.08	776.14
December	1.01	754.89	0.39	293.85

Here, the standard air density 1.225 kgm^{-3} is considered for related calculations [202]. Equation 6.22 and 6.23 are used to calculate the P_d and E_d respectively and presented in Table 6.4.

From Table 6.4 it is observed that the power and energy density is considerably low. Before proceeding for the output power calculation the k and c are obtained for different heights to calculate power and energy output using same equation. Before that all wind speed data is converted for desired heights using Hellman exponent.

6.3.4 Weibull k and c for Higher Heights

To improve the site performance this analysis finds the wind speed at different heights. As the project aims to analyze the green hydrogen production and the wind power to be harnessed from urban buildings, it counts for the taller buildings in Dhaka and Chattogram cities. In Chattogram, the tallest building is about 120 meters in height. There are other several tall buildings. In next chapter detail of those sites are given. Similarly in Dhaka city the top building is about 170 meters in height. Hence, the analysis selects 60 m, 100 m, 130 m and 200 meter for two different cities to cover the tall buildings' heights. Table 6.5 shows the projected wind speeds at different heights for each month of the year. The wind speed data at different height is calculated using equation 6.24 and calculation by the graphical method is repeated as earlier to find the new k and c, at new heights.

Table 6.5. Projected wind speed at different heights

Month	Dhaka			Chattogram		
	23 m	100 m	200 m	30 m	60 m	130 m
January	1.04	1.64	2.08	1.00	1.38	1.8
February	1.19	1.9	2.41	1.15	1.22	1.59
March	1.75	2.88	3.65	1.75	1.43	1.86
April	2.70	4.44	5.63	2.70	4.59	5.97
May	2.61	4.3	5.44	2.61	3.30	4.30
June	2.99	4.93	6.24	2.99	4.02	5.23
July	2.11	3.46	4.38	2.10	3.87	5.04
August	2.57	4.24	5.37	2.57	2.43	3.16
September	1.73	2.82	3.57	1.71	3.23	4.20
October	1.12	1.76	2.23	1.07	1.31	1.70
November	0.81	1.22	1.54	0.74	0.45	0.59
December	0.90	1.41	1.78	0.85	0.26	0.33

From the projected wind speed, data sets at different heights of the separate sites, the k and c are obtained using previously discussed method. Table 6.6 shows the month wise values for k and c. Then, the obtained k and c for different heights are used to calculate the corresponding most probable speed and maximum energy carrying speed and presented the result sets in Table 6.7. Result obtained for below 100 meter, shows the potential of most probable wind speed over 2 ms^{-1} in the months of April, May, June, August and September for Chattogram site. For Dhaka site, it is for April, May, June, July and August. For both site it lasts for five months.

Table 6.6. Weibull k and c at different heights in Dhaka and Chattogram

Month	Chattogram				Dhaka			
	60 Meter		130 Meter		100 Meter		200 Meter	
	k	c	k	c	k	c	k	c
January	1.31	1.73	1.33	2.26	1.79	1.92	1.83	2.44
February	1.04	1.39	1.04	1.82	1.05	1.86	1.08	2.44
March	1.09	1.61	1.09	2.11	1.43	3.16	1.44	4.02
April	2.92	5.11	3.00	6.67	1.91	4.98	1.92	6.32
May	3.05	5.02	3.06	6.56	2.1	4.88	2.10	6.19
June	2.82	4.52	2.83	5.91	2.59	5.55	2.61	7.04
July	1.45	3.89	1.46	5.11	1.98	3.94	1.99	4.98
August	1.92	3.28	1.84	4.20	2.35	4.8	2.37	6.09
September	2.11	3.98	2.07	5.13	1.72	3.26	1.72	4.14
October	1.03	1.36	1.04	1.78	1.37	1.99	1.37	2.51
November	1.09	0.92	1.09	1.22	1.36	1.38	1.37	1.73
December	1.51	1.1	1.52	1.44	1.87	1.67	1.82	2.08

6.3.5 Determination of Turbine Related Speeds at Different Heights

Using equation 6.15 and 6.16 with the data from Table 6.6, the most probable wind speed and most energy carrying wind speeds are calculated. Table 6.7 shows the result sets for Dhaka and Chattogram sites for the heights of 60 meter, 130 meter, 100 meter and 200 meter as chosen separately for specific site.

Table 6.7. V_p and V_m at different heights

Month	Chattogram				Dhaka			
	60 Meter		130 Meter		100 Meter		200 Meter	
	V_p	V_m	V_p	V_m	V_p	V_m	V_p	V_m
January	0.58	3.51	0.79	4.51	1.22	2.92	1.58	3.65
February	0.06	3.90	0.08	5.10	0.10	5.14	0.22	6.44
March	0.16	4.19	0.21	5.49	1.36	5.83	1.76	7.36
April	4.43	6.11	5.83	7.91	3.38	7.25	4.31	9.17
May	4.41	5.92	5.76	7.73	3.59	6.71	4.55	8.51
June	3.87	5.47	5.07	7.14	4.60	6.92	5.85	8.75
July	1.74	7.07	2.32	9.23	2.76	5.61	3.51	7.06
August	2.24	4.76	2.74	6.26	3.79	6.24	4.83	7.88
September	2.94	5.46	3.73	7.11	1.96	5.10	2.50	6.48
October	0.04	3.88	0.08	4.99	0.77	3.84	0.97	4.84
November	0.09	2.39	0.12	3.17	0.52	2.68	0.67	3.34
December	0.54	1.92	0.71	2.50	1.11	2.46	1.34	3.13
Average	1.8	4.5	2.3	5.9	2.1	5.1	2.7	6.4

Similarly the power and energy density is calculated using equation 6.22 and 6.23. The result sets are shown in Table 6.8. The most energy yields are found from the month of April to September. It is observed that increasing the hub height of the turbine, the power production improves significantly for both the sites. It is because, the stronger wind speed is available over 100 meters of height for both the sites.

Equation 6.17, 6.18 and 6.19 are used to find out the turbine related speeds for the selected sites. The data is given in Table 6.9. Turbines having cut in speed below 2 ms^{-1} is not available in the market yet. However, above 2.5 ms^{-1} is common nowadays. Related speeds also show the potential over 100 m height for both sites.

Table 6.8. Power and Energy Density at different heights

Month	Chittagong				Dhaka			
	60 Meter		130 Meter		100 Meter		200 Meter	
	Pd	Ed	Pd	Ed	Pd	Ed	Pd	Ed
January	8.42	6266.95	18.13	13486.87	6.57	4888.40	13.11	9751.24
February	8.55	5748.51	19.20	12904.02	19.82	13320.13	40.67	27332.38
March	11.34	8434.33	25.52	18985.43	42.39	31536.77	86.06	64028.46
April	82.70	59543.77	181.75	130862.76	105.81	76185.63	214.98	154783.23
May	76.96	57255.59	171.50	127598.14	90.10	67036.55	183.89	136811.98
June	58.18	41892.57	129.84	93482.41	112.84	81242.33	229.24	165054.19
July	76.92	57226.97	172.03	127993.19	50.34	37450.29	101.10	75216.16
August	30.05	22358.09	66.39	49393.48	77.94	57987.20	158.18	117686.49
September	48.66	35035.09	106.14	76421.05	33.97	24457.38	69.57	50090.83
October	8.29	6169.56	17.96	13365.18	11.58	8616.68	23.24	17290.28
November	2.12	1522.99	4.93	3551.50	3.92	2825.90	7.61	5478.72
December	1.61	1198.38	3.57	2656.50	4.09	3044.02	8.18	6082.72

Table 6.9. Determined turbine related speed at different heights

Month	Chattogram			Dhaka		
	30 Meter	60 Meter	130 Meter	23 Meter	100 Meter	200 Meter
V_f	14.3	18.2	23.7	12.4	20.2	25.5
V_c	2.0	2.5	3.3	1.7	2.8	3.5
V_r	5.4	6.8	8.9	4.7	7.6	9.6

6.3.6 Turbine Selection and Performance of Turbine

Considering the measured height and projected desired heights, there are variations in turbine related speeds. To choose the suitable turbine there are some consideration for high-rise building applications. The weight of turbine should be considerably lower and light weight. Easy to install type turbine sets are the preferred one. The study of turbine speeds suggests that the cut in speed should be around 2 m/s and rated speed should be less than 10 ms^{-1} for the selected sites at different heights. However, less than 10 ms^{-1} rated velocity turbine is hardly available in the market at present. The most probable wind speed for the sites ranges between 2 to 6 ms^{-1} for about 5 months of a year.

So, light weight small capacity turbines could be a good choice. Considering the above parameters, two turbines are investigated for the performance. Turbine details are given in Table 6.10.

Table 6.10. Physical properties and features of AWM-1500D and DB

Turbine Models	AWM	DB 400
Maximum Power	1000W	400W
Rated Power	700W	400W
Rated Speed	12 ms^{-1}	12 ms^{-1}
Operating Wind Speed	0.9 ms^{-1}	2.5 ms^{-1}
Cut In wind speed	3 ms^{-1}	3 ms^{-1}
Rated Power Speed	12 ms^{-1}	12 ms^{-1}
Max Power Speed	14 ms^{-1}	14 ms^{-1}
Cut Out	15 ms^{-1}	15 ms^{-1}
Survival Speed	50 ms^{-1}	40 ms^{-1}
Rated RPM	330	950

Cut Out RPM	400	-
Size/Rotor Diameter	0.75m (Width), 1.9m (Length), 1.75m (Height)	1300mm
Weight	120 kg	6.5 kg
Control System	MPPT Control, Auto and Manual Braking System	-

Fig. 6.15. DB 400 wind turbine

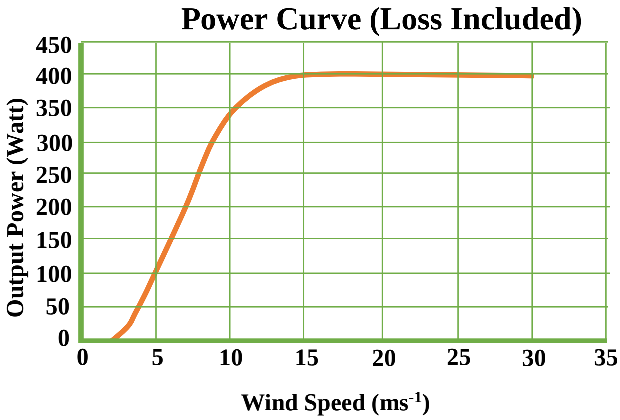


Fig. 6.16. DB 400 wind turbine power curve [219]

Fig. 6.17. AWM wind turbine

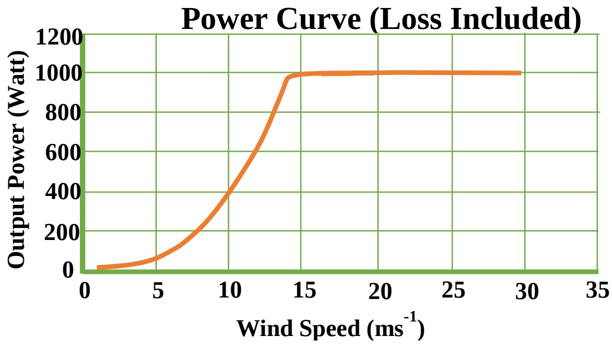


Fig. 6.18. Power curve of AWM wind turbine [220]

Table 6.11 presents month wise capacity factor for both of the sites. Equation 6.25 is used to calculate the capacity factor using the turbine related speeds from Table 6.9. The highest possible capacity factor for Chattogram site would be 36% for the month of April at 60 meter height and the peak capacity factor for the Dhaka site is found in the month of June at 200 meter. The highest capacity factor for Dhaka site would be nearly 36%.

Table 6.11. Month wise capacity factor at different heights

Month	Chattogram (Cf) [%]			Dhaka (Cf) [%]		
	30	60	130	23	100	200
January	4.23	4.45	4.17	1.57	1.43	1.40
February	4.51	4.54	4.49	7.26	7.12	7.41
March	5.74	5.97	5.93	14.95	15.05	15.30
April	34.11	35.95	35.17	31.49	31.98	32.34
May	33.01	33.58	33.31	28.87	29.37	29.77
June	26.02	26.42	26.18	34.74	35.41	35.74
July	27.95	28.17	28.14	18.11	18.21	18.28
August	14.84	15.46	15.20	25.73	26.36	26.62
September	22.72	23.60	22.95	12.75	12.77	13.10
October	3.83	4.40	4.22	4.42	4.29	4.35
November	0.89	0.87	0.90	1.00	0.96	0.92
December	0.04	0.26	0.24	0.79	0.50	0.56

6.4 Summary

The wind energy potential for all the prospective regions of Bangladesh is yet to be explored on its full scale. It is necessary to carry out resource assessment activities throughout the country. Usually the Coastline remains open from sea sides thus it gets more wind energy than the urban areas. Installing small wind turbines may be helpful to study the real time wind power generation in the coastal areas. For Chattogram site the analysis shows the Shape factor of the site is 1.8 and the yearly scale factor is 2.2ms^{-1}. The highest values of these parameters are recorded in the month of June when the maximum shape factor is 3 and the maximum yearly scale factor is 3.95 ms^{-1}. The probable wind energy density of this site would be around 148 kWhm^{-2} per year. For Dhaka site, the Shape factor of the site is found to be 1.42

and the yearly scale factor is 1.96 ms^{-1}. The shape factor is below 1.5 and represents a broader wind speed distribution. The site is found to have low wind speed; however, five months of the year might provide better performance than other months. The probable energy production capacity of this site would be around 94 $kWhm^{-2}$ per year using small lightweight turbines at measured height. The energy density significantly improves with the increase of hub height. For 30 meter increment at Chattogram site gets 1.5 times better generation profile and for 100 meter increment from measured height it gets nearly 4.5 times better generation. This relationship observed for Dhaka site also.

Several other studies conducted by organizations like NREL and Wind Minds International, indicate that the annual average wind speed can be 3ms^{-1} to 4 ms^{-1} in Bangladesh and it can be up to 6 ms^{-1} at 120 meter height in coastal regions [221-222]. The findings indicate that there is possibility to have good capacity factor and higher energy density providing wind farms in Bangladesh within 100 to 120 meters heights in contrast to the results obtained by this research.

The DB 400 turbine is found less productive in terms of capacity factor. The most productive month's capacity factor by AWM turbine is found to be nearly 30%. This turbine is actually a modified form of horizontal axis turbine. Any 1 kW turbine having the similar power curve can fit the simulation results. Thus, this turbine is selected for further analysis in next two chapters.

Usually the rooftops of garment factories remain unused. Turbines can be installed directly on the rooftop using small stands and thus can save the construction cost of big tower for each turbine. Multiple installations of such small turbines on same rooftop could increase the overall power generation capacity and could become economically viable.

Usually, the rooftops of markets, offices and in many cases, apartments remain unused. If an additional load is supported by the existing infrastructures similar wind turbines examined here can be installed directly on these rooftops using small stands and thus can save the construction cost of a big tower for each turbine. The multiple installations of such small turbines on the same rooftop could increase the overall power generation capacity of the site.

Chapter 7

Wind Powered Hydrogen Production Cost in Bangladesh

7.1 Introduction

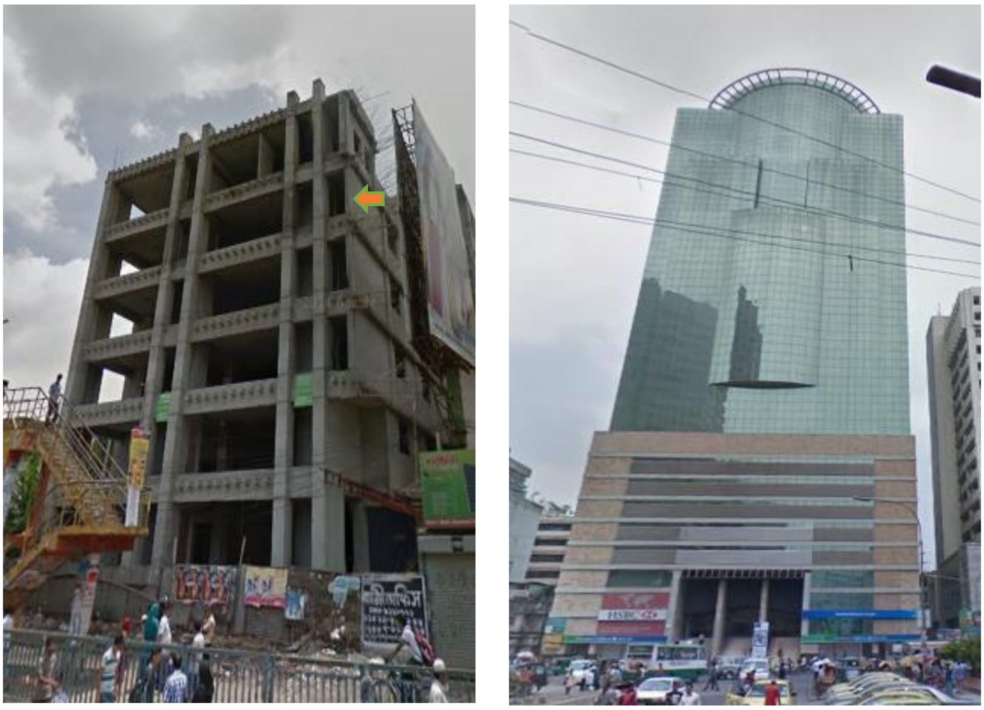
In Bangladesh solar photovoltaic has played an important role in electrifying rural households. The country has the highest number of Solar Home System (SHS) users in the world. In 2016 there were 4 million systems installed only in Bangladesh whereas worldwide it was 6 million [223]. The prospect of solar photovoltaic technology undoubtedly has shown the potential and based on that government has implemented several large PV power plants throughout the country. Government is planning to establish solar park throughout the country where nearly 44 plants will be developed having a total of 2475 MWp capacity [224]. Among these 7 plants are completed having a total of 130.23 MWp capacity. Along with these, 2.9 MWp of wind power production plants are already installed and total of 257 MWp is in planning phase. All these projects are expected to be completed within 2023.

Worldwide solar and wind are the most preferable choices to produce green hydrogen. Hydrogen is being used as a storage medium of renewable electricity produced by solar and wind. Many neighboring country has already implemented green hydrogen economy policy and started producing green hydrogen by several means. As Bangladesh is planning to implement a handful number of solar and wind power plants throughout the country, it is the high time to plan for the green hydrogen production by renewable energy sources. Worldwide, it is preferable due to the reduced production cost of hydrogen when produced from natural renewable sources which is mainly solar, wind. In Bangladesh there are a handful number of buildings in urban areas which are over 100 meters heights. Study shows that wind power potential in Dhaka and Chattogram over 100 meters height is complimentary for regular power production using small wind turbines.

On that scenario, this chapter shows an analysis on several tall buildings in Chattogram and Dhaka for the wind powered model of green hydrogen production.

7.1.1 Site Information

There are eight sites selected for data collection and analysis. Four from Dhaka and four from Chattogram, being the coastal area. There are hundreds of buildings which are having nearly 60 meters height but this research identifies 6 buildings which are having 100 meter plus heights. This is because, wind data analysis shows the prospective wind speeds above 100 meter heights for both the cities. The only measured sites are having lower heights. Among these sites, one site from each city has been set up for practical data collection as given in chapter 6.



(a) Dhanmondi Site, Dhaka
Height: 23 m
LAT: 23.7390497
Long: 90.3830172

(b) City Centre, Dhaka
Height: 171 m
LAT: 23.729444
Long: 90.399452

Fig. 7.1. (a) Dhanmondi (Measured Site) (b) City Center

(a) Hilton Dhaka, Dhaka
Height: 152 m
LAT: 23.793100
Long: 90.415300

(b) Bangladesh Bank, Dhaka
Height: 137 m
LAT: 23.726600
Long: 90.433230

Fig. 7.2. (a) Hilton (b) Bangladesh Bank

7.2 Methodology

The same methodology used in chapter five is also utilized in this chapter for HOMER parameter setup and cost components calculation.

(a) Section Seven Ltd., Chattogram
Height: 30 m
Lat: 22.2877058
Long: 91.7750588

(b) Aziz Court Imperial, Chattogram
Height: 128 m
Lat: 22.3264059
Long: 91.8163916

Fig. 7.3. (a) Section Seven (Measured Site) (b) Aziz Court Imperial

(c) Courtyard Marriott, Chattogram
Height: 120 m
Lat: 22.3215757
Long: 91.8115452

(d) Tower-71, Chattogram
Height: 104 m
Lat. 22.3272836
Long. 91.8138975

Fig. 7.4. (a) Courtyard Marriott Hotel (b) Tower-71

Fig. 7.1, 7.2, 7.3 and 7.4 shows selected sites along with latitude and longitude. The images are collected from the business websites of these buildings.

The heights of all the selected buildings are taken from published media and sources [225]. The measured sites heights were measured using a measurement tape from the ground to measurement height.

7.2.1 Components, Parameter and Costs

Wind resource data was measured for Dhanmondi site, and for other sites in Dhaka, data was retrieved from dependable sources presented in Table 7.1. Due to the legislative procedure, access was not provided for the data measurement facility towards those sites.

Table 7.1. Measured and retrieved wind data for selected sites

Months	Wind Speed (m/s)			
	Dhanmondi (23 m)	Dhaka (50 m)	Section Seven (30 m)	Chattogram (50 m)
JAN	1	3.63	1.1	3.82
FEB	1.15	3.63	1.5	3.74
MAR	1.75	4.12	1.4	4.16
APR	2.7	5.08	3.7	4.63
MAY	2.61	5.29	3.4	5.13
JUN	2.99	5.92	3.5	6.36
JUL	2.1	6.06	3.4	6.55
AUG	2.57	5.37	2.1	5.8
SEP	1.71	4.42	2.6	4.49
OCT	1.07	3.25	1.3	3.65
NOV	0.74	3.07	1.2	3.6
DEC	0.85	3.21	1.5	3.54

Table 7.1 presents measured wind data and retrieved data. In Dhaka, Weibull parameter k is found to be 1.75 and for Chattogram it is 1.78. And for retrieved data 2.21 is for Dhaka and 2.31 is for Chattogram.

The other project assumptions are same as presented in chapter 5. As the total energy requirement would be met by renewable energy, wind turbines, for this case, the annual capacity shortage is considered zero.

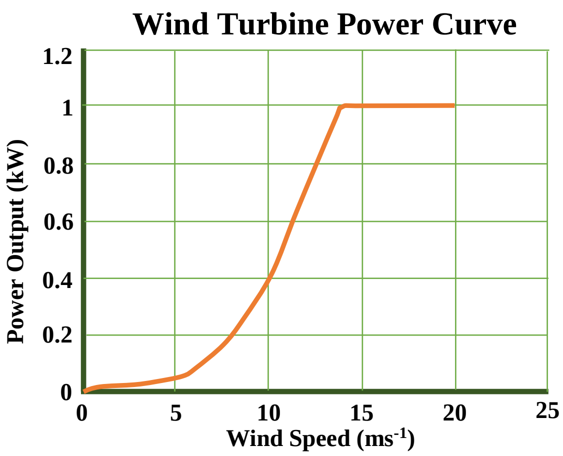


Fig. 7.5. Power curve used in simulation

In the power source module, wind turbine is configured instead of solar PV for different heights so that all possible results are obtained all together at different heights. These are set as the installation height adding 9 meters mast height to the building height.

The capital cost of turbine is set to BDT 50000, same for the replacement cost and the maintenance cost is about BDT 2000. The life time is set about 25 year's maximum. Through the analysis, this lifetime is set as a sensitivity input and conducted for 10 years lifetime, 15 years and 25 years.

To calculate the production cost of hydrogen by LCC method, the replacement cost for turbines or battery that is the power production and storage component is not considered. It is because these components' replacement cost is already considered in HOMER for calculating the cost of electricity. The annualized investment includes the cost of electrolyzer, compressor, gas storage, safety-control and miscellaneous costs. The total annualized investment cost is about BDT 14625. The annualized replacement cost considers the replacements of electrolyzer, compressor, wires-pipes, storage and safety gears and the expense is found to be BDT 2929.64 annually. The total variable cost includes the annualized replacement cost with other costs like maintenance cost of electrolyzer, compressor and salary. The total annualized variable cost is about BDT 99929.64. The annualized fixed cost accounts on the annual electricity cost, water cost and chemical cost. The amount is found to be BDT 15150 without the electricity cost. Here, in this chapter, the electricity is taken into account separately to find out the individual hydrogen production cost based on different electricity costs. The detail itemized individual costs are presented in chapter 5, Table 5.6, 5.7, 5.8 and 5.9.

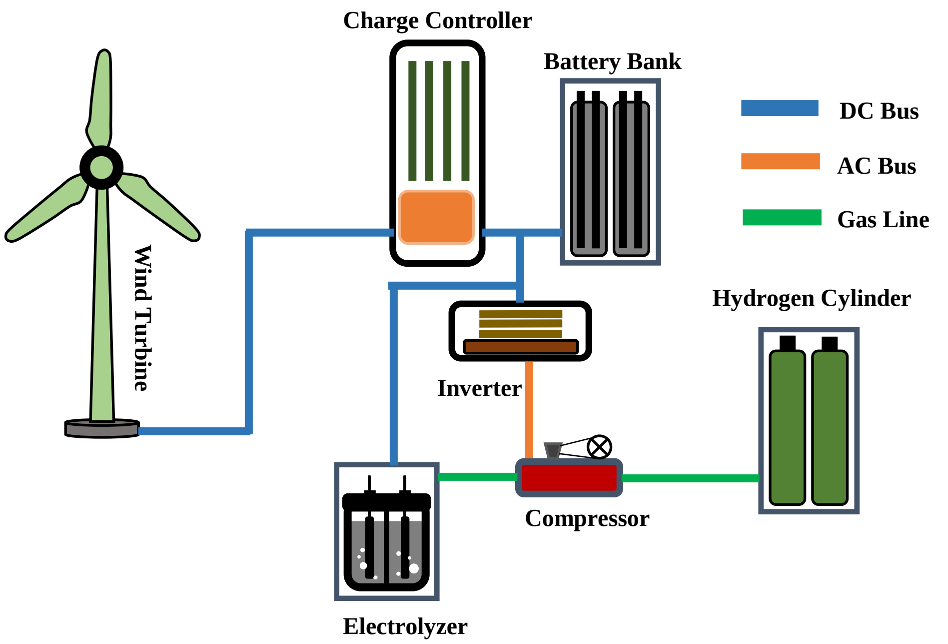


Fig. 7.6. Schematic of wind powered hydrogen production system

Fig. 7.6 shows the simplified one line diagram of the wind powered green hydrogen production scheme. As discussed in chapter 5, HOMER does not return the sizing of charge controller and also do not include its associated costs. Due to this, the cost for this system is added into LCC cost components separately after having the results derived without it.

7.3 Analysis for Dhaka Sites

There are total four sites in Dhaka. Among them one site data is measured and called as measured site. In this section, analysis and results are presented in different sections for different sites.

7.3.1 Measured site

The measured site was 23 meter high from ground level. A mast height of 9 meter is added with this height to avoid turbulence. In this section 3 consecutive analysis is presented for the measured site. One is at the installation height and rest two is on 100 and 150 meter. There are two sensitivity input for turbine which are lifetime and discount rate. It has been conducted for 10 years, 15 years and for 25 years altogether with decreasing and increasing discount rates.

At installation height HOMER finds the system configuration for the designed load. For 12% discount rate and different lifetime of turbines there are 3 configurations found.

Table 7.2. Dhanmondi site system configuration with measured data

Case No.	Nominal Discount Rate (%)	Turbine Lifetime (years)	Turbine Hub Height (m)	Turbine	Battery	Inverter (kW)
16	12	10	32	61	70	6.22
17	12	15	32	65	62	3.77
18	12	25	32	66	60	3.67

Table 7.3. Dhanmondi site system costs with measured data

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
16	10559160	198.90	494855.4	4340759	3050000	122000
17	9239609	174.06	385207.7	4399049	3250000	130000
18	8147735	153.49	296457.5	4422419	3300000	132000

Table 7.4. Dhanmondi site performance with measured data

Case No.	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
16	11621.06	87.12	1367.22
17	12383.10	77.16	1228.04
18	12573.61	74.67	1195.06

The cost of electricity (COE) varies between BDT 153.49 and BDT 198.9. The results are obtained using measured data at this site. The lowest is for case number 18 where the turbine life time is 25 years and the discount rate is 12%. For the same discount rate, due to the lesser turbine lifetime the COE increased.

Table 7.5. Dhanmondi site system configuration with retrieved data

Case no.	Nominal Discount Rate (%)	Turbine Lifetime (years)	Turbine Hub Height (m)	Turbine	Battery	Inverter (kW)
16	12	10	32	30	29	3.31
17	12	15	32	32	24	4.14
18	12	25	32	33	22	3.56

Table 7.6. Dhanmondi site system costs with retrieved data

Case no.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
16	5255197	98.98	240838.0	2228801	1500000	60000
17	4627778	84.97	188394.7	2260390	1600000	64000
18	4061056	74.55	142090.4	2275533	1650000	66000

Table 7.7. Dhanmondi site system performance with retrieved data

Case no.	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
16	11762.13	36.09	1580.90
17	12546.27	29.11	1560.11
18	12938.34	26.69	1501.17

For the retrieved data, the cost of electricity is found to be BDT 74.55 to BDT 98.98. To calculate the life cycle cost of hydrogen using the electricity cost, the method used in chapter 5 is used here. All other system component input costs are same. The calculation summary is given in Table 7.8. Measured data rows are green colored and retrieved data rows are presented in pink background.

Table 7.8. Dhanmondi site hydrogen production cost

Case No.	Discount Rate (%)	Turbine Lifetime (years)	COE	Turbine	Battery	Inverter (kW)	LCC tk/g	LCC tk/Nm^3
16	12	10	198.9	61	70	6.22	25.24	2270.52
17	12	15	174.06	65	62	3.77	22.54	2027.60
18	12	25	153.49	66	60	3.67	20.31	1826.44
16	12	10	98.98	30	29	3.31	14.38	1293.38
17	12	15	84.97	32	24	4.14	12.86	1156.37
18	12	25	74.55	33	22	3.56	11.72	1054.47

7.3.2 City Center

For the city center site, analysis uses the retrieved data. Considering the system requirement, there are three scenarios found. The electricity cost varies between BDT 61.48 to BDT 77.48. The variation of COE observed here is due to the lifetime of the turbine. For 5 year reduction in lifetime increase about BDT 8 in the cost of electricity. The highest cost of electricity is found for 10 years lifetime whereas the lowest occurred for 25 years of lifetime.

Table 7.9. City Centre system configuration

Case No.	Nominal Discount Rate (%)	Turbine Lifetime (years)	Turbine	Battery	Inverter (kW)
4	12	10	23	20	3.60
5	12	15	23	20	3.59
6	12	25	23	20	3.59

Table 7.10. City Centre system costs

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
4	4113199	77.48	186377.9	1771154	1150000	46000
5	3645772	68.68	149184.1	1771109	1150000	46000
6	3263640	61.48	118774.4	1771109	1150000	46000

Table 7.11. City Centre system performance

Case No.	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
4	40494.88	24.89	659.48
5	40494.88	24.89	659.48
6	40494.88	24.89	659.48

The calculation for hydrogen production cost shows that the production cost of hydrogen is between BDT 10.30/g or, 926.27/Nm^3 to BDT 12.04/g or 1083.13/Nm^3

Table 7.12. City Centre site hydrogen production cost

Case No.	Discount Rate (%)	Turbine Lifetime (years)	COE	Turbine	Battery	Inverter (kW)	LCC Tk/g	LCC Tk/Nm^3
4	12	10	77.48	23	20	3.6	12.04	1083.13
5	12	15	68.68	23	20	3.59	11.08	997.07
6	12	25	61.48	23	20	3.59	10.30	926.66

7.3.3 Hilton Dhaka

For the site named Hilton, the cost of electricity varies from BDT 62.65 to BDT 78.74. Table 7.13 to 7.15 shows the detail of the required system for different cases.

Table 7.13. Hilton system configuration

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine	Battery	Inverter (kW)
4	12	10	23	22	3.29
5	12	15	23	22	3.26
6	12	25	24	20	3.33

Table 7.14. Hilton system costs

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
4	4180846	78.74	190191.9	1790875	1150000	46000
5	3712383	69.92	152945.0	1790461	1150000	46000
6	3326274	62.65	120133.6	1816663	1200000	48000

Table 7.15. Hilton system performance

Case No.	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
4	36956.46	27.38	725.21
5	36956.46	27.38	725.18
6	38563.27	24.89	683.99

For Hilton site the average energy production would be nearly 37MWh/yr.

Table 7.16. Hilton site hydrogen production cost

Case No.	Discount Rate (%)	Turbine Lifetime (years)	COE	Turbine	Battery	Inverter (kW)	LCC tk/g	LCC tk/Nm^3
4	12	10	78.74	23	22	3.29	12.18	1095.45
5	12	15	69.92	23	22	3.26	11.22	1009.20
6	12	25	62.65	24	20	3.33	10.43	938.10

The highest production cost of hydrogen for this site would be BDT 12.18.

7.3.4 Bangladesh Bank

Table 7.17. Bangladesh Bank system configuration

Case No.	Nominal Discount Rate (%)	Turbine Lifetime (years)	Turbine	Battery	Inverter (kW)
4	12	10	25	19	3.50
5	12	15	25	19	3.50
6	12	25	25	19	3.50

Table 7.18. Bangladesh Bank system costs

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
4	4291616	80.84	193739.6	1857065	1250000	50000
5	3783450	71.27	153306.6	1856983	1250000	50000
6	3368089	63.44	120252.6	1856983	1250000	50000

Table 7.19. Bangladesh Bank system performance

Case No.	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
4	36947.86	23.65	700.56
5	36947.86	23.65	700.56
6	36947.86	23.65	700.56

The highest COE for Bangladesh Bank site is about BDT 80.84 and lowest is about BDT 63.44. The LCC calculation shows the range of hydrogen production cost for this site, shown in Table 7.20.

Table 7.20. Bangladesh Bank site hydrogen production cost

Case No.	Discount Rate (%)	Turbine Lifetime (years)	COE	Turbine	Battery	Inverter (kW)	LCC Tk/g	LCC Tk/Nm^3
4	12	10	80.84	25	19	3.5	12.41	1115.98
5	12	15	71.27	25	19	3.5	11.37	1022.40
6	12	25	63.44	25	19	3.5	10.52	945.83

7.4 Analysis for Chattogram Sites

Maintaining the same method of analysis as previous sections, Chattogram sites are also been assessed. One of the site which is section seven has been analyzed using both measured data and retrieved data. Rest of the three sites are analyzed using the retrieved data according to the installation height of the site. There are at least 15 high-rise buildings in Bangladesh which are having more than 100 meters of height. Among them only 3 are situated in Chattogram. These 3 are selected in this analysis to evaluate the potential of hydrogen production using wind turbines.

7.4.1 Measured site

Using the measured and retrieved data, Section Seven site is analyzed at the installation height and the system configuration results are presented in Table 7.21 to 7.26.

Table 7.21. Section Seven system configuration with measured data

Case No.	Nominal Discount Rate (%)	Turbine Lifetime (years)	Turbine Hub Height (m)	Turbine	Battery	Inverter (kW)
16	12	10	40	34	61	3.57
17	12	15	40	42	29	3.77
18	12	25	40	43	28	3.46

Table 7.22. Section Seven system costs with measured data

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
16	8317358	156.69	436424.3	2833206	1700000	170000
17	7317130	134.35	358147.8	2816608	2100000	210000
18	6676037	122.56	304567.1	2848815	2150000	215000

Table 7.23. Section Seven system performance with measured data

Case No.	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
16	7599.11	75.92	2213.36
17	9387.14	35.18	1896.06
18	9610.64	33.97	1846.38

Table 7.24. Section Seven system configuration with retrieved data

Case No.	Nominal Discount Rate (%)	Turbine Lifetime (years)	Turbine Hub Height (m)	Turbine	Battery	Inverter (kW)
16	12	10	40	24	29	3.32
17	12	15	40	24	29	3.32
18	12	25	40	24	29	3.32

Table 7.25. Section Seven system costs with retrieved data

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
16	5487987	103.37	283225.3	1928949	1200000	120000
17	5000369	94.19	244421.0	1928949	1200000	120000
18	4601623	86.68	212689.1	1928949	1200000	120000

Table 7.26. Section Seven system performance with retrieved data

Case No.	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
16	19681.86	36.09	1158.42
17	19681.86	36.09	1158.42
18	19681.86	36.09	1158.42

LCC calculation gives the hydrogen production cost for this site at the installation height which ranges between BDT 13.04/g or 1173.09/Nm^3 to BDT 20.65/g or 1857.83/Nm^3. The average energy production would be yearly 19.6 MWh having the battery autonomy of 1.5 days. The Annual throughput of battery would be around 1158 kWh. The capital required for turbine is about 12 Lac for this site.

Table 7.27. Section Seven site hydrogen production cost

Case No.	Discount Rate (%)	Turbine Lifetime (years)	COE	Turbine	Battery	Inverter (kW)	LCC Tk/g	LCC Tk/Nm^3
16	12	10	156.7	34	61	3.57	20.65	1857.83
17	12	15	134.4	42	29	3.77	18.23	1639.76
18	12	25	122.6	43	28	3.46	16.95	1524.36
16	12	10	103.4	24	29	3.32	14.86	1336.60
17	12	15	94.19	24	29	3.32	13.86	1246.54
18	12	25	86.68	24	29	3.32	13.04	1173.09

7.4.2 Aziz Court Imperial

For Aziz court imperial site the building height is selected for the hub height during the analysis. There are three cases of only wind power generation model returned by HOMER. The configuration data is shown in Table 7.28.

Table 7.28. Aziz Court system configuration

Case No.	Nominal Discount Rate (%)	Turbine Lifetime (years)	Turbine	Battery	Inverter (kW)
4	12	10	19	26	3.3
5	12	15	20	23	3.22
6	12	25	20	23	3.22

Table 7.29. Aziz Court system costs

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
4	4614661	86.91	236627.90	1641170	950000	95000
5	4230542	79.68	205173.00	1652317	1000000	100000
6	3898254	73.42	178729.80	1652317	1000000	100000

Table 7.30. Aziz Court system performance

Case No.	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
4	33304.03	32.36	747.99
5	35056.88	28.62	702.46
6	35056.88	28.62	702.46

Table 7.31. Aziz Court site hydrogen production cost

Case No.	Discount Rate (%)	Turbine Lifetime (years)	COE	Turbine	Battery	Inverter (kW)	LCC tk/g	LCC tk/Nm^3
4	12	10	86.91	19	26	3.3	13.07	1175.34
5	12	15	79.68	20	23	3.22	12.28	1104.64
6	12	25	73.42	20	23	3.22	11.60	1043.42

7.4.3 Courtyard Marriott

For this site, the analysis is done using retrieved data. Results are shown in Table 7.32 to Table 7.35. The system configuration shows that at least 19 turbines are required in this site having the highest number of batteries to be 29. The lowest number of batteries for this site is 20 where 22 wind turbines are required. The highest NPC is about 47 Lacs with an operating cost of 2.5 lacs per year.

Table 7.32. Courtyard Marriot system configuration

Case No.	Nominal Discount Rate (%)	Turbine Lifetime (years)	Turbine	Battery	Inverter (kW)
4	12	10	20	26	3.76
5	12	15	19	29	3.59
6	12	25	22	20	3.31

Table 7.33. Courtyard Marriot system configuration

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
4	4751204	87.24	244496.30	1678838	1000000	100000
5	4366174	82.25	213478.20	1683585	950000	95000
6	4004450	75.41	182086.30	1716334	1100000	110000

Table 7.34. Courtyard Marriot system configuration

Case No.	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
4	33067.16	31.54	801.85
5	31413.80	36.09	794.91
6	36373.88	24.89	660.35

Table 7.35. Courtyard Marriot site hydrogen production cost

Case No.	Discount Rate (%)	Turbine Lifetime (years)	COE	Turbine	Battery	Inverter (kW)	LCC tk/g	LCC tk/Nm^3
4	12	10	87.24	20	26	3.76	13.10	1178.57
5	12	15	82.25	19	29	3.59	12.56	1129.77
6	12	25	75.41	22	20	3.31	11.82	1062.88

The highest COE at this site is about BDT 87.24. The hydrogen production cost for this site is BDT 11.82/g or, BDT 1062.88/Nm^3 to BDT 13.10/g or BDT 1178.57/Nm^3, depending on the lifetime of the turbines.

7.4.4 Tower-71

Table 7.37 to 7.39 shows the configuration, costs and performance of the proposed systems. The highest coe is found to be BDT 90.99 for this site at installation height. The analysis uses the retrieved data for the simulation.

Table 7.36. Tower-71 system configuration

Case No.	Nominal Discount Rate (%)	Turbine Lifetime (years)	Turbine	Battery	Inverter (kW)
4	12	10	21	24	3.30
5	12	15	21	24	3.28
6	12	25	21	24	3.29

Table 7.37. Tower-71 system costs

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Turbine O&M Cost (BDT)	Initial capital (BDT)	Turbine Capital Cost (BDT)
4	4831521	90.99	247922.00	105000	1716106	1050000
5	4403971	82.94	213923.00	105000	1715792	1050000
6	4055486	76.37	186179.00	105000	1715941	1050000

The annual average energy production for this site would be around 30 MWh.

Table 7.38. Tower-71 system performance

Case No.	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
4	30354.42	29.87	811.63
5	30354.42	29.87	811.61
6	30354.42	29.87	811.62

Table 7.39. Tower-71 site hydrogen production cost

Case No.	Discount Rate (%)	Turbine Lifetime (years)	COE	Turbine	Battery	Inverter (kW)	LCC tk/g	LCC tk/Nm^3
4	12	10	90.99	21	24	3.3	13.51	1215.24
5	12	15	82.94	21	24	3.28	12.64	1136.52
6	12	25	76.37	21	24	3.29	11.92	1072.27

For the Tower 71 site, the lowest production cost is found to be BDT 11.92/g or BDT 1072.27/Nm^3 and the highest is BDT 13.51/g or BDT 1215.24/Nm^3 as shown in Table 7.39.

7.5 Sensitivity Analysis for Hydrogen Production Cost

There are total eight sites that undergone for the analysis. To perform the sensitivity analysis, several parameters are selected to examine the change in the cost of electricity. These parameters are nominal discount rate, turbine lifetime and turbine hub height for the measured sites. And for all other sites the hub height remains fixed only the turbine lifetime and discount rate is selected as sensitivity parameter.

Table 7.40. Sensitivity parameters

Parameters	Values
Discount Rate (%)	8,10,12,14
Turbine Lifetime (Years	10,15,25
Hub Height (Meters)	Installation height, 100, 150

7.5.1 Dhaka Site Sensitivity

Considering all the selected sensitivity factors HOMER returns total 36 cases for retrieved and measured data set of the Dhanmondi site. Due to the data volume, only case wise changes in electricity cost due to sensitivity is presented in this chapter. Detail data are given in appendix E, Table E- 7 to E-21 for the reference of Dhaka sites test cases. The highest COE for this site using measured data is found to be BDT 211.73 which is the case number 25 and the lowest is BDT 92.37 for case number 33. This implies the production cost to be 26.64/g or 2395.98/Nm^3 highest. Fig. 7.7 shows the COE for Dhanmondi site.

Similarly Fig. 7.8 shows the variation for City Centre site and Hilton site. The maximum COE for City Centre is found to be BDT 82.07 and lowest is BDT 50.87. The production cost for this site is between BDT 12.54/g or BDT 1128.01/Nm^3 to BDT 9.15/g or BDT 822.90/Nm^3. For Hilton, the highest COE is BDT 83.34 and lowest is BDT 51.76 which results the production cost to be BDT 12.68/g or BDT 1140.43/Nm^3 to BDT 9.25/g or BDT 831.60/Nm^3.

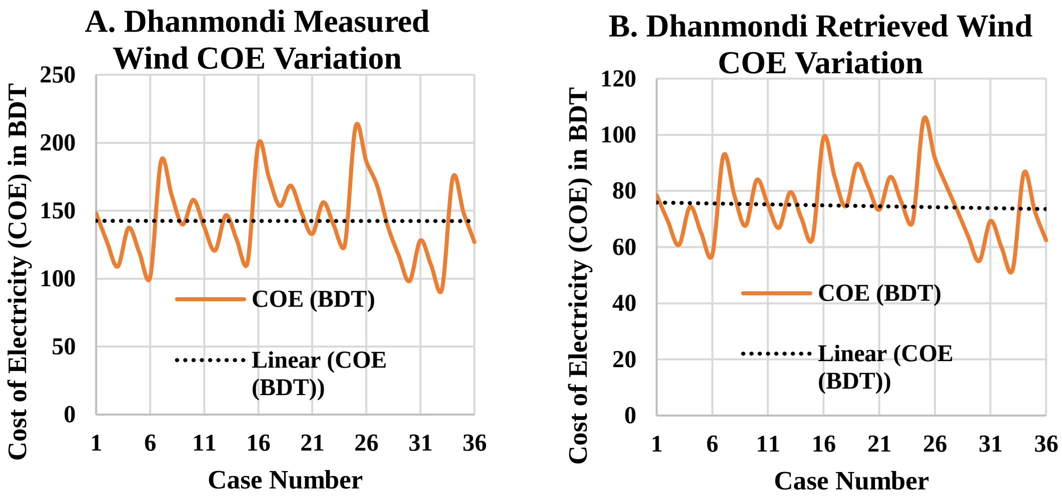


Fig. 7.7. Variation of COE based on cases of Dhanmondi site

Fig. 7.9 shows the variation of cost of electricity between test cases for sensitivity of Bangladesh Bank site. This site shows the highest electricity cost to be BDT 86.33 and lowest about BDT 52.32. This implies the production cost for this site ranges between BDT 13.00/g or 1169.67/Nm^3 to BDT 9.31/g or 837.08/Nm^3.

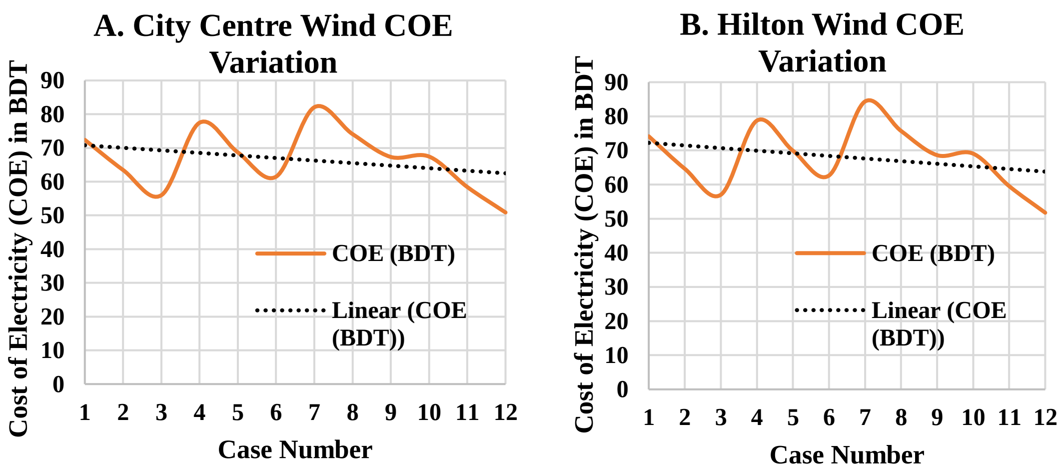


Fig. 7.8. Variation of COE for City Centre (A) and Hilton (B)

7.5.2 Chattogram Site Sensitivity

For Chattogram, measured site that is Section Seven, the highest COE is BDT 165.06 among 36 cases for the measured data set which is given in appendix E in detail. In appendix Table E-22 to E-32 present all Chattogram site sensitivity cases. The lowest COE is about BDT 88.22. The lowest cost of hydrogen to be BDT 13.21/g or 1188.15/Nm^3 for the lowest cost of electricity.

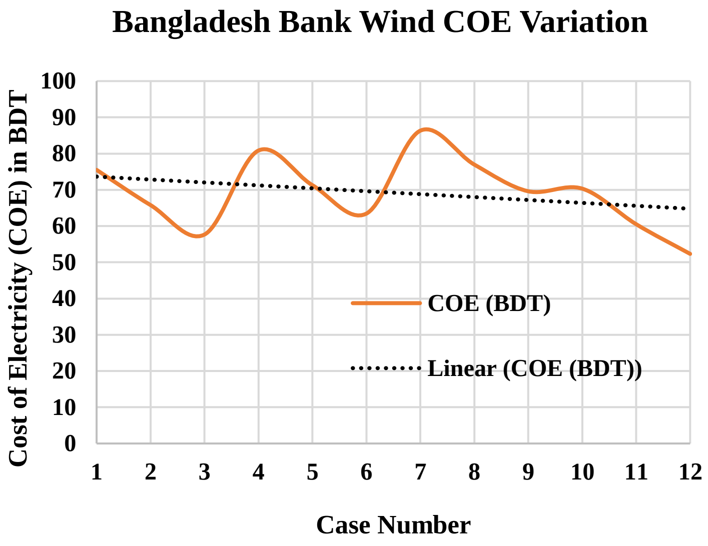


Fig. 7.9. Variation of COE for Bangladesh Bank site

For the retrieved data set the highest COE is BDT 109.07 and the lowest is BDT 54.76 among 36 cases. The cost of hydrogen is found to be BDT 15.48/g or 1392.05/Nm^3 and BDT 9.57/g or 860.94/Nm^3 for this electricity cost range. Fig. 7.10 shows the variation for retrieved data and measured data of section seven site.

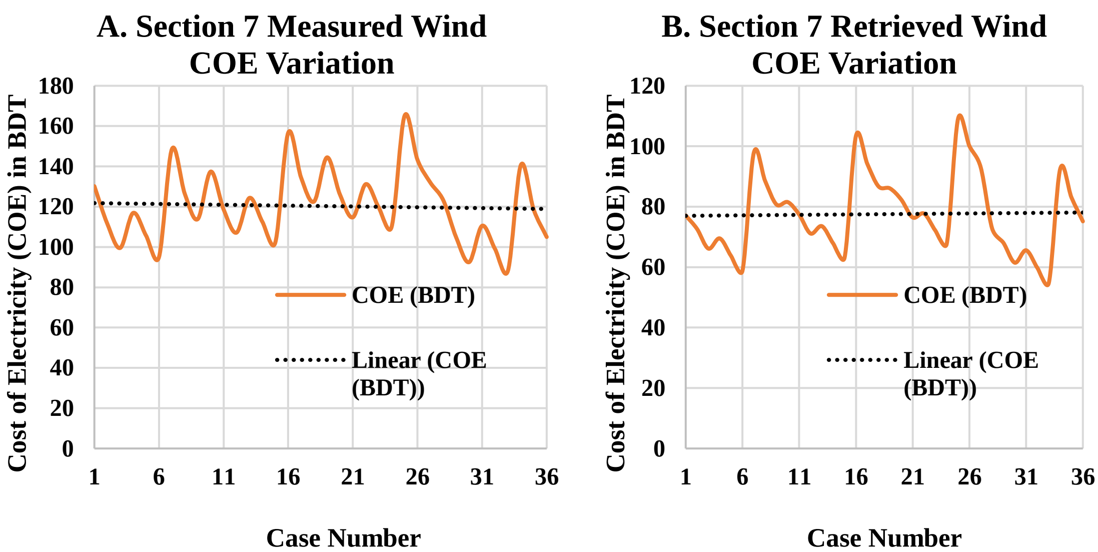


Fig. 7.10. Variation of COE based on cases of Section Seven

Fig. 7.11 shows the electricity cost variation of Aziz Court Imperial and Courtyard Marriot site. For Aziz court the highest COE is BDT 91.77 and lowest is BDT 63.56 which implies the hydrogen cost for BDT 13.60/g or 1222.87/Nm^3 and BDT 10.53/g or 947.00/Nm^3. Similar analysis shows for Courtyard Marriot site, highest COE BDT 92.08 and lowest for BDT 65.14. The levelized cost of hydrogen is highest BDT 13.63/g or 1225.90/Nm^3 and lowest BDT 10.70/g or 962.45/Nm^3 for Courtyard Marriot.

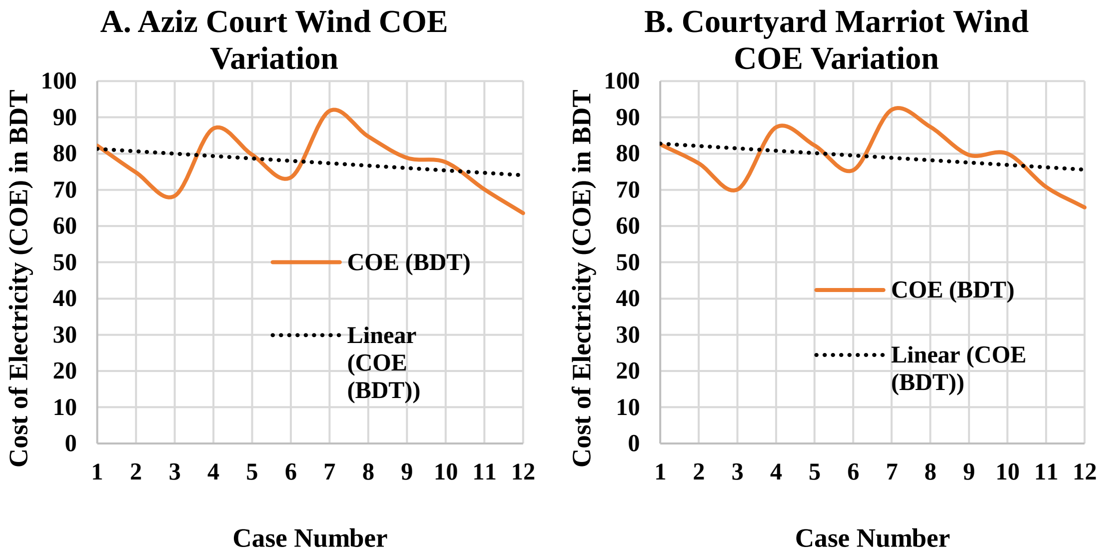


Fig. 7.11. Variation of COE for Aziz Court (A) and Courtyard (B)

The Fig. 7.12 shows the variation of COE of the last site named Tower-71 among the eight subjected wind harvesting sites. Tower-71 has the highest COE of BDT 96.06 and the lowest about BDT 66.13. It results the highest hydrogen production cost about BDT 14.06/g or 1264.82/Nm^3 and lowest about BDT 10.81/g or 972.13/Nm^3 for this site.

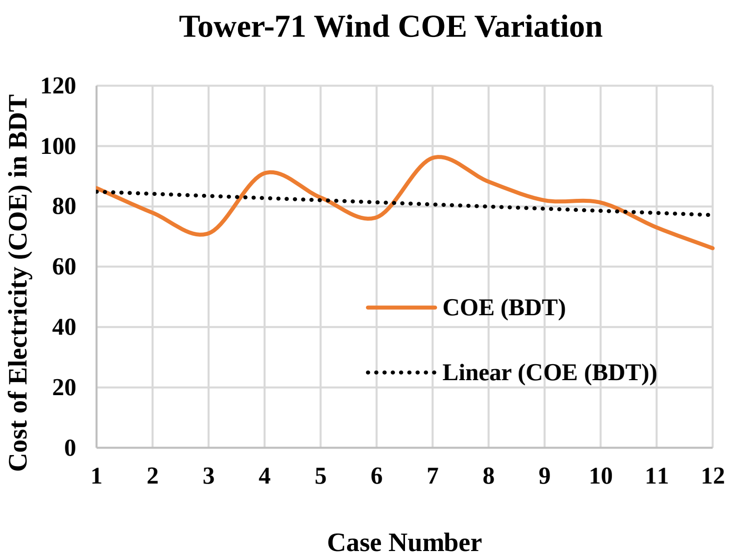


Fig. 7.12. Variation of COE for Tower-71

7.6 Summary

Considering the least and max cases, analysis shows that the Levelized cost of green hydrogen by wind power is nearly BDT 12/g. The result includes the highest case of sensitivity that is the discount rate of 14%. The most production costs are found around BDT 0.92/L or 10.30/g or 926.66/Nm^3 for the wind powered model of hydrogen production. The production cost is dependent on the electricity cost. For only wind powered model the required number of batteries are higher which results the higher production cost. As several recent reports indicate that the average wind speed in Bangladesh is nearly 4 ms^{-1} at 50 m and 6 ms^{-1} at 120 m height, the required number of batteries might be lesser or exempted and hence, there is possibility to get improved production cost by wind or wind-solar powered hydrogen production schemes for Bangladesh rather using only Solar PV technology alone.

Nevertheless, the number of turbine could be a key factor due to any space issue. The lower the installation height, the less the power is produced and the higher the production cost is found. The number of turbines required for the system is below 36 in numbers. An array of 6X6 turbine would require 8400 ft^2 (square feet) empty rooftop. Selected building's rooftops have enough space for the installation if not used otherwise. As an example, the City Centre has 482413 ft^2 rooftop space. The space calculation considers the 1.3 m rotor diameter of the simulated turbine and 3.6 m X 8.4 m spacing for each consecutive turbines.

In Bangladesh, power generation from wind is comparatively challenging at lower heights, but it shows prospects above 100 meter height near coast line or urban cities. Evident to that Bangladesh government has taken initiatives to establish and develop a handful number of wind power harnessing plants in different locations in Bangladesh. Bangladesh may produce green hydrogen using wind power to store the electricity in the form of hydrogen gas.

Chapter 8

Wind-Solar-Hybrid powered Hydrogen production cost in Bangladesh

8.1 Introduction

In chapter five and seven the analytical study dealt with the solar powered hydrogen production and wind powered hydrogen production cost determination separately. It is observed that there is a significant number of lead acid battery required for system implementation. To reduce the usage of lead acid battery from the system wind-solar hybrid model analysis is performed and presented in this chapter.

8.1.1 Site Information

All the eight sites analyzed in previous chapters are used again for this analysis.

8.2 Methodology

The same methodology used in chapter five and seven is used again in this chapter. The data presentation for this chapter is different from the chapter seven. Here, all sensitivity cases are incorporated into the analysis and all possible case results are shown altogether. The sites having more than 15 case results are discussed only with some chronological samples.

8.3 Analysis by HOMER Energy

The analysis configuration for solar-wind hybrid model requires the change in power module configuration. Solar module and wind module are configured together in the power system input panel in HOMER. Along with this, the resource data is given input for solar GHI and wind as same as chapter five and seven.

8.3.1 Components, Parameters and Costs

HOMER components and parameters are also set similarly as chapter five and seven. The LCC component values are same as shown in chapter five as no other cost changed except the power production modules. Rest all are same as chapter 5 and chapter 7. Fig. 8.1 gives a general one line diagram for the proposed hybrid system. The system has solar panel, wind turbine, inverter and battery as power components with electrolyzer and compressor as loads and cylinder as storage unit.

8.4 Analysis for Dhaka Sites

Analysis for the four sites in Dhaka is presented one after another. Measured site is analyzed by both measured and retrieved data.

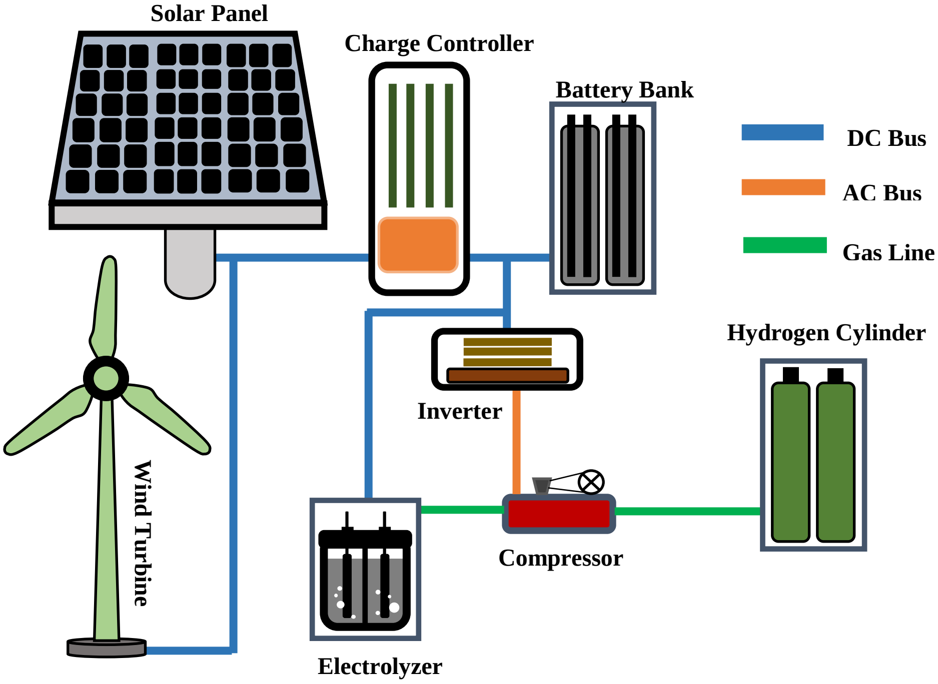


Fig. 8.1. Schematic of hybrid power hydrogen production system

8.4.1 Dhanmondi Site

The Dhanmondi site exhibits total 8 hybrid cases for measured data shown in Table 8.1. The hub height is required 100 and 150 meter. The range of electricity cost for these case is from BDT 49.82 to BDT 60.53. The variation for cost of electricity is shown in Fig. 8.2. The hydrogen production cost is around BDT 9.03/g or 812.63/Nm^3 to BDT 10.20/g or 917.37/Nm^3. HOMER results are shown in Table 8.1 to 8.3 for measured data of this site.

Table 8.1. Case wise system architecture for Dhanmondi site (Measured data)

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine Hub Height (m)	PV (kW)	Turbine	Battery	Converter (kW)
1	10	25	100	12.68	1	18	3.46
2	10	15	150	12.10	1	19	3.51
3	10	25	150	9.56	6	17	3.49
4	12	25	100	10.92	3	19	3.44
5	12	15	150	12.10	1	19	3.51
6	12	25	150	9.59	6	17	3.44
7	14	25	150	9.42	5	19	3.55
8	8	25	150	11.31	4	16	3.44

Table 8.2. Case wise system costs for Dhanmondi site using measured data

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	PV Capital Cost (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	3200096	49.95	96093.37	1743161	1099327	50000	2000
2	3203290	50.00	98732.20	1706346	1049208	50000	2000
3	3191300	49.82	97627.12	1711111	829307.8	300000	12000
4	2934259	55.27	97964.41	1703228	947193.3	150000	6000
5	2935293	55.29	97798.59	1706346	1049208	50000	2000

6	2928003	55.15	96718.57	1712628	831631.1	300000	12000
7	2712198	60.53	97865.95	1674368	816599.6	250000	10000
8	3521629	44.66	94986.35	1749154	980714.1	200000	8000

Table 8.3. Case wise performance for Dhanmondi site using measured data

Case No.	PV Production (kWh/y)	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
1	18486.94	353.54	22.40	209.50
2	17644.11	475.70	23.65	219.10
3	13946.14	2854.19	21.16	222.33
4	15928.57	1060.61	23.65	232.48
5	17644.11	475.70	23.65	219.10
6	13985.21	2854.19	21.16	221.60
7	13732.43	2378.49	23.65	239.81
8	16492.28	1902.79	19.91	198.12

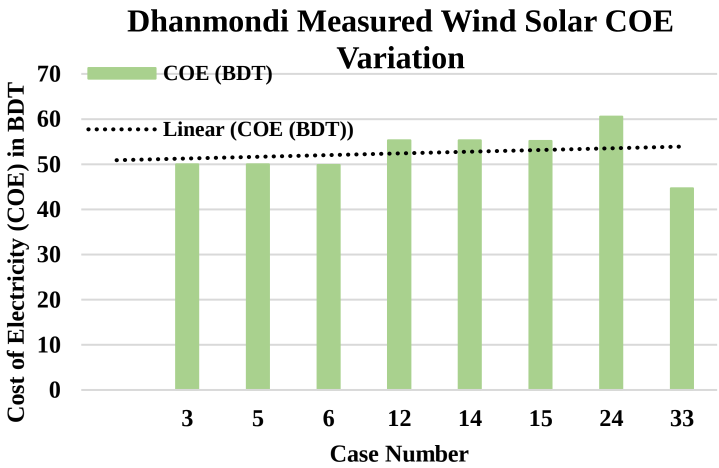


Fig. 8.2. Dhanmondi site COE variation for measured data

From Table 8.4 to 8.6, the results of retrieved data are shown. A total of 33 hybrid cases are found for this data. Among these cases, a sample of results are shown in below Tables. Fig. 8.3 shows the variation of electricity cost for this site by retrieved data. Using retrieved data set, the system design shows that the electricity cost at installation height would be between BDT 53.03 to BDT 54.28. This results the hydrogen production cost between BDT 9.38/g or, 844.02/Nm^3 to 9.52/g or 856.25/Nm^3.

Table 8.4. Case wise system architecture for Dhanmondi site (retrieved data)

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine Hub Height (m)	PV (kW)	Turbine	Battery	Converter (kW)
1	12	10	100	5.64	5	19	3.59
2	12	15	100	3.74	5	23	3.57
3	12	25	100	3.53	8	18	3.52
4	12	10	150	4.55	3	23	3.71
5	12	15	150	4.02	4	22	3.68
6	12	25	150	3.63	7	17	3.57
7	12	15	32	9.69	2	22	3.51
8	12	25	32	7.37	6	20	3.69
9	14	10	100	3.95	5	24	3.61
10	14	15	100	3.50	6	22	3.53
11	14	25	100	3.53	8	18	3.52

Table 8.5. Case wise system costs for Dhanmondi site for retrieved data

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	PV Capital Cost (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	2685226	50.58	106457.9	1347464	488857.1	250000	10000
2	2535347	47.76	103675.6	1232549	324301.1	250000	10000
3	2445390	46.07	91081.5	1300850	305958.1	400000	16000
4	2510006	47.29	103844.0	1205091	394455.8	150000	6000
5	2439090	45.95	98894.9	1196367	348787.9	200000	8000
6	2342141	44.12	87100.2	1247631	314480.2	350000	14000
7	2881856	54.28	103183.9	1585237	840492.9	100000	4000
8	2815146	53.03	99746.4	1561723	638999.4	300000	12000
9	2424892	52.76	111386.5	1243681	342262.6	250000	10000
10	2332852	52.08	102240.4	1248632	303635.3	300000	12000
11	2252881	50.29	89775.2	1300850	305958.1	400000	16000

Table 8.6. Case wise performance for Dhanmondi site using retrieved data

Case No.	PV Production (kWh/yr)	Turbine Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	8341.10	5254.00	23.65	252.23
2	5533.37	5254.00	28.62	428.84
3	5220.39	8406.41	22.40	340.97
4	6730.38	4539.82	28.62	349.92
5	5951.17	6053.09	27.38	350.26
6	5365.80	10592.91	21.16	275.90
7	14340.86	784.14	27.38	252.75
8	10902.89	2352.43	24.89	273.43
9	5839.84	5254.00	29.11	439.14
10	5180.76	6304.81	27.38	420.91
11	5220.39	8406.41	22.40	340.97

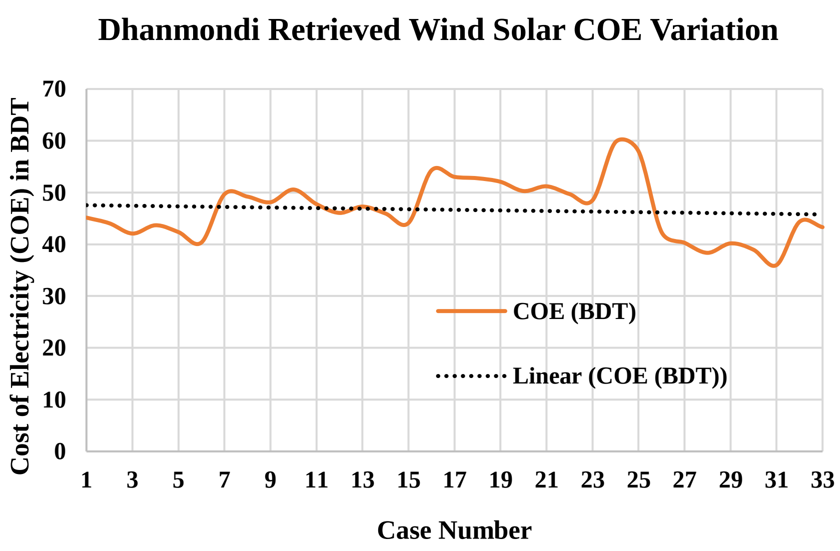


Fig. 8.3. Dhanmondi site COE variation for retrieved data

8.4.2 City Center

For the city center site, analysis uses the retrieved data. All simulation results are shown in Table 8.7 to 8.9. The installation height includes the mast height for the turbine. Here, discount, height and lifetime is selected as a sensitivity input.

Table 8.7. Case wise system architecture for City Center

Case No.	Discount Rate (%)	Turbine Lifetime (years)	PV (kW)	No of Turbine	Battery	Converter (kW)
1	10	10	4.45	4	20	3.59
2	10	15	3.26	6	19	3.81
3	10	25	2.91	8	15	3.69
4	12	10	4.45	4	20	3.59
5	12	15	3.50	5	20	3.55
6	12	25	2.88	8	16	3.76
7	14	10	4.45	4	20	3.59
8	14	15	3.49	5	20	3.58
9	14	25	2.82	7	17	3.60
10	8	10	4.95	4	19	3.65
11	8	15	2.86	7	17	3.49
12	8	25	2.84	7	17	3.49

The estimated cost of electricity from City Centre site would be in the range from BDT 41.63 to 46.75. The cost is estimated for the 12% discount rate taking the variable turbine lifetime into account. The total number of cases for this site is twelve. All the cases are hybrid in configuration where the hydrogen production cost would be within BDT 8.14/g or 732.54/Nm^3 to 8.70/g or 782.61/Nm^3.

The variation of COE between all test conditions are found within the range of BDT 35.41 to BDT 50.53. It is observed that the requirement for lead acid battery reduced significantly for the hybrid model in a range of 5 to 8, in numbers. Fig. 8.4 shows the pictorial view for the variation of electricity cost of this site. The hydrogen production cost is between BDT 7.47/g or, BDT 671.71/Nm^3 to BDT 9.11/g or BDT 819.58 /Nm^3 at the installation height.

Table 8.8. Case wise system costs for City Center

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	PV Capital Cost (BDT)	Turbine Capital Cost (BDT)
1	2763195	43.14	102631.70	1207128	386099.6	200000
2	2651910	40.36	97442.61	1174518	282241.8	300000
3	2489110	38.86	84197.88	1212530	252342.1	400000
4	2481640	46.75	101424.60	1207128	386099.6	200000
5	2383256	44.90	96266.08	1173566	303247.7	250000
6	2267313	41.63	84616.68	1204011	250143.2	400000
7	2263476	50.53	99612.17	1207128	386099.6	200000
8	2176515	48.59	94571.59	1173620	302842.3	250000
9	2072287	46.26	84287.77	1178448	244778.7	350000
10	3140007	39.83	101898.50	1238551	429009.1	200000
11	2975436	37.74	96223.30	1179879	248068.5	350000
12	2791572	35.41	86480.77	1177815	245980.1	350000

Table 8.8 shows the system costs of the City Center site due to the input sensitivity parameters. The average net present cost for this site is around BDT 25 Lac. Average initial capital is about BDT 11.9 Lac. The average capital required for PV module is about 3 Lac and it is about 2.9 Lac for wind turbines. Table 8.9 shows the performance of the designed system for different sensitivity cases. The yearly average energy production from PV module is about 5.2 MWh and the average yearly energy production from wind turbines is about 10 MWh.

Table 8.9. Case wise performance for City Center

Case No.	PV Production (kWh/y)	Turbine Production (kWh/y)	Turbine O&M Cost (BDT)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
1	6491.98	7042.587	8000	24.89	285.99
2	4745.69	10563.88	12000	23.05	369.29
3	4242.95	14085.17	16000	18.67	307.98
4	6491.98	7042.587	8000	24.89	285.99
5	5098.89	8803.234	10000	24.89	340.84
6	4205.97	14085.17	16000	19.41	350.50
7	6491.98	7042.587	8000	24.89	285.99
8	5092.07	8803.234	10000	24.89	341.47
9	4115.77	12324.53	14000	21.16	359.25
10	7213.47	7042.587	8000	23.65	250.13
11	4171.09	12324.53	14000	21.16	352.51
12	4135.98	12324.53	14000	21.16	356.76

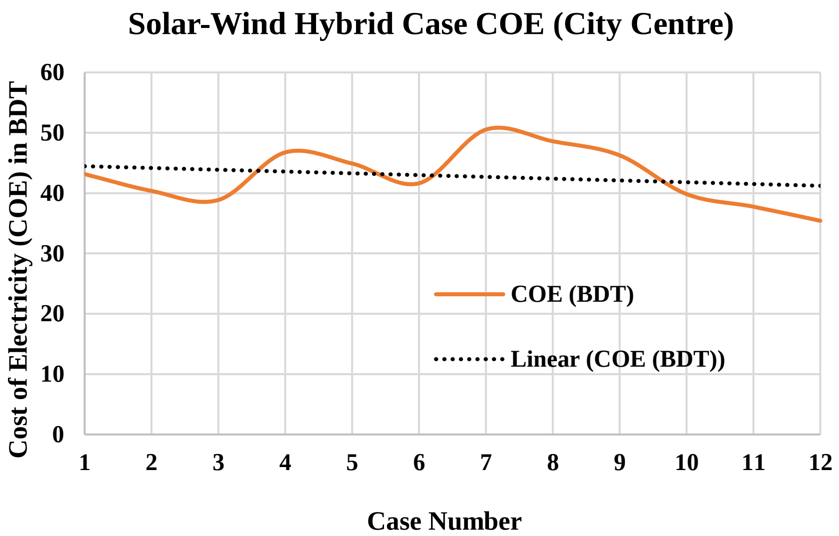


Fig. 8.4. City Centre site COE variation

In Fig. 8.4 it shows a deeper rise in COE from case number 3 to 4 and 6 to 7 and then a steady fall from case number 9. It is because of the increment of discount rate by 2%.

8.4.3 Hilton Dhaka

From Table 8.10 to 8.12 HOMER results are given in an order of architecture, costs and system performance data for Hilton Dhaka site. A total of twelve cases are found for this site at the installation height.

Table 8.10. Case wise system architecture for Hilton Dhaka

Case No.	Discount Rate (%)	Turbine Lifetime (years)	PV (kW)	Turbine	Battery	Converter (kW)
1	10	10	4.45	4	21	3.50
2	10	15	4.33	4	21	3.64
3	10	25	2.88	7	18	3.59
4	12	10	4.35	4	21	3.62
5	12	15	3.80	5	20	3.64
6	12	25	2.87	7	18	3.57

7	14	10	4.37	4	21	3.62
8	14	15	3.79	5	20	3.64
9	14	25	2.87	7	18	3.57
10	8	10	4.41	4	21	3.56
11	8	15	3.70	6	19	3.77
12	8	25	2.91	8	16	3.58

Table 8.11. Case wise costs for Hilton Dhaka

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	PV Capital Cost (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	2805614	43.80	104715.8	1217949	385921.6	200000	8000
2	2699690	42.15	98253.9	1209998	375579.9	200000	8000
3	2541887	39.69	88803.4	1195480	249491.0	350000	14000
4	2513134	47.34	103581.4	1211519	377525.2	200000	8000
5	2421691	45.62	97100.8	1201513	329623.3	250000	10000
6	2298259	43.30	87862.7	1194167	248542.7	350000	14000
7	2292652	51.18	101783.5	1213277	379251.8	200000	8000
8	2211342	49.37	95326.6	1200441	328522.7	250000	10000
9	2112052	47.15	86555.3	1194167	248542.7	350000	14000
10	3179099	40.33	105227.8	1215515	382501.6	200000	8000
11	3052644	37.75	98615.5	1212448	320878.2	300000	12000
12	2838190	36.00	86543.0	1223271	252375.6	400000	16000

Table 8.12. Case wise performance for Hilton Dhaka

Case No.	PV Production (kWh/yr)	Turbine Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	6492.94	6427.21	26.13	306.86
2	6318.95	6427.21	26.13	317.70
3	4197.56	11247.62	22.40	378.93
4	6351.67	6427.21	26.13	315.58
5	5545.75	8034.01	24.89	327.10
6	4181.61	11247.62	22.40	380.95
7	6380.72	6427.21	26.13	313.73
8	5527.23	8034.01	24.89	328.58
9	4181.61	11247.62	22.40	380.95
10	6435.40	6427.21	26.13	310.34
11	5398.62	9640.82	23.05	332.44
12	4246.09	12854.42	19.91	334.84

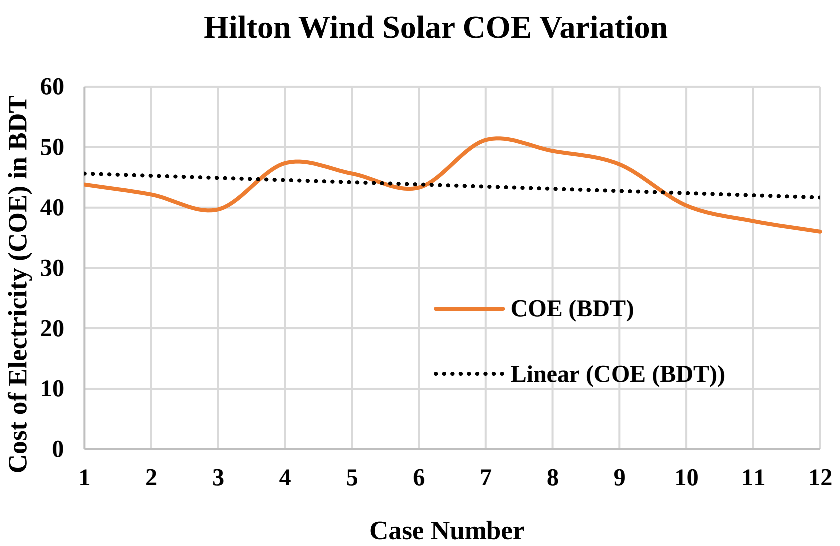


Fig. 8.5. Hilton Dhaka site COE variation

The cost of electricity for the 12% discount is found in the limit of BDT 43.30 to BDT 47.34. This results the production cost of hydrogen by LCC about BDT 8.33/g or 748.87/Nm^3 to BDT 8.76/g or 788.38/Nm^3. Fig. 8.5 shows the variation of COE due to sensitivity for the Hilton Dhaka site.

8.4.4 Bangladesh Bank

As seen from other two sites in Dhaka, Bangladesh Bank site has total 12 hybrid cases. The analysis considers 12% discount rate at the installation height that is the 9 meter higher from the rooftop, considering the maximum mast height for 1kW wind turbines to remove the effect of turbulence. The electricity cost ranges between BDT 44.16 to BDT 47.82. These COE results the hydrogen production cost at this site to be BDT 8.42/g or 757.28/Nm^3 to BDT 8.82/g or 793.07/Nm^3. Fig. 8.6 shows the variation of COE based on the several sensitivity impacts for this site.

Table 8.13. Case wise system architecture for Bangladesh Bank site

Case No.	Discount Rate (%)	Turbine Lifetime (years)	PV (kW)	Turbine	Battery	Converter (kW)
1	10	10	5.24	3	22	3.55
2	10	15	3.65	7	18	3.78
3	10	25	3.20	7	18	3.74
4	12	10	4.21	4	22	3.63
5	12	15	4.08	6	18	3.63
6	12	25	3.20	7	18	3.74
7	14	10	4.49	3	24	3.62
8	14	15	4.08	6	18	3.63
9	14	25	2.93	8	18	3.71
10	8	10	5.24	3	22	3.55
11	8	15	5.20	3	22	3.60
12	8	25	2.97	8	17	3.48

Table 8.14. Case wise system costs for Bangladesh Bank site

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	PV Capital Cost (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	2822683	44.07	103722.80	1250072	454643.3	150000	6000
2	2750312	41.86	99232.94	1245775	316447.8	350000	14000
3	2588055	40.41	89822.83	1226191	277653.3	350000	14000
4	2538309	47.82	105598.70	1211345	364666.9	200000	8000
5	2461674	46.37	96377.23	1250587	353915.7	300000	12000
6	2343998	44.16	88954.08	1226191	277653.3	350000	14000
7	2313653	51.65	103976.90	1211019	389413.6	150000	6000
8	2253842	50.31	94605.48	1250587	353915.7	300000	12000
9	2164605	47.10	87903.39	1232424	254383.8	400000	16000
10	3193492	40.51	104147.20	1250072	454643.3	150000	6000
11	3098550	39.31	99200.52	1247437	451260.2	150000	6000
12	2894488	36.72	88710.13	1239130	257553.8	400000	16000

Table 8.15. Case wise system costs for Bangladesh Bank site

Case No.	PV Production (kWh/y)	Turbine Production (kWh/y)	Battery Autonomy (h)
1	7644.47	4433.74	27.38
2	5320.82	10345.40	21.84
3	4668.52	10345.40	22.40
4	6131.59	5911.66	27.38

5	5950.82	8867.49	22.40
6	4668.52	10345.40	22.40
7	6547.69	4433.74	29.87
8	5950.82	8867.49	22.40
9	4277.26	11823.32	21.84
10	7644.47	4433.74	27.38
11	7587.59	4433.74	27.38
12	4330.57	11823.32	21.16

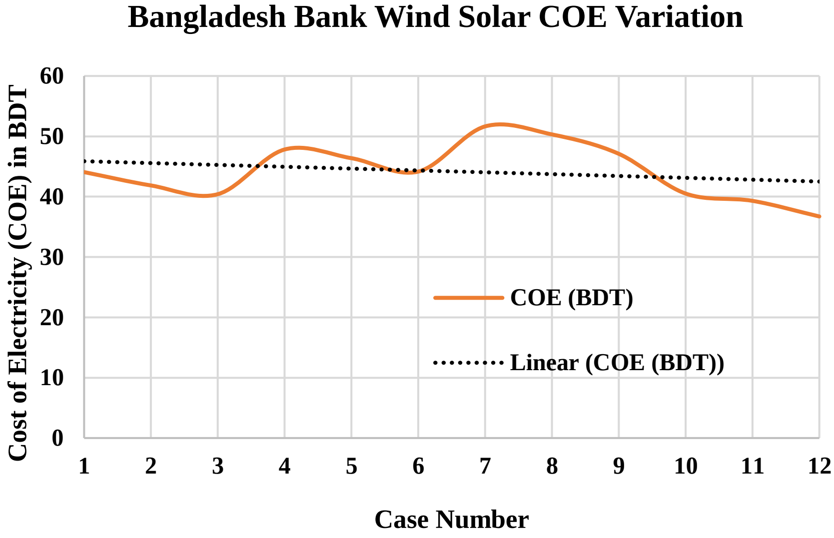


Fig. 8.6. Bangladesh Bank site COE variation

8.5 Analysis for Chattogram Sites

Maintaining the same pattern of analysis as previous sections Chattogram sites are also been assessed. One of the sites which is section seven has been analyzed using both measured data and retrieved data. Rest of the three sites are analyzed with the retrieved data according to the height of the specific site.

8.5.1 Measured site

Using the measured data, section seven site is analyzed at different height and the system configuration results are presented in Table 8.16. There are total 23 hybrid cases for this site at 100 meter and 150 meter installation height. The cost of electricity for this site is found to be within the range of BDT 52.89 to BDT 54.15 for 12% discount rate and 100 meter installation height.

Table 8.16. System architectures of Section Seven by measured data (Sample)

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine Hub Height (m)	PV (kW)	Turbine	Battery	Converter (kW)
1	12	10	100	11.16	1	20	3.63
2	12	15	100	8.12	4	18	3.49
3	12	25	100	8.37	3	20	3.56
4	12	10	150	7.88	3	18	3.52
5	12	15	150	7.89	3	18	3.47
6	12	25	150	7.89	3	18	3.50
7	14	10	100	10.99	1	19	3.42

8	14	15	100	8.05	3	21	3.55
9	14	25	100	6.89	5	19	3.40

Table 8.17. System costs of Section Seven site using measured data (Sample)

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	PV Capital Cost (BDT)	Turbine Capital Cost (BDT)
1	2900678	53.26	101949.00	1619576	967870.5	50000
2	2874690	54.14	109492.70	1498793	704369.6	200000
3	2808276	52.89	104431.90	1495975	725382.4	150000
4	2779698	52.36	107590.90	1427700	682809.8	150000
5	2718527	51.20	102659.40	1428499	684431.0	150000
6	2669544	50.28	98749.32	1428650	684144.3	150000
7	2654051	59.24	98539.00	1609083	953506.2	50000
8	2630640	58.72	108400.60	1481095	698235.2	150000
9	2593213	57.87	107477.30	1453458	598142.6	250000

For these electricity costs, the LCC analysis returns the Levelized cost to be BDT 9.37/g or 842.66/Nm^3 to 9.51/g or 854.98/Nm^3. The cost of electricity variation pattern between all cases are presented in Fig. 8.7.

Table 8.18. System performance of Section Seven by measured data (Sample)

Case No.	Turbine O&M Cost (BDT)	PV Production (kWh/y)	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
1	5000	16795.00	425.56	24.26	227.42
2	20000	12222.59	1702.22	22.40	249.33
3	15000	12587.22	1276.67	24.89	261.33
4	15000	11848.48	1899.22	22.40	247.44
5	15000	11876.61	1899.22	22.40	246.63
6	15000	11871.63	1899.22	22.40	246.77
7	5000	16545.74	425.56	23.65	216.27
8	15000	12116.15	1276.67	26.14	275.80
9	25000	10379.29	2127.78	23.65	290.22

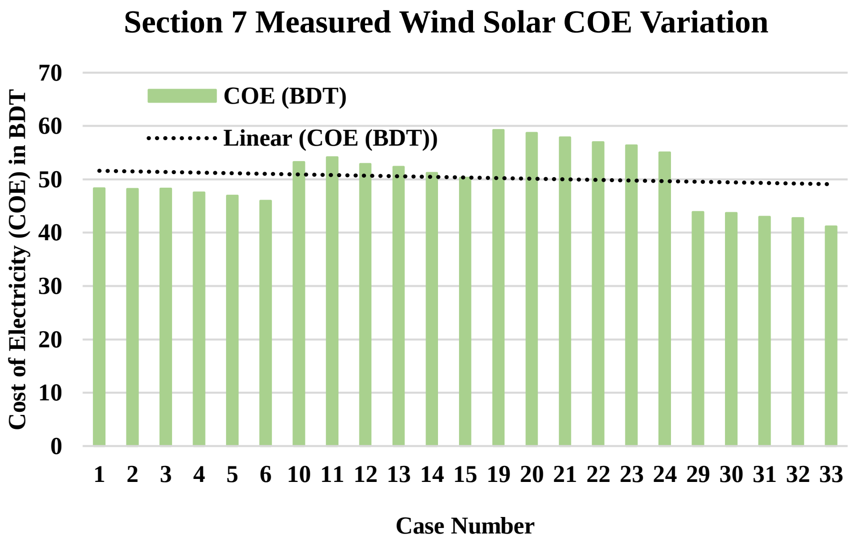


Fig. 8.7. Section Seven site COE variation

Using retrieved data for the same site, the analysis results are shown in Table 8.19 to Table 8.21. There are 35 cases for Wind-PV hybrid model including the cases for building height. For 40 meter height and 12% discount, the wind-solar hybrid electricity cost would be within BDT 51.47 to BDT 53.80. The LCC cost method returns the hydrogen production cost to be within BDT 9.21/g or 828.77/Nm^3 to 9.47/g or 851.55/Nm^3 for this particular setting.

Table 8.19. System architectures of Section Seven by retrieved data (Sample)

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine Hub Height (m)	PV (kW)	Turbine	Battery	Converter (kW)
1	12	10	100	4.73	2	24	3.75
2	12	15	100	4.08	4	18	3.57
3	12	25	100	3.20	5	17	3.61
4	12	10	150	3.64	3	17	3.60
5	12	15	150	3.89	4	14	3.62
6	12	25	150	3.31	4	15	3.77
7	12	10	40	6.31	3	24	3.60
8	12	15	40	6.31	3	24	3.60
9	12	25	40	7.06	4	19	3.54
10	14	10	100	3.22	5	17	3.57
11	14	15	100	3.21	5	17	3.60
12	14	25	100	3.20	5	17	3.61

Table 8.20. System costs of Section Seven site using retrieved data (Sample)

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	PV Capital Cost (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	2501793	45.94	106471.80	1163857	410062.1	100000	10000
2	2425529	45.69	101574.10	1149139	353503.4	200000	20000
3	2334386	43.98	97340.14	1111200	277385.4	250000	25000
4	2268802	42.74	97028.93	1049527	315813.5	150000	15000
5	2207069	40.52	90991.81	1063657	337195.5	200000	20000
6	2124676	39.01	87214.33	1028731	287145.0	200000	20000
7	2855955	53.80	118379.40	1368387	547155.1	150000	15000
8	2795002	52.65	113528.90	1368387	547155.1	150000	15000
9	2732375	51.47	104474.10	1419543	611801.9	200000	20000
10	2280164	50.90	110150.90	1112057	278799.6	250000	25000
11	2196805	49.04	102296.90	1111987	278231.9	250000	25000
12	2129886	47.55	96060.63	1111200	277385.4	250000	25000

Table 8.21. System performance of Section Seven by retrieved data (Sample)

Case No.	PV Production (kWh/y)	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
1	7115.61	4207.90	29.11	328.51
2	6134.18	8415.80	22.40	229.50
3	4813.34	10519.75	21.16	274.11
4	5480.16	8703.23	21.16	246.83
5	5851.19	11604.31	16.98	202.80
6	4982.69	11604.31	18.20	256.72
7	9494.52	2460.23	29.87	296.17
8	9494.52	2460.23	29.87	296.17
9	10616.31	3280.31	23.65	224.67
10	4837.88	10519.75	21.16	272.04
11	4828.03	10519.75	21.16	272.87
12	4813.34	10519.75	21.16	274.11

In Fig. 8.8, the variation of electricity cost due to sensitivity impact is picturized which is obtained using retrieved data. The bar chart shows a series of high peaks from case number 25 to 27. It is due to the low installation height and high discount rate. The project discount rate here is considered 12% and the sensitivity goes as much as high up to 14%. The high peaks are for 14% discount rate and 40 meter height.

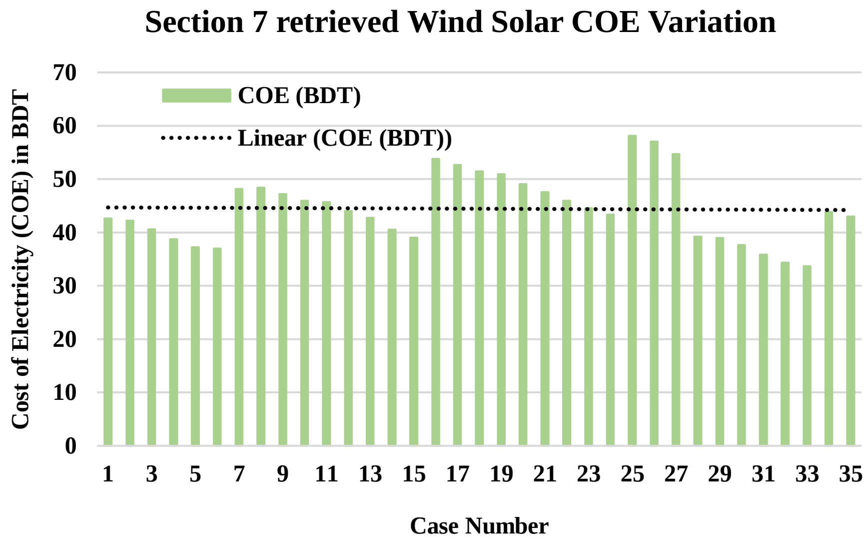


Fig. 8.8. Section Seven site COE variation

8.5.2 Aziz Court Imperial

For Aziz court imperial site, the building height is added with the mast height to set the hub height for the analysis. There are 12 cases found for wind-solar hybrid power generation model. This model can reduce lead acid batteries up to 7 units depending on the discount rate and turbine lifetime. At the rate of 12% discount the cost of electricity varies between BDT 46.35 to BDT 47.80. This results the hydrogen cost to be between BDT 8.66/g or 778.70/Nm^3 to BDT 8.81/g or 792.88/Nm^3.

Table 8.22. Case wise system architecture for Aziz Court Imperial site

Case No.	Discount Rate (%)	Turbine Lifetime (years)	PV (kW)	Turbine	Battery	Converter (kW)
1	10	10	4.51	2	25	3.54
2	10	15	5.22	2	23	3.54
3	10	25	3.96	5	18	3.69
4	12	10	5.14	2	23	3.67
5	12	15	4.75	2	24	3.63
6	12	25	3.58	5	19	3.61
7	14	10	4.05	3	23	4.29
8	14	15	4.74	2	24	3.71
9	14	25	3.55	5	19	3.65
10	8	10	5.65	2	23	3.78
11	8	15	5.14	2	23	3.63
12	8	25	4.00	5	18	3.67

Fig. 8.9 shows the sensitivity impact on the electricity production cost for this site. The cost peaks at case number 4 then it rises further from case number 7 and remains steady up to case number 9 and then it falls toward case number 10.

Table 8.23. Case wise system costs for Aziz Court Imperial site

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	PV Capital Cost (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	2842772	44.39	110104.80	1173400	390803.10	100000	10000
2	2781713	43.43	103649.10	1210220	452497.50	100000	10000
3	2741193	42.80	102229.90	1191218	343441.00	250000	25000
4	2537338	47.80	105973.60	1205662	445836.30	100000	10000
5	2492538	46.96	104153.00	1183740	412077.20	100000	10000
6	2460079	46.35	102696.50	1169584	310673.90	250000	25000
7	2353710	52.54	111460.10	1171718	351232.50	150000	15000
8	2273118	50.74	102693.00	1184099	411021.50	100000	10000
9	2241951	50.05	101372.90	1166930	307389.90	250000	25000
10	3238561	40.05	107560.10	1231455	489713.80	100000	10000
11	3146475	39.92	104061.70	1204651	445512.10	100000	10000
12	3108198	39.43	102560.00	1194396	347065.80	250000	25000

Table 8.24. Case wise system performance for Aziz Court Imperial site

Case No.	PV Production (kWh/y)	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
1	6783.71	3505.69	31.11	363.19
2	7854.63	3505.69	28.62	298.53
3	5961.58	8764.22	22.40	239.37
4	7739.00	3505.69	28.62	304.32
5	7153.00	3505.69	29.87	338.02
6	5392.80	8764.22	23.65	276.16
7	6096.83	5258.53	28.62	330.36
8	7134.67	3505.69	29.87	339.16
9	5335.79	8764.22	23.65	280.52
10	8500.64	3505.69	27.90	295.96
11	7733.37	3505.69	28.62	304.61
12	6024.50	8764.22	22.40	235.86

In Fig. 8.9, the dotted line represents the linear relationship of COE between sensitivity parameters. After reaching the case number 10 the cost of electricity is merely changed its course and maintained a stable trend.

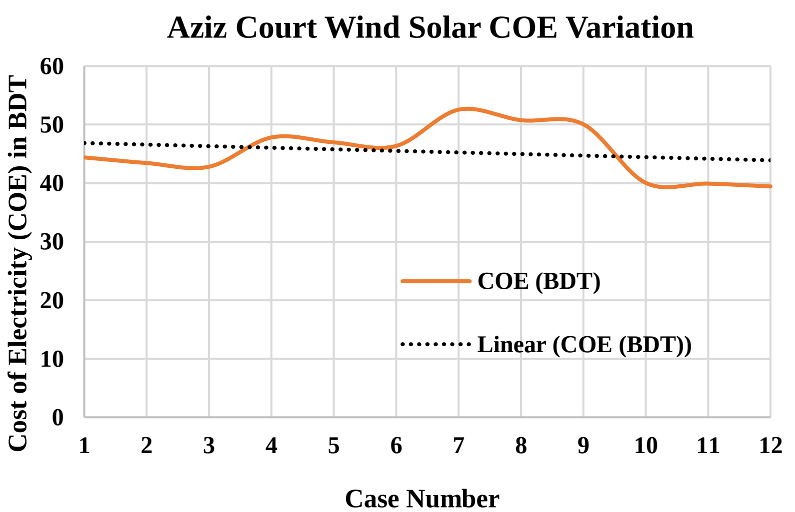


Fig. 8.9. Aziz Court Imperial site COE variation

8.5.3 Courtyard Marriott

As previous site, this site also exhibits 12 cases. The reduction possibility of battery for this site is up to 5 units by the proposed hybrid model. The electricity cost variation of this site is between BDT 46.68 to BDT 48.14. The hydrogen production cost is about BDT 8.69/g or 781.93/Nm^3 to 8.85/g or 796.20/Nm^3. Fig. 8.10 shows the variation of electricity cost for different sensitivity cases of this site.

Table 8.25. Case wise system architecture for Courtyard Marriot site

Case No.	Discount Rate (%)	Turbine Lifetime (years)	PV (kW)	Turbine	Battery	Converter (kW)
1	10	10	5.35	2	23	3.53
2	10	15	4.06	4	21	3.56
3	10	25	4.01	4	21	3.61
4	12	10	5.01	2	24	3.49
5	12	15	4.28	3	23	3.57
6	12	25	4.01	4	21	3.61
7	14	10	4.95	2	24	4.04
8	14	15	4.01	4	21	3.61
9	14	25	4.01	4	21	3.61
10	8	10	5.81	2	23	3.83
11	8	15	5.09	3	21	3.65
12	8	25	4.46	4	20	3.64

Table 8.26. Case wise system costs for Courtyard Marriot site

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	Capital Cost (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	2845491	44.43	107147.00	1220964	463529.8	100000	10000
2	2845190	44.42	109503.00	1184942	351941.5	200000	20000
3	2759359	43.08	104044.20	1181876	348043.6	200000	20000
4	2555582	48.14	107573.70	1203799	434414.2	100000	10000
5	2524969	47.57	107096.30	1179185	371026.3	150000	15000
6	2477717	46.68	103122.00	1181876	348043.6	200000	20000
7	2343797	52.32	107088.40	1208167	429436.8	100000	10000
8	2313458	51.64	106706.60	1181876	348043.6	200000	20000
9	2260645	50.47	101726.40	1181876	348043.6	200000	20000
10	3261296	40.33	108000.80	1245967	503359.3	100000	10000
11	3200136	40.60	105787.10	1226116	441602.6	150000	15000
12	3131588	39.73	103034.90	1208925	387095.3	200000	20000

Table 8.27. Case wise system performance for Courtyard Marriot site

Case No.	PV Production (kWh/y)	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
1	8046.09	3306.72	28.62	301.32
2	6109.11	6613.43	26.13	286.43
3	6041.45	6613.43	26.13	290.89
4	7540.69	3306.72	29.87	328.34
5	6440.39	4960.07	28.62	320.10
6	6041.45	6613.43	26.13	290.89
7	7454.30	3306.72	29.87	333.35
8	6041.45	6613.43	26.13	290.89
9	6041.45	6613.43	26.13	290.89
10	8737.46	3306.72	27.90	297.24
11	7665.47	4960.07	26.13	254.87
12	6719.32	6613.43	24.89	251.74

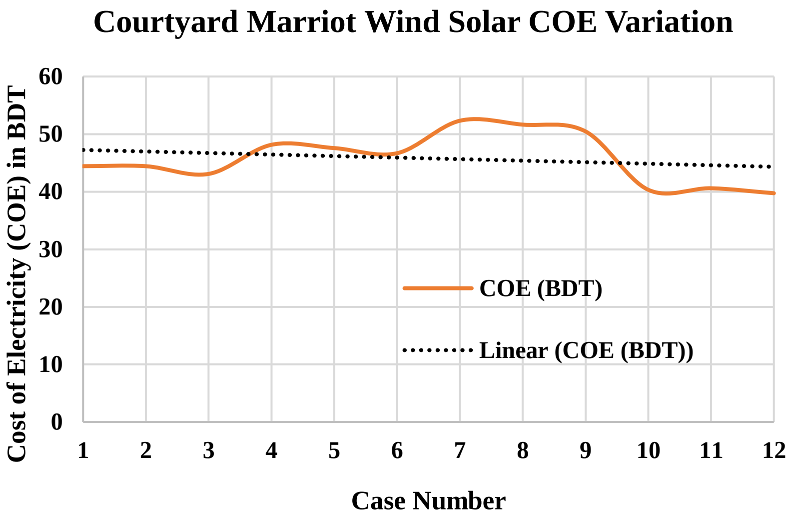


Fig. 8.10. Courtyard Marriot site COE variation

8.5.4 Tower-71

For Tower 71 site, again 12 hybrid cases are returned by HOMER simulation. It has been observed that the site behavior and configuration analysis for examined sites are similar in nature due to the use of same retrieved data. However, there are difference in configurations. The range of electricity cost is also similar. The source of difference is due to the building heights. The system architecture for Tower-71 site is presented in Table 8.28 to Table 8.30.

Table 8.28. Case wise system architecture for Tower 71 site

Case No.	Discount Rate (%)	Turbine Lifetime (years)	PV (kW)	Turbine	Battery	Converter (kW)
1	10	10	4.58	3	23	3.65
2	10	15	4.58	3	23	3.59
3	10	25	4.55	3	23	3.71
4	12	10	4.58	3	23	3.65
5	12	15	5.01	3	23	3.82
6	12	25	4.55	3	23	3.71
7	14	10	4.56	3	23	3.61
8	14	15	4.55	3	23	3.71
9	14	25	4.07	4	22	3.57
10	8	10	5.49	3	22	3.84
11	8	15	4.99	3	22	3.74
12	8	25	4.99	3	22	3.62

The range of electricity cost at 12% discount rate is between BDT 47.33 to BDT 49.41. Considering these COE, the hydrogen production cost is between BDT 8.76/g or 788.28/Nm^3 to 8.99/g or 808.62/Nm^3. Fig. 8.11 shows the sensitivity impacts on the electricity cost at Tower-71. Table 8.29 and Table 8.30 are presenting the system costs and performance of the site varied by sensitivity. The average NPC is about BDT 27.5 Lac. The yearly average energy production is about 7 MWh by solar PV and 4.5 MWh by wind turbines. The electricity production is less in hybrid configuration in contrast to the only wind or only solar configuration. It is because the hybrid model requires reduced number of PV panels and turbines rather the single power model to support the load. Additionally the wind turbine supplies energy in night time also. This reduces the requirement of batteries. The autonomy of the battery is 28 hours which is more than a day.

Table 8.29. Case wise system costs for Tower 71 site

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/y)	Initial capital (BDT)	PV Capital Cost (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	2933644	45.81	113925.60	1206342	396823.9	150000	15000
2	2856912	44.61	108879.40	1206120	397530.8	150000	15000
3	2796886	43.67	104988.20	1205091	394455.8	150000	15000
4	2623017	49.41	112737.80	1206342	396823.9	150000	15000
5	2583637	47.44	107998.90	1226512	434013.9	150000	15000
6	2512305	47.33	104027.00	1205091	394455.8	150000	15000
7	2379507	53.12	110815.50	1204351	395560.7	150000	15000
8	2332423	52.07	106305.80	1205091	394455.8	150000	15000
9	2301275	51.37	103994.00	1198459	352838.2	200000	20000
10	3367765	41.64	113142.20	1256497	476135.3	150000	15000
11	3249081	41.22	108131.00	1231323	432674.7	150000	15000
12	3163413	40.13	103665.90	1228976	432410.9	150000	15000

Table 8.30. Case wise system performance for Tower 71 site

Case No.	PV Production (kWh/y)	Turbine Production (kWh/y)	Battery Autonomy (h)	Battery Annual Throughput (kWh/y)
1	6888.23	4336.35	28.62	321.93
2	6900.50	4336.35	28.62	321.18
3	6847.12	4336.35	28.62	324.47
4	6888.23	4336.35	28.62	321.93
5	7533.79	4336.35	27.90	315.81
6	6847.12	4336.35	28.62	324.47
7	6866.30	4336.35	28.62	323.29
8	6847.12	4336.35	28.62	324.47
9	6124.71	5781.79	27.38	316.45
10	8264.95	4336.35	26.69	280.14
11	7510.54	4336.35	27.38	287.45
12	7505.96	4336.35	27.38	287.68

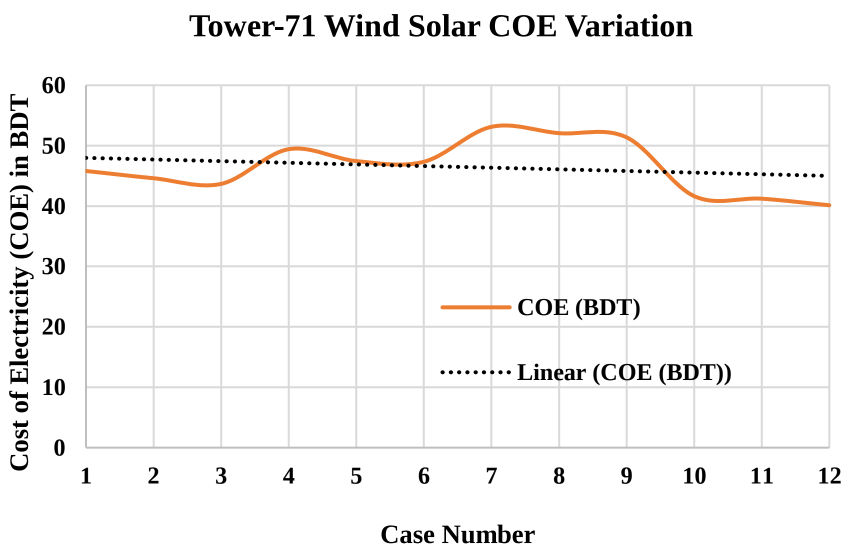


Fig. 8.11. Tower-71 site COE variation

8.6 Sensitivity Summary

The sensitivity impact is observed for all the cases evaluated by HOMER. In this analysis the cost of electricity is the point of interest. It is because the Levelized cost of hydrogen by LCC method exclusively depends on the electricity cost. Hence, the rise and drop in electricity cost extensively affect the production cost of hydrogen. The highest cost and lowest cost for all sites among all cases are listed in Table 8.31.

Table 8.31. Site wise highest and lowest cost by sensitivity impact

Site Names	Lowest COE	Highest COE	Lowest Production Cost (per gram)	Lowest Production Cost (per Nm^3)	Highest Production Cost (per gram)	Highest Production Cost (per Nm^3)
Section Seven (M.)	41.20	59.24	8.10	728.34	10.06	904.75
Section Seven (R.)	33.65	58.14	7.28	654.50	9.94	894.00
Aziz Court Imperial	39.43	52.54	7.90	711.03	9.33	839.23
Courtyard Marriot	39.73	52.32	7.94	713.96	9.31	837.08
Tower-71	40.13	53.12	7.98	717.87	9.39	844.90
Dhanmondi Site (M.)	55.15	55.29	9.61	864.76	9.63	866.13
Dhanmondi Site (R.)	35.99	59.74	7.53	677.39	10.11	909.64
City Centre	35.41	50.53	7.47	671.71	9.11	819.58
Hilton Dhaka	36.00	51.18	7.53	677.48	9.18	825.93
Bangladesh Bank	36.72	51.65	7.61	684.53	9.23	830.53

The lowest electricity cost ranges between BDT 33.65 to BDT 55.15 and the highest is between BDT 50.53 to BDT 59.74.

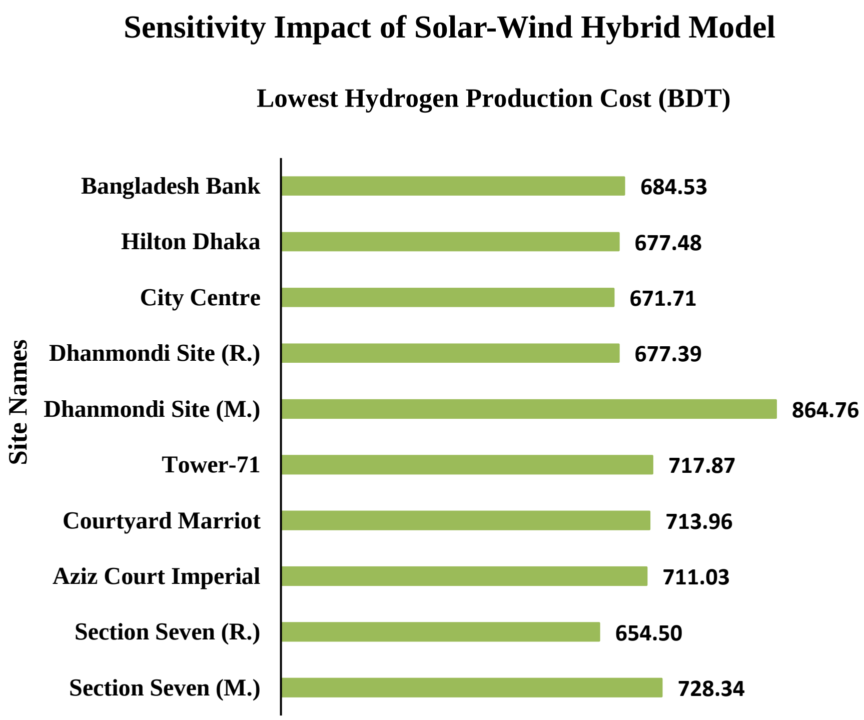


Fig. 8.12. Site-wise lowest hydrogen production cost by sensitivity

In Fig. 8.12, left side of the diagram shows the site names and the bars are presenting the associated cost of hydrogen production in normal-meter-cube. It is also similarly presented in Fig. 8.13. Depending on the electricity cost range, the lowest hydrogen production cost by hybrid model is between BDT 7.28/g or, 654.50/Nm^3 to 9.61/g or 864.76/Nm^3 and the highest is between BDT 9.11/g or 819.58/Nm^3 to 10.11/g or 909.64/Nm^3. Fig.12 and Fig.13 shows the lowest and highest hydrogen production costs for all the sites.

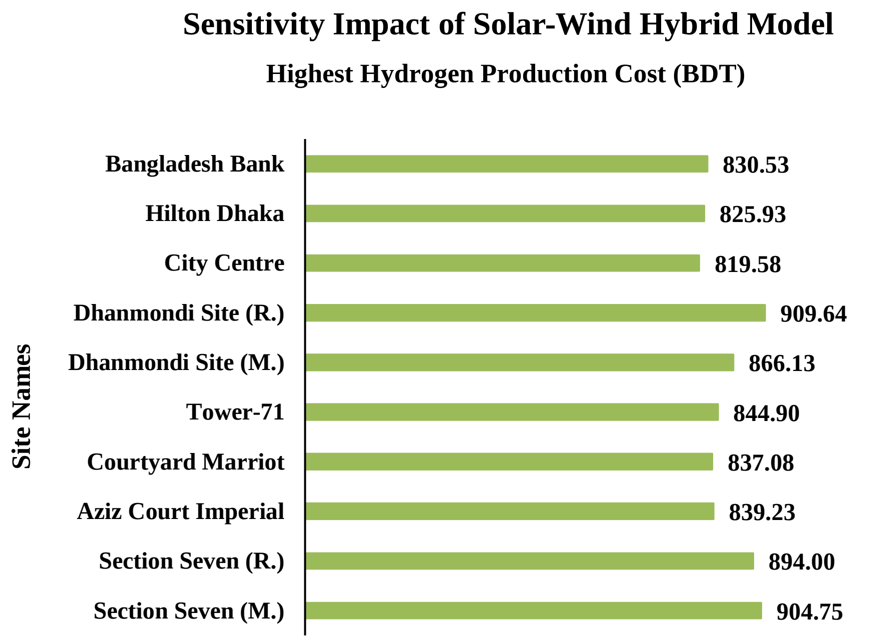


Fig. 8.13. Site-wise highest hydrogen production cost by sensitivity

8.7 Summary

In Bangladesh, power generation from wind is comparatively challenging at lower heights, but it shows prospects above 150 meter height near coast line or urban cities. Bangladesh government has already taken initiatives to establish and develop a handful number of wind power harnessing plants in different locations in the country. On the other hand, solar photovoltaic is being extensively used for the last ten years. Now, green hydrogen has come into the global interest. Bangladesh can take part by producing hydrogen using renewable energy and step forward toward the green hydrogen economy.

Chapter 9

Hydrogen Demand Potential in Bangladesh by 2040

9.1 Introduction

Hydrogen is being considered as the cleanest fuel for the future. It has the potential to take over fossil fuels. However, much research and development are still required to establish general purpose use of hydrogen as a fuel. Many Asian countries have already made policy on the hydrogen economy but countries like Bangladesh are yet to account the hydrogen into their energy scenario [226-227]. England, USA, Canada, Australia, Germany, Ireland, Japan, South Korea and China has accounted on hydrogen and invested millions of dollars on establishing the hydrogen economy [228]. Among them, Australia, India, China, Japan, and Korea have completed the formulation of hydrogen policy [229]. India and China are the close neighbors of Bangladesh. In contrast to them, sufficient research are yet to be facilitated in Bangladesh.

Argonne National Laboratory performed a hydrogen demand analysis in USA for the year of 2050. The analysis is focused for fuel cell vehicles, synthetic hydro-carbon production, bio fuel production and injection into natural gas pipeline. For fuel cell, the assumption is the reduced cost at H_2 filling station that is 8$/kg to 5$/kg. For synthetic hydrocarbon production the assumption is made to produce 100 MMT of CO_2. For bio-fuel production the assumption is that the 50% of total demand of jet fuel will be replaced by H_2 based bio fuel by 2050 and 20% of natural gas in gas pipeline will be replaced by injection of H_2. The estimated demand for FCEVs is 16.9 MMT, Synthetic Methanol 14 MMT, Biofuels production 8.7 MMT and Injection into NG pipelines is about 16 MM [230].

Another study conducted for European countries, states the similar approaches of assumption to estimate hydrogen demand. For medium temperature applications, 5% of current natural gas demand is assumed to be replaced by hydrogen in 2030, 20% by 2040 and 30% by 2050. For high temperature application, it is set to replace natural gas up to 15% by using hydrogen in 2030, 40% by 2040 and 50% by 2050 [231].

A study conducted by National Renewable Energy Laboratory (NREL), the national laboratory of the U.S. Department of Energy, estimated the hydrogen demand by 4 scenarios. It identifies the transport sector as the biggest hydrogen market opportunity within 2050. Transportation sector is divided into light, medium and heavy vehicles among which 27% are to be replaced by Fuel Cell Vehicles (FCVs). The study assumes economic potential scenarios which includes the lowest-cost of electrolysis scenario at which 15% petroleum would be replaced by H_2. In The aggressive Electrolysis Research and Development scenario, Steam Methane

Reforming (SMR) is assumed to be reduced up to 22% and nuclear falls about 43% [232].

Another demand potential estimation is conducted for East Asia region by Economic Research Institute for ASEAN and East Asia (ERIA). The estimation is based on three sectors by three scenario up to 2040. The sectors are Power Industry and Transport. The assumptions are quite straight forward. The conventional fuels like Coal, Natural Gas, Petrol and diesel are to be replaced partly by hydrogen. For scenario 1 it is 10%, 20% for scenario 2 and 30% for scenario 3 [229].

For East Asian Summit (EAS) region countries like Srilanka, it is set that 20% of the new coal-fired electricity generation would be converted into natural gas and H_2 mixed fuel-fired generation within 2040 [233]. About 20% of the new natural gas-fired electricity generation would be converted to natural gas and H_2 mixed fuel-fired generation. 20% of the natural gas consumption for industrial purposes would be replaced by natural gas and H_2 mixed fuel. For transport, a percentage of Gasoline demand would be converted into H_2 by introducing new vehicles that consume hydrogen. Similarly, common diesel demand would be converted to H_2 and diesel consumption for rail transport would be converted to H_2. The target is set for 2040 [234].

Considering the approaches taken by the NREL, ERIA, Argonne etc. the assumptions and methods are composed for Bangladesh. In Bangladesh, the pattern of fuel usage varies within a few number of sources. Electricity production is mostly dependent on natural gas. Here, the transport sector uses imported petroleum products. The indigenous natural gas reserve is depleting quickly. Bangladesh has started importing liquefied petroleum gas (LPG) to support increasing demands. So, the country is mostly dependent on energy imports other than for natural gas (NG). In future, it has to reduce the usage of NG to save the NG reserve as well as reduce the petroleum usage to mitigate climate issues [235].

Like some other Asian countries, Bangladesh needs to step on finding reliable new energy sources and making proper policy to achieve sustainable development goals (SDGs). The demand and supply potential of East Asian countries are showing that this part of the world is revising energy policy and choosing hydrogen as a new fuel mix [236]. Though most of the countries are yet to complete the policy [237], it is high time for Bangladesh to start on it. It is because green hydrogen would be a key factor in world energy economy in next few decades.

In recent years, Bangladesh government has initiated 41 solar park projects which have altogether 2175 MWp capacity. From these, 7 projects are completed and producing power, eight are being implemented, and 26 are in planning phase. Beside these, there are ten wind power plants are initiated, having 259.9 MWp total capacity. From wind projects, three plants are in live operation, one is in implementation, and the rest is in planning stage. These initiatives depicts a keen interest of the government to maximize the renewable energy (RE) penetration in energy mix within 2030 [238]. Notably, Bangladesh Council of Scientific Research (BCSIR) in Chattogram has started research on hydrogen production and refueling for Fuel Cell Vehicles (FCVs).The project is funded by Bangladesh Government, [239]. Study shows that due to the geographical location, the green hydrogen production cost might get reduced. As Bangladesh has potential solar and wind resources, these may help introduce the use of green hydrogen in the energy mix of the country [240].

To make a proper hydrogen policy, Bangladesh needs to exercise on its future demand. This research aims to calculate hydrogen demand projection of 2040 for Bangladesh perspective.

9.2 Methodology

In this research, the current scenario of energy usage in Bangladesh has been analyzed. The method of the analysis and calculation process has been composed from various assumptions and approaches used by several international research institute, agency and laboratories. The data used for the analysis is sourced from the various document and reports published by the respective regulatory or government bodies of Bangladesh like Hydrocarbon Unit, Energy and Mineral Resources Division, Ministry of Power, Energy and Mineral Resources and Bangladesh Power Development Board (BPDB).

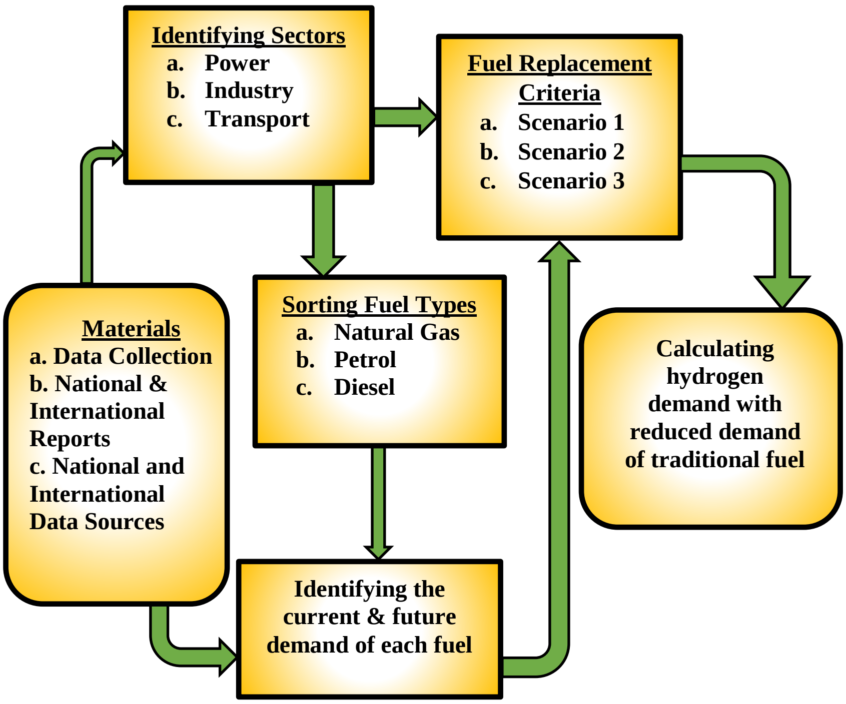


Fig. 9.1. Flow of hydrogen demand determination

Such reports are Energy Demand Potential 2030 and Power System Master Plan 2040. In first phase of this research, major fuel consuming sectors are identified according to the published data. Replaceable traditional fuels are sorted along with the current and future demand. In this research, future demand has been calculated in two stages. One is up to the year of 2030 and another is for 2040. Three replacement scenario are set to estimate the hydrogen demand. Finally, the traditional fuel demand is replaced by hydrogen according to the parameters set in respective scenarios for each sectors. The flow of the analysis is shown in Fig. 9.1.

9.2.1 Sector Wise Demand of Traditional Fuel

In Bangladesh, fossil fuels are the major contributors for meeting the energy demands. It includes petroleum products like octane, petrol, diesel, kerosene, coal, LPG, LNG, NG and biomass. A small portion is sourced from RE sources like solar, wind, hydro. In recent years, Bangladesh has started importing electricity. Here, fossil fuels are mainly managed by import though Bangladesh has natural gas and coal mines. In the 2020-2021 fiscal year, estimated usage of energy was 42.12 metric ton oil equivalent (MTOE) [226]. Bangladesh has the lowest per capita energy usage among the South Asian countries; 293 kgOE. Per capita generation of electricity is 446 kWh [241].

Table 9.1. Energy calculation for 2020-21 (MTOE). Source: (Energy Scenario Bangladesh 2020-21 published by Hydrocarbon Unit, Energy and Mineral Resources Division, Ministry of Power, Energy and Mineral Resources)

Name of Fuel	Unit	MTOE
Oil (Crude & Refined) in K ton	8805.00	8.81
LPG	1441.00	1.44
Natural Gas in Bcf	892.76	20.70
LNG	216.10	5.01
Coal (Imported) in K ton	6751.00	4.27
Coal (Local) in K ton	754	0.48
RE (Hydro) in MW	230	0.17
RE (Solar & Wind) in MW	535.4	0.40
Electricity (Imported) in MW	1160	0.86
Sub- total		42.12
Biomass		14.80
TOTAL		56.92

In Table 9.1 biomass is presented though it is not considered as the commercial energy. It presents the overall demand and usage including commercially available and non-commercial form of energy sources. The total commercial energy usage in 2020-2021 is 42.12 MTOE [227]. The usage pattern by different sectors of Bangladesh is shown in Fig. 9.2.

Fig. 9.2 depicts that the most used fuel in Bangladesh is natural gas. After that the second most used fuel is crude and refined oil. Liquid natural gas is in third position and after that the coal has the fourth position in terms of usage. Bangladesh imports LNG and Coal, though it has own coal mines.

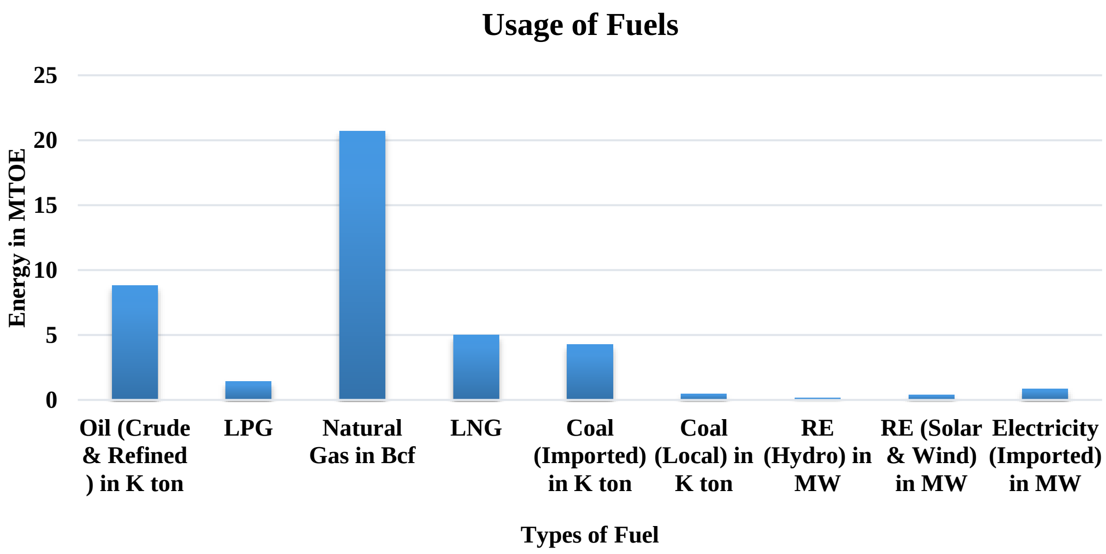


Fig. 9.2. Total usage of commercial energy in 2020-2021

It has been observed that, nearly 50% commercial energy usage is natural gas and 21% is fossil fuel oil. Indigenous natural gas resources are depleting. It has been projected that natural gas production would be 63.69 Bcf in 2040 whereas about 892.76 Bcf has been produced in 2020-2021 [242]. The rate of depletion is alarming. So, Bangladesh need to reduce the use of its own natural gas reserve to slower the depletion rate. LPG and LNG have come into the scene recently as a substitute of natural gas. New fuel mix technology is a must to help the situation.

There are four major sectors identified that hold the capital share of gross energy demands of the country. Power generation, transport, agriculture and industrial sectors are the main consumers. The focus of this research is on the petroleum and natural gas demands. Table 9.2 shows the sector wise usage of petroleum and natural gas in the year of 2020-2021. Power sector is the major user of natural gas. About 59% is consumed here [243]. After power sector, use of natural gas in industries and households are remarkable. Though new gas line connection towards home users are not being facilitated, still it has 13% share whereas industries having 18%. Petroleum products are mainly used in transport sector having 50% of its national demand [244].

Table 9.2. Petroleum and natural gas usage in 2020-21

Sectors	Fuel Type	Unit
Power Sector	Petroleum	880487 MT
	Natural Gas	425.70 Bcf
	Natural Gas (Captive Power)	169.05 Bcf
Transport	Petroleum	5547067.90MT
	Natural Gas (CNG)	44.64 Bcf
Industries	Petroleum	616340.9 MT
	Natural Gas	181.75 Bcf
Agriculture	Petroleum	1320770 MT
	Natural Gas (fertilizers)	64.65 Bcf
Household	Petroleum	176097.40 MT

	Natural Gas	134.15 Bcf
Other	Petroleum	264146 MT
	Natural Gas	6.02 Bcf

9.2.2 Change in Traditional Fuel Demand in 2030 and 2040

Energy Scenario Bangladesh 2020-21 published by Hydrocarbon Unit, Energy and Mineral Resources Division [226], Ministry of Power, Energy and Mineral Resources on March 2022, presents the Energy demand potential on 2030 and Power system master plan presents for 2040 [238]. It has been predicted that natural gas demand will be about 8000 MMscfd in 2030 which is nearly 2920 Bcf. On the other hand total petroleum demand will be 10 M metric Tonnes. Considering the current percentage share of each fuels, sector wise future demand is obtained and presented in Table 9.3 and 9.4. Accepting that there would be no major changes within 10 year time period. Bangladesh government is planning to reduce the supply of natural gas toward captive power plants and increase supply to public and private power plants along with industries. It is assumed that about 6 % will be reduced in captive and 4% will be increased in domestic and 2% in industries within 2030. For industry and transport sector the annual average growth will be 6.3% up to 2040. The natural gas consumption for 2040 would be nearly 62% less and oil in same sector will increase about 16% from the year 2018 as indicated in master plan [238].

Table 9.3. Sector wise demand by fuel type in 2030

Sectors	Fuel Type	Unit
Power Sector	Petroleum	1694000 MT
	Natural Gas (domestic)	1284.8 Bcf
	Natural Gas (captive)	292 Bcf
Transport	Petroleum	4940000 MT
	Natural Gas (CNG)	146 Bcf
Industries	Petroleum	486000 MT
	Natural Gas	554.8 Bcf
Agriculture	Petroleum	1570000 MT
	Natural Gas (fertilizers)	146 Bcf
Household	Petroleum	226000 MT
	Natural Gas	467.2 Bcf
Other	Petroleum	84000 MT
	Natural Gas	29.2 Bcf

In Bangladesh among other petroleum products, furnace oil and diesel is used in power production.

Table 9.4. Projected fuel demands in 2030 and 2040

Sector	Fuel	Demand in 2020-2021 (in MTOE)	Demand in 2030 (in MTOE)	Demand in 2040 (in MTOE)
Power	Diesel + Furnace	0.89	1.60	1.15
	Natural Gas	14.87	39.42	7.79
Transport	Diesel	2.30	3.31	5.60
	Gasoline	1.10	1.63	2.76
	Natural Gas	1.12	3.65	6.18
Industries	Natural Gas	4.54	13.87	23.48

In 2018, fuel oil demand of power sector is about 0.89 MTOE which might reach up to 1.6 MTOE in 2030. In 2030, natural gas demand would be nearly 39 MTOE. In transport sector 1.01 MTOE would be increased from current requirement. Projected demands in 2040 is present in Table 9.4 also.

9.2.3 Scenarios and Estimation Parameters

The demand is estimated based on three scenarios for 2030 and 2040. Each scenario is parameterized by the percentages of traditional fuel, mixed with hydrogen as the replacement of that fuel. The percentage of replacement is set upon the gross domestic product growth of the country. The scenario-1 is assumed for the same GDP growth as previous years. The expected increase of GDP growth is considered for Scenario-2 which is 1.23% increase for upcoming year due to the economic impact of Padma Bridge. For, more than the expected GDP growth is considered for Scenario 3. The current GDP growth of Bangladesh is 7.25%. Scenario-1 is the lowest target of replacement in each sector like 5% replacement of any fuel by hydrogen for 2030. Scenario-2 is the medium target of 10% and scenario-3 is the highest target assumed for 15% replacement. For 2040 the targets are half increased for each scenario of 2030. Table 9.5 presents the category wise parameterized scenario for the year 2030 and 2040.

Table 9.5. Estimation parameters for Bangladesh for 2030 and 2040

Sector	**Fuel**	**Scenario 1**		**Scenario 2**		**Scenario 3**	
Target Year		**2030**	**2040**	**2030**	**2040**	**2030**	**2040**
Power	Gasoline	H_2: 5%	7.5%	H_2: 10%	15%	H_2: 15%	22.5%
		Pet: 95%	92.5%	Pet: 90%	85%	Pet: 85%	77.5%
	NG	H_2: 5%	7.5%	H_2: 10%	15%	H_2: 15%	22.5%
		NG: 95%	92.5%	NG: 90%	85%	NG: 85%	77.5%
Industry	NG	H_2: 5%	7.5%	H_2: 10%	15%	H_2: 15%	22.5%
		NG: 95%	92.5%	NG: 90%	85%	NG: 85%	77.5%
Transport	Gasoline	H_2: 0.5%	0.75%	H_2: 2.5%	3.75%	H_2: 5%	7.5%
		Pet: 99.5%	99.25%	Pet: 97.5%	96.25%	Pet: 95%	92.5%
	Diesel	H_2:0.0125%	0.025%	H_2: 0.025%	0.05%	H_2: 0.05%	0.1%
		Pet: 99.9875%	99.975%	Pet: 99.975%	99.95%	Pet: 99.95%	99.9%
	NG	H_2: 5%	7.5%	H_2: 10%	15%	H_2: 15%	22.5%
		NG: 95%	92.5%	NG: 90%	85%	NG: 85%	77.5%

9.3 Results and Discussions

In 2030 and 2040, the energy demand is assumed to be supplied from several mix of fuels. In power sector, fuel oils could be mixed with hydrogen gas to reduce its consumption alone. In data analysis, furnace oil and diesel is considered together and mentioned as diesel in Table 9.5.

In 2030, it is assumed that 5% gasoline and natural gas would be replaced by hydrogen gas. Gradually it would be up to 7.5% in 2040 for scenario 1. For scenario 2, it is 10% for 2030 and 15% for 2040. In scenario 3, it is estimated for 15% in 2030 and gradually up to 22.5% replacement within 2040 by hydrogen.

9.3.1 Demand Potential of Hydrogen in 2030 and 2040

Based on the estimation parameters and projected demand of traditional fuels in 2030 and 2040 the demand potential of hydrogen is calculated. The categorical data is shown in Table 9.6.

Table 9.6. Demand potential of Hydrogen in 2030 and 2040

	Hydrogen Demand in 2030						Hydrogen Demand in 2040					
Sector	**Scenario 1**		**Scenario 2**		**Scenario 3**		**Scenario 1**		**Scenario 2**		**Scenario 3**	
Power	Oil	H_2	Oil	H_2	Oil	H_2	Oil	H_2	Oil	H_2	Oil	H_2
	1.52	0.08	1.44	0.16	1.36	0.24	1.48	0.12	1.36	0.24	1.24	0.36
	NG	H_2	NG	H_2	NG	H_2	NG	H_2	NG	H_2	NG	H_2
	37.45	1.97	35.48	3.94	33.51	5.91	7.21	0.58	6.62	1.17	6.04	1.75
Transport	Diesel	H_2	Diesel	H_2	Diesel	H_2	Diesel	H_2	Diesel	H_2	Diesel	H_2
	3.31	0.001	3.31	0.001	3.31	0.002	5.60	0.0014	5.60	0.003	5.59	0.01
	Gasol.	H_2	Gasol.	H_2	Gasol.	H_2	Gasol.	H_2	Gasol.	H_2	Gasol.	H_2
	1.62	0.01	1.59	0.04	1.55	0.08	2.74	0.02	2.66	0.10	2.55	0.21
	NG	H_2	NG	H_2	NG	H_2	NG	H_2	NG	H_2	NG	H_2
	3.47	0.18	3.29	0.37	3.10	0.55	5.72	0.46	5.25	0.93	4.79	1.39
Industries	NG	H_2	NG	H_2	NG	H_2	NG	H_2	NG	H_2	NG	H_2
	13.18	0.69	12.48	1.39	11.79	2.081	21.72	1.76	19.96	3.52	18.20	5.28
Total		2.94		5.89		8.86		2.94		5.97		8.99

Similarly, the natural gas consumption could be reduced by hydrogen mix. In transport sector, all diesel vehicles could be replaced by gasoline and hydrogen mix to reduce the usage of conventional fuel oil.

In Bangladesh, compressed natural gas (CNG) is used in transport sector. To reduce the use of natural gas in transport sector it has been considered for replacing a part by fuel cell vehicles (FCVs) and maximum by the gasoline vehicles. Some part of existing gasoline vehicles might get replaced by FCVs also. BCSIR has started research on FCV refueling technology and started import of fuel cell vehicles. If Scenario 1 is implemented, the total demand of hydrogen would be around 2.94 MTOE which is the lowest among all other scenarios. The third scenario results nearly 9 MTOE. Hydrogen demand will be highest on power sector. Fig. 9.3 shows the sector wise demand share by 2030.

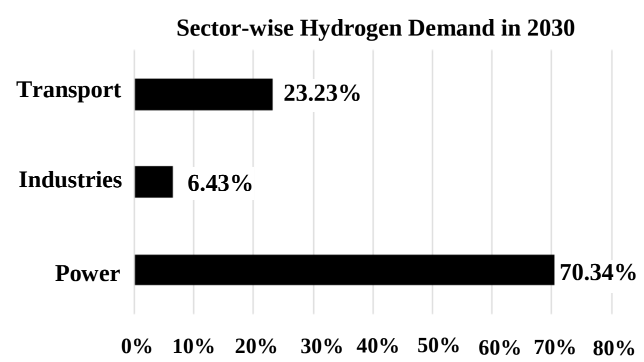


Fig. 9.3. Hydrogen demand potential in 2030 by sectors

The demand is expected to be 70% by power sector. Industries will have approximately 23% and transport will have nearly 6% of the total hydrogen demand. The demand will be based on technology transfer at user end. In power sector, Hydrogen and natural gas mixed fuel gas turbine could replace the conventional gas turbines. Hydrogen and natural gas mixed fuel based large and small scale boilers would be used in various industries as well as in power plants. Passenger fuel cell vehicles and Fuel cell buses will be used in transport sector. These technologies will create the demand for hydrogen in future.

9.3.2 Scopes and Challenges

Due to the climate issues, fossil fuels are no more the noble choice. Most advanced countries are rushing toward the green fuel solutions. Above all, hydrogen is the most prominent solution up to date. But there are some technological barrier towards establishing the hydrogen economy for any country. First of all it requires energy input to produce. There are some technical challenges for the storage also. There are several established methods of hydrogen production each of these has different categories of issues, however, electrolysis and bio-mass gasification might be suitable for Bangladesh [245].

In Bangladesh, solar photovoltaic and wind power technology is being exploited in the form of small and large scale applications. Availability of solar radiation is useful here. The price of renewable electricity has been lowered by government policy. Electricity can be used to produce hydrogen to store energy as well as there would be various commercial and non-commercial use of hydrogen.

As discussed in earlier chapters, high-rise buildings can be used to generate electricity for hydrogen production. As Bangladesh started research on FCV refueling stations, such stations can be constructed near high-rise buildings so that the transportation complexity becomes lesser due to the short distance from the hydrogen production site. The urban cities like Dhaka and Chattogram has the most transportation vehicles. If FCV vehicles are introduced in these cities, hydrogen refueling stations will be required to fuel up those vehicles. Hence, the demand of hydrogen will arise in the transport sector and can be supplied from renewable production scheme, shown in this research. In Bangladesh market, liquid fuel based cars are converted to CNG using CNG conversion technologies. Similar technology can be developed to convert existing gasoline cars into hydrogen cars. Electric motors, control units and fuel cell stack technology will be required for this and research is also needed to develop and analyze the conversion technology.

Additionally, the crude oil refineries, chemical, metal and food industries are using hydrogen for various purposes. These industries can also use green hydrogen and green hydrogen can serve for existing hydrogen demand.

The price of hydrogen is a barrier to expand its use. Large scale photovoltaic technology based hydrogen production projects might result a competitive production cost of hydrogen where MW scale electrolyzers would be used. Which may help Bangladesh becoming a green hydrogen producer. To fulfill and maximize the outcome, research and investments should be extended to develop large scale electrolyzers in Bangladesh.

To use hydrogen domestically, current technologies need to be changed, added and modified. Using natural gas and hydrogen mix fuels in boilers and gas turbines shows prospective results. It has a safe range of mix ratio which is 8:2. Research is going on to increase it up to 7:3. In this ratio, NOx formation has been identified and mitigation method is also developed. However, the technology is still in development phase. In transport sector FCVs can be launched but in that case hydrogen filling station to be established first.

9.4. Summary

Having potential in renewable energy sector, especially in solar, Bangladesh could become a producer of green hydrogen in Asian region. As many neighboring countries in the same region are trying to establish the hydrogen economy, Bangladesh should step forward to achieve the same. A very few countries have already completed the documentation for the hydrogen policy like India and China but most of the cases it has not yet been started. However, most of the countries have set the timeline and had the hydrogen demand projection for 2040. If technology transfer and adaptation toward the hydrogen economy is accepted here, in Bangladesh, power sector would require the most of it as the form of commercially available hydrogen. Along with this, the industrial and transport sector will experience a demand of this clean fuel as a fuel mix in 2040. Analysis shows that if the current GDP growth 7.25% continues, Bangladesh could replace traditional fuels in power and transport sector and the demand of hydrogen would be nearly 2.9 MTOE. If the GDP growth becomes 8.48% as expected due to the opening of Padma Bridge, it could reach up to 5.97 for 2040. If the GDP growth substantially crosses the expected growth then the demand might increase up to 9 MTOE by 2040.

Hydrogen will reduce the gross usage of fossil fuels and help fighting the climate issues more firmly. The demand projection is based on some specific assumptions and some future plans of the government. However, the approach can be taken into account and many other sector specific considerations can be incorporated to it for a closer projection. Still this work can contribute to make hydrogen policy in Bangladesh and provide some information based on certain considerations and scenarios on the demand by 2030 and 2040.

Chapter 10

Conclusions and Recommendations

10.1 Conclusions

This research identifies the prospective sectors where green hydrogen can be used to replace the conventional fuels. In chapter 1, it has been identified that the utilization of RE resources for hydrogen production would increase the use of clean energy in the under-developing countries like Bangladesh. The identified sectors includes transport, chemical industry, power sectors, households etc.

The target of this work is to develop a green hydrogen production system using PV and Wind power. The system is developed using locally available materials. From the results of practical study on water electrolysis presented in chapter 3, the electrolyzer is designed and developed. From the performance evaluation of the developed electrolyzer presented in chapter 4 concludes that the electrolyzer as well as the system work properly. The developed electrolyzer is found to be 30.62% efficient with its highest production rate of 206 mL/min or 0.0123 Nm^3/hr. The purity of hydrogen is found to be more than 92% and justified with the burn test. The developed system can be operated from any DC power source hence, it is usable in PV, Wind or PV-Wind hybrid systems.

In chapter 5, analysis shows the Levelized cost of green hydrogen production by the developed system using only Solar PV technology. The electricity consumption of the hydrogen production plant for all the models is 3897.6 kWh/year and the amount of hydrogen yield is or 35.85 kg/year or 398.56 Nm^3/year. Energy Required for H_2 production is about 108.72 kWh/kg for the developed electrolyzer unit.

It is found that the Levelized cost of green hydrogen is between BDT 7.99/g to BDT 10.93/g or BDT 718.85/Nm^3 to BDT 982.99/Nm^3 by LCC for solar powered hydrogen production system. A similar analysis for only wind and Solar-Wind hybrid system is presented in chapter 7 and 8. The Levelized cost of green hydrogen by only wind powered system is about BDT 10.30/g or 926.66/Nm^3. For Wind-PV hybrid systems the cost ranges between BDT 7.28/g or 654.50/Nm^3 to BDT 10.11/g or 909.64/Nm^3 by LCC. The analysis is based on the practical data collection and analysis for two sites, one in Dhaka and another in Chattogram. The analysis of wind power potential of these two sites are given in chapter 6. Suitable wind turbines are identified by this analysis. The Shape factor of the measured Dhaka site is 1.42 and the scale factor of the site is 1.96 m/s. For Chattogram site the shape factor of the site is 1.8 and the yearly scale factor is 2.2 m/s. Along with the measured data the retrieved data from other sources like NASA and NREL is also used to evaluate other prospective sites in Dhaka and Chattogram.

The most high-rise buildings are selected for this analysis which are no less than 100 meters of height.

It is necessary to have a hydrogen policy to establish a hydrogen economy. For the development of the policy, it is necessary to predict on hydrogen demand for Bangladesh. This research prepares a demand potential for Bangladesh, presented in chapter 9, which states the demand based on three scenarios, each having a specific percentage of a different fuel mix. These three scenarios are modified and set for Bangladesh. For scenario-1, Bangladesh would require about 2.94 MTOE of hydrogen in 2040, whereas for scenario-2 and scenario-3 the amount would be 5.97 and 8.99 MTOE. The Power sector would consume about 70% whereas industries and transport would consume 23% and 6%, namely. Many East Asian countries are to deploy the policy within 2040. Keeping pace with neighbors, Bangladesh should establish the green hydrogen economy and policy.

The resulted production cost is higher than the international market due to the plant capacity and yearly yield. More research and investment is required to develop MW scale electrolyzers, so that the yield becomes higher. However, Bangladesh can start green hydrogen production using renewable energy resources like solar and wind. Beside this, the demand potential indicates the requirement to move toward the hydrogen economy like other countries. We can hope that Bangladesh would start exploring the green hydrogen production, business and usage soon as like as other developed and developing countries.

10.2 Risks and Mitigation

There might be several risk for the hydrogen economy or business of green hydrogen in Bangladesh. The nature of risk and impacts may vary with the pivoting conditions of the country. Unavailability of base chemical and de-mineralized water would stop the production. However, there are number of companies that produce lye and demi water locally. So the chance of chemical being absent from the market is narrow. If this happens there would be other complex conditions that may cause production issues in garments and dyeing industries in Bangladesh. Unavailability of Space for system installation or increased rent would impact to the production cost. In Bangladesh, usable land is scarce. Projects might face difficulties if fresh empty land is used but multiple use of space or unused spaces might be useful for this venture.

Hydrogen storage is a challenge. If hydrogen demand is less or no, and produced hydrogen requires to be stored then the production might get stopped due to the difficulty of storage and space. It would affect to increase the price of it. So, the supply chain management is very crucial for smooth operation for production. If the provisioned compressor is used to compress the produced gas and used for 1 hour daily it would increase the production cost up to BDT 115/Nm^3.

The technology cost for power production is a major contributor to the green hydrogen price. International market price of solar PV, wind turbine and battery technology would largely pivot the cost. The availability of spare parts like blade, gears and brakes for the turbine is a key factor. Suppliers must be operational during the project lifetime. Legislation to be maintained for the after sales services and maintenance for each components. As wind prospect of Bangladesh shows for a higher heights and the country is prone to the monsoon cyclones and thunderstorm, wind turbines are always a vulnerable object to the sudden damage. Proper safety mechanism should be ensured to protect the PV panels as well as for turbines. Insurance could cover up for any loss of system equipment due to the natural disaster or accidents like fire or earthquake. Special subsidies and encouraging discounts may be introduced into government's energy policy to make an impact of green hydrogen in Bangladesh within a target for the year like 2050 as many other countries are doing the same to promote it. Favorable policies may attract investor for starting business in renewable sectors in Bangladesh for green hydrogen production.

10.3 Recommendations for Further Development

For further development the following works can be done.

I. The efficiency of the developed system can be improved by reducing some of the system losses due to some mechanical and physical placements of its parts. Other locally available metals or alloys can also be examined for the development of large capacity electrolyzers.

II. In this work, two methods are used to calculate the cost of hydrogen. Some other methods like Monte Carlo could also be used to obtain more filtered results for large scale installations and developments.

III. In situ wind data collection has been done for below 50 meters height in mentioned sites and retrieved DATA from various sources is used for the analysis. Practical data might be collected at 100 and 150 meters from the sea level to get the actual potential of the selected sites.

IV. The projection of demand potential follows the method used by Economic Research Institute for ASEAN and East Asia (ERIA). However, the assumption are modified to fit for Bangladesh, still it requires to set the goals by the policy makers to develop a practical Hydrogen policy and demand projection by 2030 and further for 2040.

V. Method, mechanism and control system can be developed to store Solar and Wind energy during off peak hours through the production of green hydrogen.

VI. Byproduct of the developed system is oxygen. At present it is released by the system but method can be developed to capture and store the produced oxygen as well. The ready oxygen might be usable for industries but low cost purification method can be introduced to upgrade it to medical or health standard.

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Appendix A

Table A-1. Test apparatus electrode weight measurements in grams

Types	Parameters	Measurement 1	Measurement 2	Measurement 3	Average
Type 1	1a(Weight)	24.00	25.00	23.00	24.00
	1b(Weight)	23.00	23.00	23.00	23.00
	Calculated Total(Weight)	47.00	48.00	46.00	47.00
	Measured Total(Weight)	46.00	46.00	46.00	46.00
Type 2	2a(Weight)	31.00	32.00	31.00	31.33
	2b(Weight)	32.00	32.00	32.00	32.00
	Calculated Total(Weight)	63.00	64.00	63.00	63.33
	Measured Total(Weight)	64.00	64.00	64.00	64.00
Type 3	3a(Weight)	36.00	37.00	36.00	36.33
	3b(Weight)	37.00	37.00	37.00	37.00
	Calculated Total(Weight)	73.00	74.00	73.00	73.33
	Measured Total(Weight)	75.00	75.00	75.00	75.00
Type 4	4a(Weight)	44.00	46.00	45.00	45.00
	4b(Weight)	45.00	45.00	45.00	45.00
	Calculated Total(Weight)	89.00	91.00	90.00	90.00
	Measured Total(Weight)	89.00	89.00	89.00	89.00
Type 5	5a(Weight)	51.00	51.00	50.00	50.67
	5b(Weight)	51.00	51.00	51.00	51.00
	Calculated Total(Weight)	102.00	102.00	101.00	101.67
	Measured Total(Weight)	102.00	102.00	102.00	102.00

Table A-2. Test apparatus electrode area measurements in cm^2

Types	Measured Units in cm	Measurement 1	Measurement 2	Measurement 3	Average
Type 1	1a(Length)	8.0950	8.0900	8.0750	8.0867
	1a(Width)	2.9850	3.0000	3.0300	3.0050
	Calculated Area	24.1636	24.2700	24.4673	24.3004
	1b(Length)	8.0400	8.0600	8.0300	8.04
	1b(Width)	2.9750	3.0000	3.0200	3.00
	Calculated Area	23.9190	24.1800	24.2506	24.12
Type 2	2a(Length)	8.0450	8.0900	8.1350	8.0900
	2a(Width)	4.1000	4.0650	4.0500	4.0717
	Calculated Area	32.9845	32.8859	32.9468	32.9398
	2b(Length)	8.1600	8.2100	8.2250	8.20
	2b(Width)	4.1200	4.1250	4.1250	4.12
	Calculated Area	33.6192	33.8663	33.9281	33.80
Type 3	3a(Length)	7.9750	7.9550	7.9500	7.9600
	3a(Width)	4.9750	4.9550	4.9850	4.9717
	Calculated Area	39.6756	39.4170	39.6308	39.5745
	3b(Length)	8.0900	8.0500	8.0450	8.06
	3b(Width)	5.0100	5.0050	5.0000	5.01
	Calculated Area	40.5309	40.2903	40.2250	40.35
Type 4	4a(Length)	8.0300	8.0150	8.0200	8.0217
	4a(Width)	6.0500	6.0350	6.0500	6.0450
	Calculated Area	48.5815	48.3705	48.5210	48.4910
	4b(Length)	8.0000	7.9800	7.9900	7.99
	4b(Width)	5.9850	5.9750	5.9950	5.99
	Calculated Area	47.8800	47.6805	47.9001	47.82
Type 5	5a(Length)	7.9450	7.9400	7.9900	7.9583
	5a(Width)	6.9400	6.9650	7.0000	6.9683
	Calculated Area	55.1383	55.3021	55.9300	55.4563
	5b(Length)	8.0500	8.0850	8.0500	8.06
	5b(Width)	7.0350	7.0200	7.0250	7.03
	Calculated Area	56.6318	56.7567	56.5513	56.65

Table A-3. Type 1 electrode current distribution and gas production data for 10cm gap

Applied Voltage	Current (1.5M)	Gas Produced (1.5M)	Current (1M)	Gas Produced (1M)	Current (0.5M)	**Gas Produced (0.5M)**	**Current (0.25M)**	**Gas Produced (0.25M)**
0	0	0						
0.1	0	0						
0.2	0	0						
0.3	0	0						
0.4	0	0						
0.5	0	0						
0.6	0	0						

0.7	0	0						
0.8	0	0						
0.9	0	0						
1	0	0	0.14	5			0	0
1.1	0	0						
1.2	0	0						
1.3	0	0						
1.4	0	0						
1.5	0	0					0	0
1.6	0	0						
1.7	0	0						
1.8	0.01	0						
1.9	0.03	0						
2	0.07	0.5	0.91	65			0.02	5
2.1	0.14	9.5			0.1	1		
2.2	0.18	10						
2.3	0.23	22						
2.4	0.29	34						
2.5	0.36	34					0.15	5
2.6	0.42	35						
2.7	0.48	40						
2.8	0.54	25						
2.9	0.63	50						
3	0.76	60	1.86	130	0.52	29	0.25	10
3.1	0.81	60						
3.2	0.89	30						
3.3	0.95	70						
3.4	1.12	80						
3.5	1.15	60					0.38	20
3.6	1.26	100						
3.7	1.38	110						
3.8	1.5	120						
3.9	1.64	35						
4	1.72	35	2.73	210	1.04	70	0.51	30
4.1	1.9	30						
4.2	1.99	30						
4.3	2.1	30						
4.4	2.18	30						
4.5	2.27	40					0.63	30
4.6	2.39	30						
4.7	2.65	35						
4.8	2.75	45						
4.9	2.85	30						
5	2.96	25	3.16	190	1.56	60	0.77	40
5.1	3.13	45						
5.2								
5.3								
5.4								
5.5							0.91	45
5.6								
5.7								
5.8								
5.9								
6					2.09	60	1.08	55
6.1								
6.2								
6.3								
6.4								
6.5							1.22	45
6.6								
6.7								
6.8								
6.9								
7					2.69	145	1.34	35
7.1								
7.2								
7.3								
7.4								
7.5							1.5	80
7.6								
7.7								
7.8								
7.9								
8					3.16	195	1.64	80
8.1								
8.2								
8.3								
8.4								
8.5							1.74	70

8.6								
8.7								
8.8								
8.9								
9							1.89	90
9.1								
9.2								
9.3								
9.4								
9.5							2.08	100
9.6								
9.7								
9.8								
9.9								
10							2.21	110
10.1								
10.2								
10.3								
10.4								
10.5							2.36	110
10.6								
10.7								
10.8								
10.9								
11							2.56	100
11.1								
11.2								
11.3								
11.4								
11.5							2.73	120
11.6								
11.7								
11.8								
11.9								
12							2.84	130
12.5							3.06	

Table A-4. Type 1 electrode current distribution and gas production data for 8cm gap

Applied Voltage	Current (1.5M)	Gas Produced (1.5M)	Current (1M)	Gas Produced (1M)	Current (0.5M)	Gas Produced (0.5M)	Current (0.25M)	Gas Produced (0.25M)
1	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0.01	0	0	0
2	0.17	4	0.08	2	0.08	0	0.05	0
2.5	0.78	21	0.63	18	0.42	8	0.14	0
3	1.44	60	1.18	60	0.65	22	0.35	5
3.5	2.17	125	1.91	85	0.99	60	0.49	15
4	2.86	90	2.56	105	1.43	55	0.62	22.5
4.2	3.16	120						
4.4			3.16	140				
4.5					1.78	85	0.8	37.5
5					2.06	100		
5.5					2.47	80	1.13	50
6					2.84	130		
6.5					3.14	160	1.48	70
7								
7.5							1.81	80
8								
8.5							2.2	70
9								
9.5							2.52	120
10								
10.5							2.9	220
11								
11.2							3.16	140

Table A-5. Type 1 electrode current distribution and gas production data for 6cm gap

Applied Voltage	Current (1.5M)	Gas Produced (1.5M)	Current (1M)	Gas Produced (1M)	Current (0.5M)	Gas Produced (0.5M)	Current (0.25M)	Gas Produced (0.25M)
1					0		0	0
1.5	0	0	0	0	0	0		
1.7							0.02	0
1.8	0.02	0	0.03	0				
2					0.06	0		
2.1	0.21	4	0.26	5				

2.4	0.58	24	0.52	15			0.15	0
2.5					0.36	5		
2.7	1.04	50	0.88	40				
3	1.56	62	1.42	60	0.66	25		
3.1							0.42	3
3.3	2.11	90	1.7	70				
3.5					1.05	50		
3.6	2.71	90	2.15	85				
3.8							0.69	22
3.9	3.16	100	2.59	105				
4					1.51	60		
4.2			3.06	150				
4.5			3.16	130	1.83	70	0.93	45
5					2.22	95		
5.2							1.24	40
5.5					2.65	120		
5.9							1.51	60
6					3.05	135		
6.1					3.16	70		
6.6							1.79	80
7.3							2.08	70
8							2.39	110
8.7							2.7	120
9.4							3.02	140
9.69							3.16	160

Appendix B

Table B-1. Materials and cost for a single unit development

Item Name	Price in BDT
Steel Plate	400
Nut and Bolts	200
PVC Sheet	250
Diaphragm	50
Gasket	150
Washer	100
Nozzle	150
Pipes	100
Ring	100
Jars	300
Ports	200
Workmanship	500
Total	2500

Table B-2. Electrolyzer power consumption and gas production rate

Time	Voltage	Current	wattage	Calculated	Gas Volume
04:24	11.31	10.63	120.4	120.23	0
04:27	11.28	10.63	120	119.91	875
04:30	11.28	10.62	119.9	119.79	2000
04:33	11.24	10.62	119.5	119.37	2750
04:36	11.23	10.62	119.3	119.26	3300
04:39	11.2	10.62	118.9	118.94	3750
04:42	11.18	10.62	118.7	118.73	4250
04:45	11.16	10.62	118.5	118.52	4875
04:46	11.16	10.62	118.4	118.52	5000

Table B-3. Electrolyzer current consumption for different molarity

Time Sequence	1.5M	1M	0.5M	0.25M
1	10.66	10.67	10.69	10.67
2	10.65	10.66	10.68	10.67
3	10.64	10.65	10.66	10.67
4	10.63	10.64	10.65	10.65
5	10.63	10.63	10.64	10.64
6	10.62	10.62	10.63	10.63
7	10.62	10.62	10.62	10.62
8	10.61	10.62	10.62	10.62
9	10.61	10.62	10.62	10.61
10	10.6	10.61	10.61	10.6
11	10.6	10.61	10.61	10.6
12	10.6		10.61	10.6
13	10.6		10.61	10.6
14	10.6		10.6	
15			10.6	

Table B-4. Electrolyzer current consumption for different molarity

Sample	1	2	3	4	5	6	7	8	9
1.5M	0	500	625	750	875	1250	1625	2000	2250
1.0M	0	480	875	1375	1850	2250	2750	3500	4000
0.5M	0	875	2000	2750	3300	3750	4250	4875	5000
0.25M	0	460	1035	1660	2160	2610	3010	3535	3910

Appendix C

Table C-1. Chattogram site measured wind speed data (Sample)

Date	Speed (m/s)	Angle (degree)	Date	Speed (m/s)	Angle (degree)	Date	Speed (m/s)	Angle (degree)
17/05/2015 05:10	2.7	132	17/05/2015 17:50	0.5	144	18/05/2015 06:30	2.6	169
17/05/2015 05:20	3	88	17/05/2015 18:00	0	312	18/05/2015 06:40	2.5	159
17/05/2015 05:30	2.6	95	17/05/2015 18:10	0	318	18/05/2015 06:50	2.9	130
17/05/2015 05:40	2.5	111	17/05/2015 18:20	0	270	18/05/2015 07:00	2.6	125
17/05/2015 05:50	2.5	106	17/05/2015 18:30	0	192	18/05/2015 07:10	3.1	132
17/05/2015 06:00	2.8	106	17/05/2015 18:40	4	90	18/05/2015 07:20	2.7	123
17/05/2015 06:10	3.5	99	17/05/2015 18:50	3.4	87	18/05/2015 07:30	2.5	121
17/05/2015 06:20	2.7	89	17/05/2015 19:00	2.9	95	18/05/2015 07:40	2.6	123
17/05/2015 06:30	3.3	88	17/05/2015 19:10	3.1	90	18/05/2015 07:50	2.7	123
17/05/2015 06:40	3.6	86	17/05/2015 19:20	3.2	91	18/05/2015 08:00	3.1	113
17/05/2015 06:50	3.9	82	17/05/2015 19:30	3.1	92	18/05/2015 08:10	1.9	108
17/05/2015 07:00	3.8	85	17/05/2015 19:40	2.8	95	18/05/2015 08:20	2.6	102
17/05/2015 07:10	4.5	102	17/05/2015 19:50	2	114	18/05/2015 08:30	2.5	91
17/05/2015 07:20	4.5	99	17/05/2015 20:00	2.5	97	18/05/2015 08:40	2.6	96
17/05/2015 07:30	5	101	17/05/2015 20:10	3.1	89	18/05/2015 08:50	2.4	108
17/05/2015 07:40	4.2	96	17/05/2015 20:20	2.7	90	18/05/2015 09:00	2.1	121
17/05/2015 07:50	4.4	98	17/05/2015 20:30	2.6	90	18/05/2015 09:10	2.2	130
17/05/2015 08:00	4.1	96	17/05/2015 20:40	1.9	101	18/05/2015 09:20	2.1	101
17/05/2015 08:10	4	105	17/05/2015 20:50	2.2	114	18/05/2015 09:30	1.8	130
17/05/2015 08:20	4.2	92	17/05/2015 21:00	0.9	114	18/05/2015 09:40	2.4	134
17/05/2015 08:30	4.7	109	17/05/2015 21:10	1.7	103	18/05/2015 09:50	1.8	128
17/05/2015 08:40	4.2	85	17/05/2015 21:20	1.5	121	18/05/2015 10:00	2	139
17/05/2015 08:50	3.1	68	17/05/2015 21:30	1.5	125	18/05/2015 10:10	1.9	170
17/05/2015 09:00	2.4	129	17/05/2015 21:40	2.1	123	18/05/2015 10:20	2.4	172
17/05/2015 09:10	3.5	198	17/05/2015 21:50	2	115	18/05/2015 10:30	1.8	169
17/05/2015 09:20	3.3	130	17/05/2015 22:00	1.6	121	18/05/2015 10:40	1.6	198
17/05/2015 09:30	2.3	135	17/05/2015 22:10	2	120	18/05/2015 10:50	1.3	180
17/05/2015 09:40	1.5	123	17/05/2015 22:20	2.4	115	18/05/2015 11:00	1.7	158
17/05/2015 09:50	1.4	125	17/05/2015 22:30	2.2	119	18/05/2015 11:10	1.6	126
17/05/2015 10:00	2.1	116	17/05/2015 22:40	1.6	122	18/05/2015 11:20	1.8	139
17/05/2015 10:10	0.8	118	17/05/2015 22:50	1.8	122	18/05/2015 11:30	2.8	168
17/05/2015 10:20	0.9	173	17/05/2015 23:00	1.1	123	18/05/2015 11:40	2.8	170
17/05/2015 10:30	1.2	154	17/05/2015 23:10	1.2	125	18/05/2015 11:50	2.3	152
17/05/2015 10:40	3.1	182	17/05/2015 23:20	1.5	119	18/05/2015 12:00	2.3	142
17/05/2015 10:50	1.5	134	17/05/2015 23:30	1.7	119	18/05/2015 12:10	2.1	170
17/05/2015 11:00	1.8	139	17/05/2015 23:40	1.6	123	18/05/2015 12:20	2.2	148
17/05/2015 11:10	2	155	17/05/2015 23:50	1.6	116	18/05/2015 12:30	2.9	184
17/05/2015 11:20	1.8	125	18/05/2015 00:00	1.9	111	18/05/2015 12:40	3.2	210
17/05/2015 11:30	3.3	179	18/05/2015 00:10	2.2	116	18/05/2015 12:50	3.6	209
17/05/2015 11:40	2.1	174	18/05/2015 00:20	2.5	114	18/05/2015 13:00	3.2	204
17/05/2015 11:50	2.7	174	18/05/2015 00:30	2.8	116	18/05/2015 13:10	3.1	202
17/05/2015 12:00	3.1	186	18/05/2015 00:40	2.1	110	18/05/2015 13:20	3	194
17/05/2015 12:10	2.9	202	18/05/2015 00:50	2.6	111	18/05/2015 13:30	3.5	221
17/05/2015 12:20	3.9	205	18/05/2015 01:00	2.6	118	18/05/2015 13:40	4.2	218
17/05/2015 12:30	3.1	218	18/05/2015 01:10	2.6	122	18/05/2015 13:50	4.8	218
17/05/2015 12:40	3.5	213	18/05/2015 01:20	2.1	126	18/05/2015 14:00	4.2	212
17/05/2015 12:50	3.5	218	18/05/2015 01:30	1.9	115	18/05/2015 14:10	4.4	223
17/05/2015 13:00	3	234	18/05/2015 01:40	1.8	113	18/05/2015 14:20	4.1	219
17/05/2015 13:10	3.1	217	18/05/2015 01:50	2.2	100	18/05/2015 14:30	4.5	219
17/05/2015 13:20	3.2	240	18/05/2015 02:00	2.4	107	18/05/2015 14:40	4.2	231
17/05/2015 13:30	4	216	18/05/2015 02:10	2.1	117	18/05/2015 14:50	4.5	233
17/05/2015 13:40	3.1	228	18/05/2015 02:20	2.4	115	18/05/2015 15:00	4.4	227
17/05/2015 13:50	2.9	218	18/05/2015 02:30	2	115	18/05/2015 15:10	4.5	229
17/05/2015 14:00	3.2	214	18/05/2015 02:40	2.2	110	18/05/2015 15:20	4.1	221
17/05/2015 14:10	3.1	229	18/05/2015 02:50	1.9	105	18/05/2015 15:30	4.2	213
17/05/2015 14:20	3.7	229	18/05/2015 03:00	2.3	114	18/05/2015 15:40	3.8	221
17/05/2015 14:30	3.4	226	18/05/2015 03:10	2.5	114	18/05/2015 15:50	4.8	215
17/05/2015 14:40	2.9	230	18/05/2015 03:20	2.6	116	18/05/2015 16:00	4.8	216
17/05/2015 14:50	3.7	232	18/05/2015 03:30	3.3	124	18/05/2015 16:10	4.8	219
17/05/2015 15:00	3.2	235	18/05/2015 03:40	4.6	181	18/05/2015 16:20	4.5	207
17/05/2015 15:10	2.7	243	18/05/2015 03:50	5.6	225	18/05/2015 16:30	4.8	211
17/05/2015 15:20	3	244	18/05/2015 04:00	2.7	176	18/05/2015 16:40	5	221
17/05/2015 15:30	2.5	254	18/05/2015 04:10	2.4	174	18/05/2015 16:50	4.6	209
17/05/2015 15:40	2.7	259	18/05/2015 04:20	4.5	198	18/05/2015 17:00	4.1	212
17/05/2015 15:50	3.2	252	18/05/2015 04:30	4.6	193	18/05/2015 17:10	4.3	208
17/05/2015 16:00	1.7	265	18/05/2015 04:40	2.9	165	18/05/2015 17:20	4	210
17/05/2015 16:10	2.6	274	18/05/2015 04:50	2.6	151	18/05/2015 17:30	4	215
17/05/2015 16:20	3.9	287	18/05/2015 05:00	1.7	133	18/05/2015 17:40	3.8	206
17/05/2015 16:30	4.9	317	18/05/2015 05:10	2.2	116	18/05/2015 17:50	3.7	205
17/05/2015 16:40	4.5	314	18/05/2015 05:20	2.3	116	18/05/2015 18:00	3.7	213
17/05/2015 16:50	4.2	306	18/05/2015 05:30	2.2	108	18/05/2015 18:10	3.8	213

17/05/2015 17:00	3.1	319	18/05/2015 05:40	2.1	118	18/05/2015 18:20	4.2	211
17/05/2015 17:10	2.7	285	18/05/2015 05:50	1.8	126	18/05/2015 18:30	4.3	215
17/05/2015 17:20	3.1	270	18/05/2015 06:00	2	132	18/05/2015 18:40	3.9	208
17/05/2015 17:30	2	210	18/05/2015 06:10	2.1	134	18/05/2015 18:50	3.8	197
17/05/2015 17:40	1.1	116	18/05/2015 06:20	2.1	154	18/05/2015 19:00	3.7	196

Table C-2. Dhaka site measured data (Sample)

Date	Speed (m/s)	Angle (Degree)	Date	speed (m/s)	Angle (degree)	Date	Speed (m/s)	Angle (degree)
11/05/2015 11:17	1.2	219	11/05/2015 23:57	1.03	151	12/05/2015 12:37	1.22	162
11/05/2015 11:27	1.44	214	12/05/2015 00:07	1.33	145	12/05/2015 12:47	1.8	198
11/05/2015 11:37	1.12	216	12/05/2015 00:17	0.96	189	12/05/2015 12:57	1.26	148
11/05/2015 11:47	1.77	187	12/05/2015 00:27	0.93	184	12/05/2015 13:07	2.58	181
11/05/2015 11:57	2.29	182	12/05/2015 00:37	1	181	12/05/2015 13:17	2.69	181
11/05/2015 12:07	2.95	182	12/05/2015 00:47	1.68	182	12/05/2015 13:27	2.34	181
11/05/2015 12:17	1.29	161	12/05/2015 00:57	1.96	184	12/05/2015 13:37	2.93	180
11/05/2015 12:27	1.89	185	12/05/2015 01:07	2	176	12/05/2015 13:47	2.73	178
11/05/2015 12:37	2.19	179	12/05/2015 01:17	2.3	184	12/05/2015 13:57	2.34	194
11/05/2015 12:47	2.38	181	12/05/2015 01:27	2.68	182	12/05/2015 14:07	2.21	153
11/05/2015 12:57	2.49	175	12/05/2015 01:37	2.31	178	12/05/2015 14:17	1.2	156
11/05/2015 13:07	2.37	169	12/05/2015 01:47	2.03	178	12/05/2015 14:27	2.72	181
11/05/2015 13:17	1.36	136	12/05/2015 01:57	2.22	177	12/05/2015 14:37	3.89	187
11/05/2015 13:27	1.83	207	12/05/2015 02:07	1.81	176	12/05/2015 14:47	2.23	184
11/05/2015 13:37	2.57	179	12/05/2015 02:17	1.8	177	12/05/2015 14:57	2.35	180
11/05/2015 13:47	2.73	197	12/05/2015 02:27	2.6	176	12/05/2015 15:07	2.79	179
11/05/2015 13:57	2.06	195	12/05/2015 02:37	2	175	12/05/2015 15:17	1.86	191
11/05/2015 14:07	2.29	189	12/05/2015 02:47	1.4	183	12/05/2015 15:27	2.4	165
11/05/2015 14:17	1.83	207	12/05/2015 02:57	0.57	145	12/05/2015 15:37	1.01	199
11/05/2015 14:27	1.69	192	12/05/2015 03:07	1.07	127	12/05/2015 15:47	1.68	199
11/05/2015 14:37	1.85	187	12/05/2015 03:17	1.38	115	12/05/2015 15:57	1.12	172
11/05/2015 14:47	1.9	227	12/05/2015 03:27	1.3	123	12/05/2015 16:07	1.07	225
11/05/2015 14:57	2.18	231	12/05/2015 03:37	0.92	125	12/05/2015 16:17	1.6	210
11/05/2015 15:07	1.06	236	12/05/2015 03:47	1.09	116	12/05/2015 16:27	1.85	228
11/05/2015 15:17	0.68	231	12/05/2015 03:57	1.24	115	12/05/2015 16:37	2.26	202
11/05/2015 15:27	1.27	133	12/05/2015 04:07	0.91	132	12/05/2015 16:47	1.57	224
11/05/2015 15:37	1.27	77	12/05/2015 04:17	0.72	115	12/05/2015 16:57	1.4	226
11/05/2015 15:47	1.57	42	12/05/2015 04:27	0.37	134	12/05/2015 17:07	0.82	243
11/05/2015 15:57	1.58	39	12/05/2015 04:37	0.33	168	12/05/2015 17:17	1.11	241
11/05/2015 16:07	0.72	83	12/05/2015 04:47	0.42	134	12/05/2015 17:27	0.39	251
11/05/2015 16:17	0.47	85	12/05/2015 04:57	0	141	12/05/2015 17:37	1.2	237
11/05/2015 16:27	0.41	70	12/05/2015 05:07	0.61	133	12/05/2015 17:47	0.91	236
11/05/2015 16:37	0.59	128	12/05/2015 05:17	0.66	159	12/05/2015 17:57	0.67	198
11/05/2015 16:47	0.94	139	12/05/2015 05:27	0.43	139	12/05/2015 18:07	0.37	195
11/05/2015 16:57	0.99	128	12/05/2015 05:37	0.78	121	12/05/2015 18:17	0.54	139
11/05/2015 17:07	0.73	152	12/05/2015 05:47	1.02	139	12/05/2015 18:27	0.33	75
11/05/2015 17:17	1.53	198	12/05/2015 05:57	1.53	181	12/05/2015 18:37	0.55	75
11/05/2015 17:27	1.32	195	12/05/2015 06:07	2.36	176	12/05/2015 18:47	1.29	133
11/05/2015 17:37	1.58	206	12/05/2015 06:17	2.88	177	12/05/2015 18:57	1.34	129
11/05/2015 17:47	1.22	201	12/05/2015 06:27	2.93	176	12/05/2015 19:07	0.58	76
11/05/2015 17:57	0.88	192	12/05/2015 06:37	2.35	175	12/05/2015 19:17	0.58	62
11/05/2015 18:07	1.3	183	12/05/2015 06:47	2.04	192	12/05/2015 19:27	0.67	96
11/05/2015 18:17	1.61	184	12/05/2015 06:57	1.1	214	12/05/2015 19:37	1.07	116
11/05/2015 18:27	1.16	168	12/05/2015 07:07	4.05	275	12/05/2015 19:47	0.65	104
11/05/2015 18:37	0.89	158	12/05/2015 07:17	6.13	274	12/05/2015 19:57	0.68	128
11/05/2015 18:47	0.87	188	12/05/2015 07:27	4.65	272	12/05/2015 20:07	0.9	143
11/05/2015 18:57	0.62	148	12/05/2015 07:37	3.73	279	12/05/2015 20:17	0.51	102
11/05/2015 19:07	0.74	150	12/05/2015 07:47	3.78	270	12/05/2015 20:27	0.79	98
11/05/2015 19:17	0.78	115	12/05/2015 07:57	2.61	288	12/05/2015 20:37	0.8	134
11/05/2015 19:27	0.96	109	12/05/2015 08:07	2.19	256	12/05/2015 20:47	0.77	131
11/05/2015 19:37	1.35	102	12/05/2015 08:17	2.75	217	12/05/2015 20:57	1.05	138
11/05/2015 19:47	1.39	97	12/05/2015 08:27	2.91	238	12/05/2015 21:07	0.84	168
11/05/2015 19:57	1.99	113	12/05/2015 08:37	1.98	264	12/05/2015 21:17	1.4	194
11/05/2015 20:07	1.77	102	12/05/2015 08:47	0.61	306	12/05/2015 21:27	1.51	184
11/05/2015 20:17	1.19	118	12/05/2015 08:57	1.03	153	12/05/2015 21:37	1.26	185
11/05/2015 20:27	1.28	105	12/05/2015 09:07	1.73	96	12/05/2015 21:47	1.84	180
11/05/2015 20:37	1.51	81	12/05/2015 09:17	0.93	104	12/05/2015 21:57	1.64	197
11/05/2015 20:47	1.64	91	12/05/2015 09:27	0.92	144	12/05/2015 22:07	1.89	184
11/05/2015 20:57	0.91	105	12/05/2015 09:37	1.64	154	12/05/2015 22:17	1.82	181
11/05/2015 21:07	1.33	86	12/05/2015 09:47	1.5	114	12/05/2015 22:27	1.36	175
11/05/2015 21:17	1.45	119	12/05/2015 09:57	1.94	127	12/05/2015 22:37	0.92	116
11/05/2015 21:27	1.23	96	12/05/2015 10:07	2.17	212	12/05/2015 22:47	0.9	166
11/05/2015 21:37	0.9	105	12/05/2015 10:17	2.39	227	12/05/2015 22:57	1.75	181
11/05/2015 21:47	1.16	100	12/05/2015 10:27	2.69	199	12/05/2015 23:07	1.62	185
11/05/2015 21:57	1.02	101	12/05/2015 10:37	2.34	180	12/05/2015 23:17	2.32	184
11/05/2015 22:07	0.62	89	12/05/2015 10:47	2.69	199	12/05/2015 23:27	2.14	180
11/05/2015 22:17	0.88	126	12/05/2015 10:57	2.32	183	12/05/2015 23:37	2.17	177

11/05/2015 22:27	1.12	121	12/05/2015 11:07	1.56	184	12/05/2015 23:47	1.93	175
11/05/2015 22:37	0.92	119	12/05/2015 11:17	2.66	227	12/05/2015 23:57	1.83	179
11/05/2015 22:47	0.71	120	12/05/2015 11:27	2.16	217	13/05/2015 00:07	1.63	181
11/05/2015 22:57	0.77	121	12/05/2015 11:37	1.67	212	13/05/2015 00:17	1.56	187
11/05/2015 23:07	0.76	133	12/05/2015 11:47	2.12	218	13/05/2015 00:27	1.13	186
11/05/2015 23:17	1.13	121	12/05/2015 11:57	1.82	193	13/05/2015 00:37	0.49	199
11/05/2015 23:27	1.1	118	12/05/2015 12:07	1.39	185	13/05/2015 00:47	1.13	172
11/05/2015 23:37	0.83	114	12/05/2015 12:17	1.09	197	13/05/2015 00:57	1.71	181
11/05/2015 23:47	1.09	126	12/05/2015 12:27	0.58	183	13/05/2015 01:07	1.5	186

Appendix D

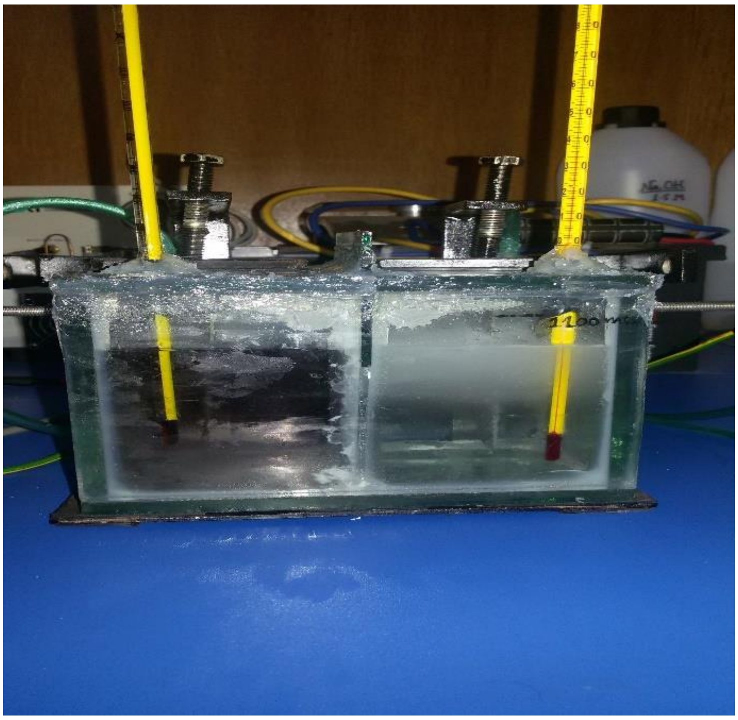

Fig. D-1. Developed parameter test apparatus

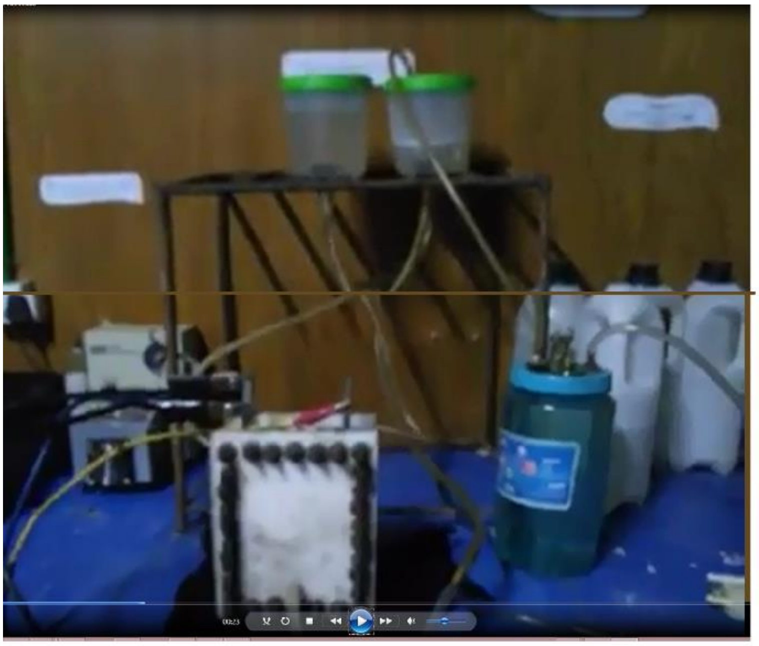

Fig. D-2. Developed electrolyzer in operation

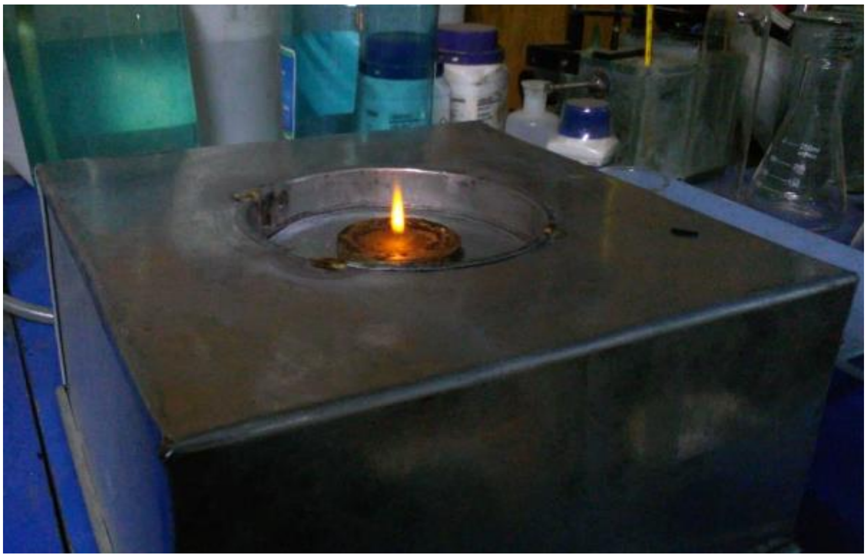

Fig. D-3. Gas burn test in laboratory

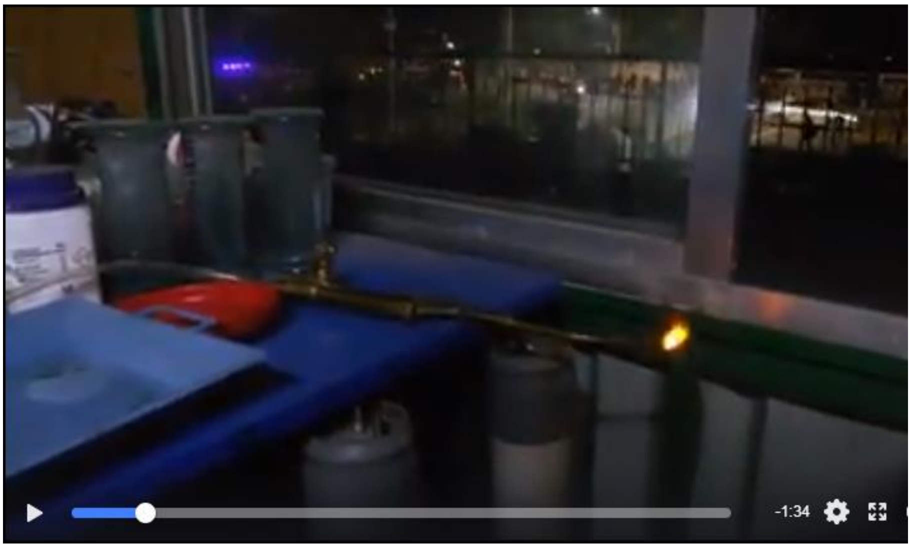

Fig. D-4. Burn test using produced hydrogen

Fig. D-5. Gas composition measurements

Fig. D-6. Pressure relief valve

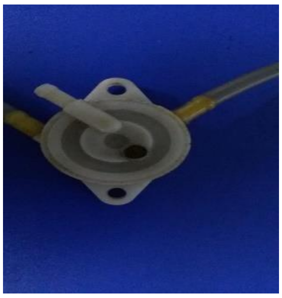

Fig. D-7. Non-returning valve

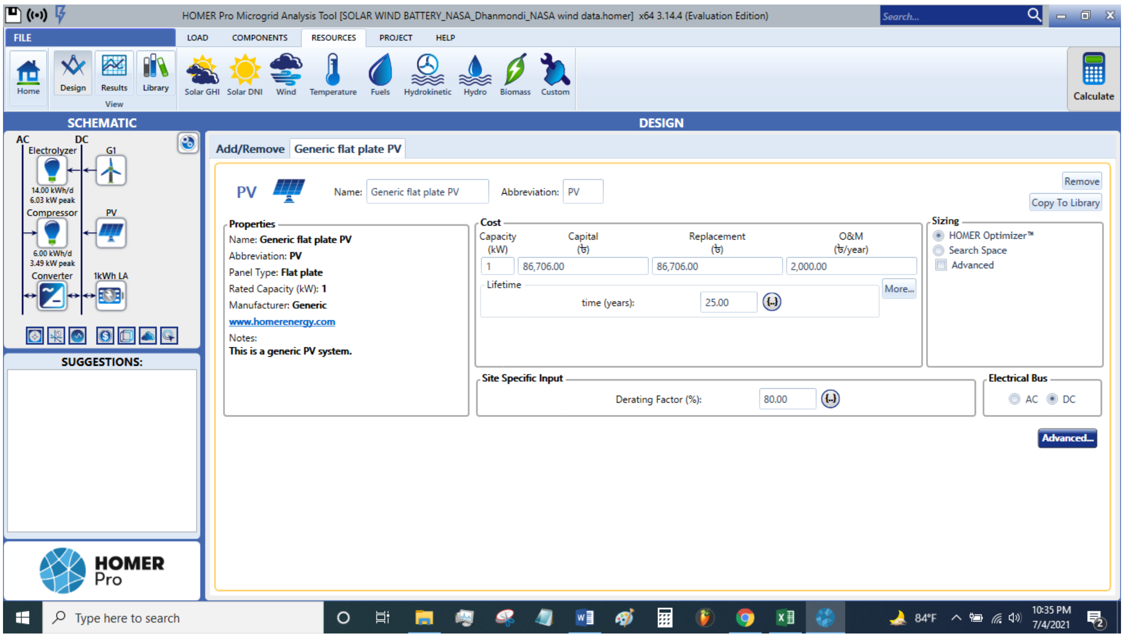

Fig. D-8. PV setup in HOMER

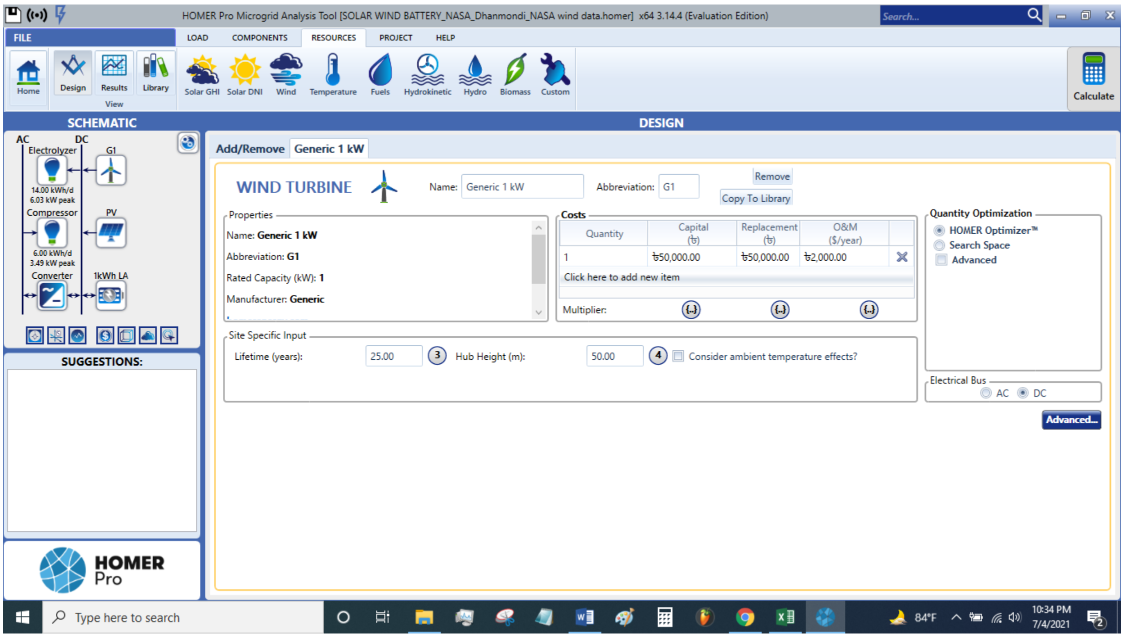

Fig. D-9. Turbine setup in HOMER

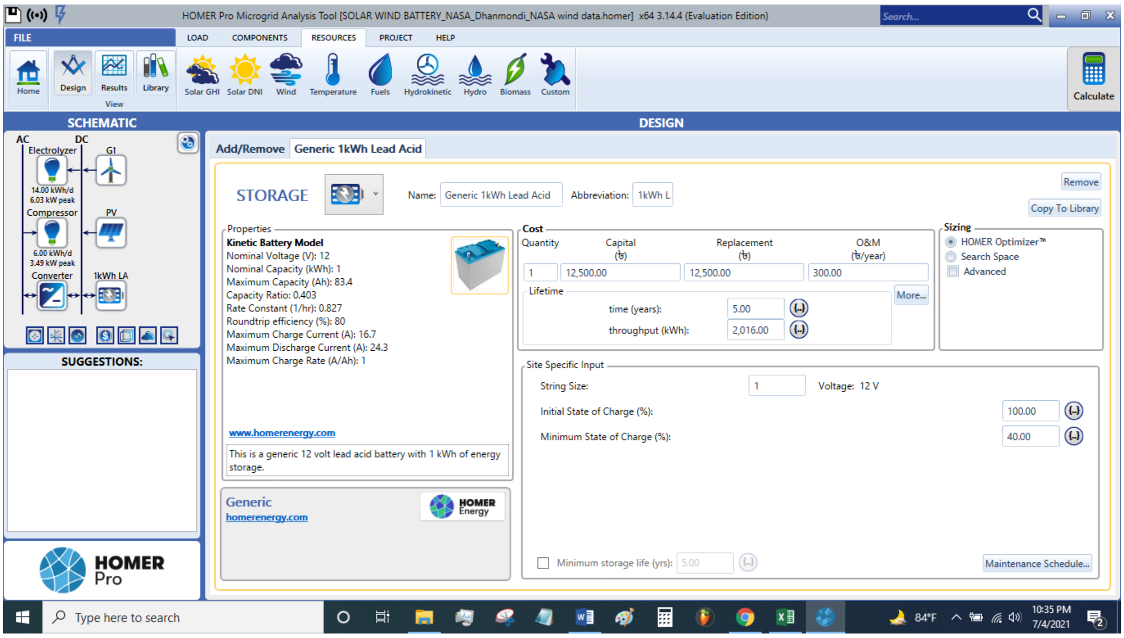

Fig. D-10. Battery setup in HOMER

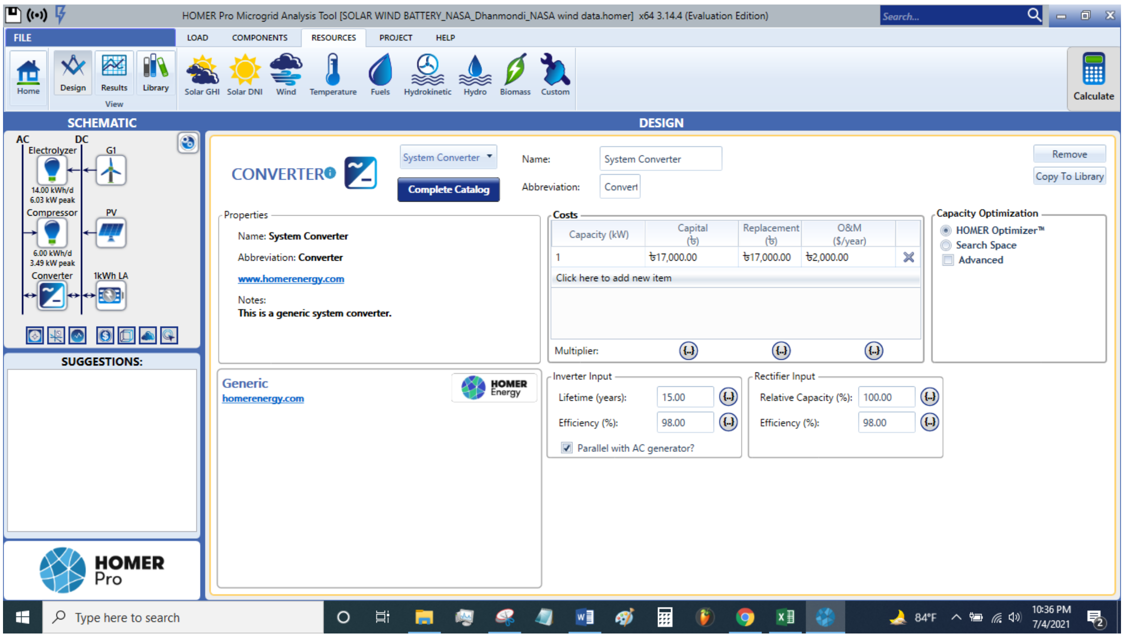

Fig. D-11. Converter setup in HOMER

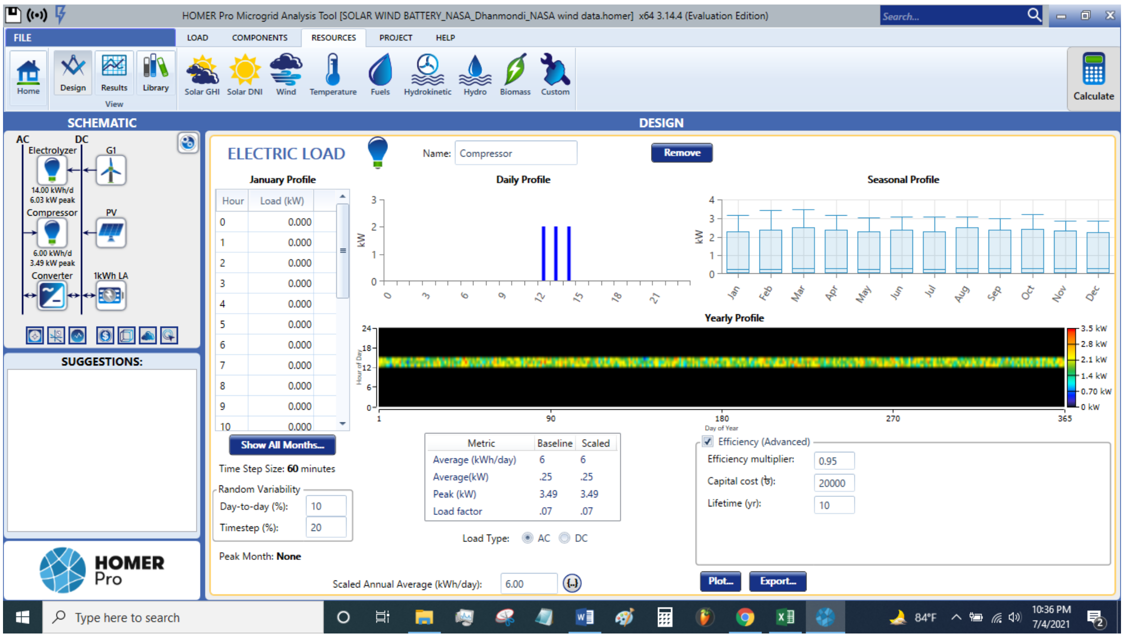

Fig. D-12. Load setup in HOMER

Appendix E

Table E-1. Battery sensitivity cases (System configuration)

Case No	Battery time (years)	Battery throughput (kWh)	Initial State Of Charge (%)	Minimum State Of Charge (%)	PV (kW)	Battery	Converter (kW)
1	3	1209	100	40	14.58	15	3.58
2	3	1612	100	40	14.58	15	3.58
3	3	2016	100	40	14.58	15	3.58
4	4	1209	100	40	12.51	19	3.82
5	4	1612	100	40	12.51	19	3.82
6	4	2016	100	40	12.51	19	3.82
7	5	1209	100	40	11.42	22	3.47
8	5	1612	100	40	11.42	22	3.47
9	5	2016	100	40	11.42	22	3.47
10	3	1209	100	50	17.00	14	3.79
11	3	1612	100	50	17.00	14	3.79
12	3	2016	100	50	17.00	14	3.79
13	4	1209	100	50	11.53	26	3.56
14	4	1612	100	50	11.53	26	3.56
15	4	2016	100	50	11.53	26	3.56
16	5	1209	100	50	11.84	25	3.48
17	5	1612	100	50	11.84	25	3.48
18	5	2016	100	50	11.84	25	3.48
19	3	1209	100	60	15.78	20	3.42
20	3	1612	100	60	15.78	20	3.42
21	3	2016	100	60	15.78	20	3.42
22	4	1209	100	60	15.71	20	3.56
23	4	1612	100	60	15.71	20	3.56
24	4	2016	100	60	15.71	20	3.56
25	5	1209	100	60	13.61	25	3.59
26	5	1612	100	60	13.61	25	3.59
27	5	2016	100	60	13.61	25	3.59
28	3	1209	80	40	14.58	15	3.58
29	3	1612	80	40	14.58	15	3.58
30	3	2016	80	40	14.58	15	3.58
31	4	1209	80	40	12.51	19	3.82
32	4	1612	80	40	12.51	19	3.82
33	4	2016	80	40	12.51	19	3.82
34	5	1209	80	40	11.42	22	3.47
35	5	1612	80	40	11.42	22	3.47
36	5	2016	80	40	11.42	22	3.47
37	3	1209	80	50	17.00	14	3.79
38	3	1612	80	50	17.00	14	3.79
39	3	2016	80	50	17.00	14	3.79
40	4	1209	80	50	11.53	26	3.56
41	4	1612	80	50	11.53	26	3.56
42	4	2016	80	50	11.53	26	3.56
43	5	1209	80	50	11.84	25	3.48
44	5	1612	80	50	11.84	25	3.48
45	5	2016	80	50	11.84	25	3.48
46	3	1209	80	60	15.78	20	3.42
47	3	1612	80	60	15.78	20	3.42
48	3	2016	80	60	15.78	20	3.42
49	4	1209	80	60	15.71	20	3.56
50	4	1612	80	60	15.71	20	3.56
51	4	2016	80	60	15.71	20	3.56
52	5	1209	80	60	13.61	25	3.59
53	5	1612	80	60	13.61	25	3.59
54	5	2016	80	60	13.61	25	3.59
55	3	1209	90	40	14.58	15	3.58
56	3	1612	90	40	14.58	15	3.58
57	3	2016	90	40	14.58	15	3.58
58	4	1209	90	40	12.51	19	3.82
59	4	1612	90	40	12.51	19	3.82
60	4	2016	90	40	12.51	19	3.82
61	5	1209	90	40	11.42	22	3.47
62	5	1612	90	40	11.42	22	3.47
63	5	2016	90	40	11.42	22	3.47
64	3	1209	90	50	17.00	14	3.79
65	3	1612	90	50	17.00	14	3.79
66	3	2016	90	50	17.00	14	3.79
67	4	1209	90	50	11.53	26	3.56
68	4	1612	90	50	11.53	26	3.56
69	4	2016	90	50	11.53	26	3.56
70	5	1209	90	50	11.84	25	3.48
71	5	1612	90	50	11.84	25	3.48
72	5	2016	90	50	11.84	25	3.48

73	3	1209	90	60	15.78	20	3.42
74	3	1612	90	60	15.78	20	3.42
75	3	2016	90	60	15.78	20	3.42
76	4	1209	90	60	15.71	20	3.56
77	4	1612	90	60	15.71	20	3.56
78	4	2016	90	60	15.71	20	3.56
79	5	1209	90	60	13.61	25	3.59
80	5	1612	90	60	13.61	25	3.59
81	5	2016	90	60	13.61	25	3.59

Table E-2. Battery sensitivity cases (System cost)

Case No	NPC (BDT)	COE(BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	PV Capital Cost (BDT)
1	3282761	61.82	116176.6	1822874	1264582
2	3282761	61.82	116176.6	1822874	1264582
3	3282761	61.82	116176.6	1822874	1264582
4	3058588	57.61	108316.8	1697467	1085094
5	3058588	57.61	108316.8	1697467	1085094
6	3058588	57.61	108316.8	1697467	1085094
7	2888967	54.42	99876.59	1633908	989926.1
8	2888967	54.42	99876.59	1633908	989926.1
9	2888967	54.42	99876.59	1633908	989926.1
10	3500164	65.93	117531	2023258	1473783
11	3500164	65.93	117531	2023258	1473783
12	3500164	65.93	117531	2023258	1473783
13	3281712	61.82	126245.7	1695295	999803.6
14	3281712	61.82	126245.7	1695295	999803.6
15	3281712	61.82	126245.7	1695295	999803.6
16	3060696	57.65	107614	1708407	1026745
17	3060696	57.65	107614	1708407	1026745
18	3060696	57.65	107614	1708407	1026745
19	3723280	70.11	138198.7	1986661	1368536
20	3723280	70.11	138198.7	1986661	1368536
21	3723280	70.11	138198.7	1986661	1368536
22	3453200	65.03	117010.4	1982835	1362366
23	3453200	65.03	117010.4	1982835	1362366
24	3453200	65.03	117010.4	1982835	1362366
25	3264286	61.47	111436.3	1863966	1180370
26	3264286	61.47	111436.3	1863966	1180370
27	3264286	61.47	111436.3	1863966	1180370
28	3282761	61.82	116176.6	1822874	1264582
29	3282761	61.82	116176.6	1822874	1264582
30	3282761	61.82	116176.6	1822874	1264582
31	3058588	57.61	108316.8	1697467	1085094
32	3058588	57.61	108316.8	1697467	1085094
33	3058588	57.61	108316.8	1697467	1085094
34	2888967	54.42	99876.59	1633908	989926.1
35	2888967	54.42	99876.59	1633908	989926.1
36	2888967	54.42	99876.59	1633908	989926.1
37	3500164	65.93	117531	2023258	1473783
38	3500164	65.93	117531	2023258	1473783
39	3500164	65.93	117531	2023258	1473783
40	3281712	61.82	126245.7	1695295	999803.6
41	3281712	61.82	126245.7	1695295	999803.6
42	3281712	61.82	126245.7	1695295	999803.6
43	3060696	57.65	107614	1708407	1026745
44	3060696	57.65	107614	1708407	1026745
45	3060696	57.65	107614	1708407	1026745
46	3723280	70.11	138198.7	1986661	1368536
47	3723280	70.11	138198.7	1986661	1368536
48	3723280	70.11	138198.7	1986661	1368536
49	3453200	65.03	117010.4	1982835	1362366
50	3453200	65.03	117010.4	1982835	1362366
51	3453200	65.03	117010.4	1982835	1362366
52	3264286	61.47	111436.3	1863966	1180370
53	3264286	61.47	111436.3	1863966	1180370
54	3264286	61.47	111436.3	1863966	1180370
55	3282761	61.82	116176.6	1822874	1264582
56	3282761	61.82	116176.6	1822874	1264582
57	3282761	61.82	116176.6	1822874	1264582
58	3058588	57.61	108316.8	1697467	1085094
59	3058588	57.61	108316.8	1697467	1085094
60	3058588	57.61	108316.8	1697467	1085094
61	2888967	54.42	99876.59	1633908	989926.1
62	2888967	54.42	99876.59	1633908	989926.1
63	2888967	54.42	99876.59	1633908	989926.1
64	3500164	65.93	117531	2023258	1473783
65	3500164	65.93	117531	2023258	1473783

66	3500164	65.93	117531	2023258	1473783
67	3281712	61.82	126245.7	1695295	999803.6
68	3281712	61.82	126245.7	1695295	999803.6
69	3281712	61.82	126245.7	1695295	999803.6
70	3060696	57.65	107614	1708407	1026745
71	3060696	57.65	107614	1708407	1026745
72	3060696	57.65	107614	1708407	1026745
73	3723280	70.11	138198.7	1986661	1368536
74	3723280	70.11	138198.7	1986661	1368536
75	3723280	70.11	138198.7	1986661	1368536
76	3453200	65.03	117010.4	1982835	1362366
77	3453200	65.03	117010.4	1982835	1362366
78	3453200	65.03	117010.4	1982835	1362366
79	3264286	61.47	111436.3	1863966	1180370
80	3264286	61.47	111436.3	1863966	1180370
81	3264286	61.47	111436.3	1863966	1180370

Table E-3. Battery sensitivity cases (Performance)

Case No	PV Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	21573.69	18.66777	168.3167
2	21573.69	18.66777	168.3167
3	21573.69	18.66777	168.3167
4	18511.64	23.64585	208.6854
5	18511.64	23.64585	208.6854
6	18511.64	23.64585	208.6854
7	16888.08	27.3794	238.1618
8	16888.08	27.3794	238.1618
9	16888.08	27.3794	238.1618
10	25142.66	14.51938	132.7413
11	25142.66	14.51938	132.7413
12	25142.66	14.51938	132.7413
13	17056.59	26.96456	234.8409
14	17056.59	26.96456	234.8409
15	17056.59	26.96456	234.8409
16	17516.21	25.92746	226.0657
17	17516.21	25.92746	226.0657
18	17516.21	25.92746	226.0657
19	23347.14	16.59357	149.369
20	23347.14	16.59357	149.369
21	23347.14	16.59357	149.369
22	23241.89	16.59357	150.3007
23	23241.89	16.59357	150.3007
24	23241.89	16.59357	150.3007
25	20137.04	20.74197	185.6015
26	20137.04	20.74197	185.6015
27	20137.04	20.74197	185.6015
28	21573.69	18.66777	168.3167
29	21573.69	18.66777	168.3167
30	21573.69	18.66777	168.3167
31	18511.64	23.64585	208.6854
32	18511.64	23.64585	208.6854
33	18511.64	23.64585	208.6854
34	16888.08	27.3794	238.1618
35	16888.08	27.3794	238.1618
36	16888.08	27.3794	238.1618
37	25142.66	14.51938	132.7413
38	25142.66	14.51938	132.7413
39	25142.66	14.51938	132.7413
40	17056.59	26.96456	234.8409
41	17056.59	26.96456	234.8409
42	17056.59	26.96456	234.8409
43	17516.21	25.92746	226.0657
44	17516.21	25.92746	226.0657
45	17516.21	25.92746	226.0657
46	23347.14	16.59357	149.369
47	23347.14	16.59357	149.369
48	23347.14	16.59357	149.369
49	23241.89	16.59357	150.3007
50	23241.89	16.59357	150.3007
51	23241.89	16.59357	150.3007
52	20137.04	20.74197	185.6015
53	20137.04	20.74197	185.6015
54	20137.04	20.74197	185.6015
55	21573.69	18.66777	168.3167
56	21573.69	18.66777	168.3167
57	21573.69	18.66777	168.3167

58	18511.64	23.64585	208.6854
59	18511.64	23.64585	208.6854
60	18511.64	23.64585	208.6854
61	16888.08	27.3794	238.1618
62	16888.08	27.3794	238.1618
63	16888.08	27.3794	238.1618
64	25142.66	14.51938	132.7413
65	25142.66	14.51938	132.7413
66	25142.66	14.51938	132.7413
67	17056.59	26.96456	234.8409
68	17056.59	26.96456	234.8409
69	17056.59	26.96456	234.8409
70	17516.21	25.92746	226.0657
71	17516.21	25.92746	226.0657
72	17516.21	25.92746	226.0657
73	23347.14	16.59357	149.369
74	23347.14	16.59357	149.369
75	23347.14	16.59357	149.369
76	23241.89	16.59357	150.3007
77	23241.89	16.59357	150.3007
78	23241.89	16.59357	150.3007
79	20137.04	20.74197	185.6015
80	20137.04	20.74197	185.6015
81	20137.04	20.74197	185.6015

Table E-4. Economics sensitivity cases (Configuration)

Case no.	Nominal Discount Rate (%)	Expected Inflation Rate (%)	Project Lifetime (years)	PV (kW)	Battery	Converter (kW)
1	10	5.48	15	10.40	25	3.49
2	10	5.48	20	10.40	25	3.49
3	10	5.48	25	10.40	25	3.49
4	12	5.48	15	10.40	25	3.49
5	12	5.48	20	10.40	25	3.49
6	12	5.48	25	10.40	25	3.49
7	14	5.48	15	10.40	25	3.49
8	14	5.48	20	10.40	25	3.49
9	14	5.48	25	10.40	25	3.49
10	16	5.48	15	10.40	25	3.49
11	16	5.48	20	10.40	25	3.49
12	16	5.48	25	10.40	25	3.49
13	8	5.48	15	12.72	20	3.61
14	8	5.48	20	12.19	20	3.51
15	8	5.48	25	12.72	20	3.61
16	10	6.5	15	10.40	25	3.49
17	10	6.5	20	12.72	20	3.61
18	10	6.5	25	12.72	20	3.61
19	12	6.5	15	10.40	25	3.49
20	12	6.5	20	10.40	25	3.49
21	12	6.5	25	10.40	25	3.49
22	14	6.5	15	10.40	25	3.49
23	14	6.5	20	10.40	25	3.49
24	14	6.5	25	10.40	25	3.49
25	16	6.5	15	10.40	25	3.49
26	16	6.5	20	10.40	25	3.49
27	16	6.5	25	10.40	25	3.49
28	8	6.5	15	12.72	20	3.61
29	8	6.5	20	12.21	20	3.40
30	8	6.5	25	12.21	20	3.40
31	10	6	15	10.40	25	3.49
32	10	6	20	10.40	25	3.49
33	10	6	25	12.72	20	3.61
34	12	6	15	10.40	25	3.49
35	12	6	20	10.40	25	3.49
36	12	6	25	10.40	25	3.49
37	14	6	15	10.40	25	3.49
38	14	6	20	10.40	25	3.49
39	14	6	25	10.40	25	3.49
40	16	6	15	10.40	25	3.49
41	16	6	20	10.40	25	3.49
42	16	6	25	10.40	25	3.49
43	8	6	15	12.72	19	3.29
44	8	6	20	12.72	20	3.61
45	8	6	25	13.01	18	3.50
46	10	7	15	12.72	20	3.61
47	10	7	20	12.72	20	3.61
48	10	7	25	12.12	20	3.67

49	12	7	15	10.40	25	3.49
50	12	7	20	10.40	25	3.49
51	12	7	25	10.40	25	3.49
52	14	7	15	10.40	25	3.49
53	14	7	20	10.40	25	3.49
54	14	7	25	10.40	25	3.49
55	16	7	15	10.40	25	3.49
56	16	7	20	10.40	25	3.49
57	16	7	25	10.40	25	3.49
58	8	7	15	12.21	20	3.40
59	8	7	20	13.01	18	3.41
60	8	7	25	13.66	18	3.53

Table E-5. Economics sensitivity cases (Cost)

Case no.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	PV Capital Cost (BDT)
1	2356208	51.17	70857.66	1583864	901979.1
2	2817282	50.32	93063.53	1583864	901979.1
3	3187403	49.76	105762.70	1583864	901979.1
4	2286073	56.38	73160.11	1583864	901979.1
5	2640974	55.31	93524.48	1583864	901979.1
6	2900393	54.64	104768.20	1583864	901979.1
7	2221865	61.74	74889.70	1583864	901979.1
8	2496038	60.53	93442.39	1583864	901979.1
9	2678893	59.80	103259.70	1583864	901979.1
10	2163634	67.24	76109.00	1583864	901979.1
11	2376214	65.95	92900.55	1583864	901979.1
12	2505816	65.22	101362.40	1583864	901979.1
13	2424612	44.81	57673.25	1704676	1103246.0
14	2991019	44.94	83431.24	1676664	1056954.0
15	3538574	43.75	98277.98	1704676	1103246.0
16	2395383	48.49	69393.98	1583864	901979.1
17	2923327	46.54	84096.64	1704676	1103246.0
18	3361464	45.97	98207.41	1704676	1103246.0
19	2322972	53.57	72000.36	1583864	901979.1
20	2731172	52.60	93349.92	1583864	901979.1
21	3044842	51.99	105373.70	1583864	901979.1
22	2256171	58.80	74012.77	1583864	901979.1
23	2571684	57.65	93549.58	1583864	901979.1
24	2792854	56.95	104139.20	1583864	901979.1
25	2195251	64.16	75490.94	1583864	901979.1
26	2439995	62.91	93253.29	1583864	901979.1
27	2596801	62.18	102457.10	1583864	901979.1
28	2451628	42.09	55590.71	1704676	1103246.0
29	3101683	42.37	82260.83	1676548	1058783.0
30	3726329	42.10	97841.89	1676548	1058783.0
31	2376093	49.79	70130.43	1583864	901979.1
32	2871211	49.01	92835.87	1583864	901979.1
33	3274711	47.21	98110.30	1704676	1103246.0
34	2304762	54.93	72587.27	1583864	901979.1
35	2685981	53.92	93455.39	1583864	901979.1
36	2971843	53.27	105098.10	1583864	901979.1
37	2239212	60.23	74460.18	1583864	901979.1
38	2533795	59.05	93515.27	1583864	901979.1
39	2735323	58.33	103725.90	1583864	901979.1
40	2179603	65.66	75810.34	1583864	901979.1
41	2408060	64.39	93096.62	1583864	901979.1
42	2550918	63.65	101934.80	1583864	901979.1
43	2415121	44.11	54708.24	1706170	1102690.0
44	3074939	42.91	82888.05	1704676	1103246.0
45	3604780	43.12	95132.76	1722537	1128087.0
46	2413021	45.97	58496.50	1704676	1103246.0
47	2973131	45.27	83720.58	1704676	1103246.0
48	3425219	45.55	98419.72	1673333	1050892.0
49	2341401	52.22	71378.05	1583864	901979.1
50	2778319	51.32	93205.87	1583864	901979.1
51	3122337	50.74	105607.40	1583864	901979.1
52	2273392	57.39	73531.46	1583864	901979.1
53	2611191	56.29	93548.20	1583864	901979.1
54	2853803	55.60	104516.90	1583864	901979.1
55	2211182	62.70	75139.61	1583864	901979.1
56	2473274	61.47	93377.94	1583864	901979.1
57	2645307	60.74	102950.30	1583864	901979.1
58	2440929	41.46	54851.37	1676548	1058783.0
59	3144388	40.97	78373.70	1720732	1127705.0
60	3871688	40.23	95131.70	1759550	1184489.0

Table E-6. Economics sensitivity cases (Performance)

Case no.	PV Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	15387.71	31.11	271.42
2	15387.71	31.11	271.42
3	15387.71	31.11	271.42
4	15387.71	31.11	271.42
5	15387.71	31.11	271.42
6	15387.71	31.11	271.42
7	15387.71	31.11	271.42
8	15387.71	31.11	271.42
9	15387.71	31.11	271.42
10	15387.71	31.11	271.42
11	15387.71	31.11	271.42
12	15387.71	31.11	271.42
13	18821.32	24.26	218.27
14	18031.57	24.89	216.95
15	18821.32	24.26	218.27
16	15387.71	31.11	271.42
17	18821.32	24.26	218.27
18	18821.32	24.26	218.27
19	15387.71	31.11	271.42
20	15387.71	31.11	271.42
21	15387.71	31.11	271.42
22	15387.71	31.11	271.42
23	15387.71	31.11	271.42
24	15387.71	31.11	271.42
25	15387.71	31.11	271.42
26	15387.71	31.11	271.42
27	15387.71	31.11	271.42
28	18821.32	24.26	218.27
29	18062.77	24.89	216.48
30	18062.77	24.89	216.48
31	15387.71	31.11	271.42
32	15387.71	31.11	271.42
33	18821.32	24.26	218.27
34	15387.71	31.11	271.42
35	15387.71	31.11	271.42
36	15387.71	31.11	271.42
37	15387.71	31.11	271.42
38	15387.71	31.11	271.42
39	15387.71	31.11	271.42
40	15387.71	31.11	271.42
41	15387.71	31.11	271.42
42	15387.71	31.11	271.42
43	18811.82	23.65	204.57
44	18821.32	24.26	218.27
45	19245.09	22.40	197.66
46	18821.32	24.26	218.27
47	18821.32	24.26	218.27
48	17928.16	24.89	218.53
49	15387.71	31.11	271.42
50	15387.71	31.11	271.42
51	15387.71	31.11	271.42
52	15387.71	31.11	271.42
53	15387.71	31.11	271.42
54	15387.71	31.11	271.42
55	15387.71	31.11	271.42
56	15387.71	31.11	271.42
57	15387.71	31.11	271.42
58	18062.77	24.89	216.48
59	19238.58	22.40	197.75
60	20207.31	21.84	197.90

Table E-7. Dhanmondi site measured data sensitivity all cases (Configuration)

Case No.	Nominal Discount Rate (%)	Turbine Lifetime (years)	Turbine Hub Height (m)	Turbine	Battery	Converter (kW)
1	10	10	100	51	48	3.45
2	10	15	100	54	40	3.46
3	10	25	100	59	31	3.31
4	10	10	150	44	52	3.56
5	10	15	150	48	41	4.39
6	10	25	150	51	34	3.27

7	10	10	32	61	70	6.22
8	10	15	32	65	62	3.77
9	10	25	32	67	59	3.41
10	12	10	100	53	42	3.70
11	12	15	100	55	38	3.74
12	12	25	100	56	36	3.71
13	12	10	150	44	52	3.56
14	12	15	150	48	41	4.39
15	12	25	150	53	30	3.48
16	12	10	32	61	70	6.22
17	12	15	32	65	62	3.77
18	12	25	32	66	60	3.67
19	14	10	100	53	42	3.70
20	14	15	100	53	42	3.70
21	14	25	100	57	34	3.79
22	14	10	150	44	52	3.56
23	14	15	150	48	41	4.39
24	14	25	150	50	36	4.78
25	14	10	32	61	70	6.22
26	14	15	32	61	70	3.49
27	14	25	32	66	60	3.67
28	8	10	100	51	48	3.41
29	8	15	100	54	40	3.46
30	8	25	100	59	31	3.31
31	8	10	150	47	44	3.45
32	8	15	150	48	41	4.39
33	8	25	150	49	38	3.58
34	8	10	32	61	70	6.22
35	8	15	32	66	60	3.67
36	8	25	32	67	59	3.41

Table E-8. Dhanmondi site measured data sensitivity all cases (Cost)

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	9487137	148.12	393654.2	3518685	2550000	102000
2	8141288	127.11	301578.5	3568857	2700000	108000
3	6984121	109.00	216352.8	3703853	2950000	118000
4	8800517	137.42	368035.3	3220490	2200000	88000
5	7632202	119.16	285928.1	3297057	2400000	96000
6	6481591	101.18	207165.0	3340625	2550000	102000
7	11942270	186.44	501364.2	4340759	3050000	122000
8	10314500	161.04	390158.4	4399049	3250000	130000
9	8960760	139.89	297151.1	4455455	3350000	134000
10	8387436	158.01	385124.6	3547920	2650000	106000
11	7331013	138.09	297023.1	3598589	2750000	110000
12	6408493	120.70	221659.2	3623101	2800000	112000
13	7784462	146.66	363197.1	3220490	2200000	88000
14	6843343	128.92	282210.4	3297057	2400000	96000
15	5924385	111.56	201358.1	3394098	2650000	106000
16	10559160	198.90	494855.4	4340759	3050000	122000
17	9239609	174.06	385207.7	4399049	3250000	130000
18	8147735	153.49	296457.5	4422419	3300000	132000
19	7548014	168.50	377203.2	3547920	2650000	106000
20	6658653	148.65	293337.7	3547920	2650000	106000
21	5955908	132.92	217498.0	3649426	2850000	114000
22	6995665	156.18	355993.7	3220490	2200000	88000
23	6229370	139.06	276512.9	3297057	2400000	96000
24	5572665	124.38	210416.8	3341277	2500000	100000
25	9485725	211.73	485163.1	4340759	3050000	122000
26	8345577	186.28	382024.3	4294358	3050000	122000
27	7539423	168.30	293929.1	4422419	3300000	132000
28	10899230	138.26	395558.2	3517988	2550000	102000
29	9217859	116.93	302728.2	3568857	2700000	108000
30	7748349	98.25	216743.3	3703853	2950000	118000
31	10102710	128.16	366233.1	3268686	2350000	94000
32	8652753	109.77	287010.0	3297057	2400000	96000
33	7281123	92.37	213572.8	3295788	2450000	98000
34	13742090	174.32	503814.2	4340759	3050000	122000
35	11702050	148.45	390113.3	4422419	3300000	132000
36	10010920	126.99	297715.8	4455455	3350000	134000

Table E-9. Dhanmondi site measured data sensitivity all cases (Performance)

Case No.	Turbine Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	18030.32	59.74	1253.23
2	19090.93	49.78	1144.60
3	20858.60	38.58	982.42
4	20930.72	64.71	1345.71
5	22833.52	51.03	1191.52
6	24260.61	42.31	1085.86
7	11621.06	87.12	1367.22
8	12383.10	77.16	1228.04
9	12764.12	73.43	1163.49
10	18737.39	52.27	1179.53
11	19444.46	47.29	1110.75
12	19798.00	44.80	1077.64
13	20930.72	64.71	1345.71
14	22833.52	51.03	1191.52
15	25212.01	37.34	1020.34
16	11621.06	87.12	1367.22
17	12383.10	77.16	1228.04
18	12573.61	74.67	1195.06
19	18737.39	52.27	1179.53
20	18737.39	52.27	1179.53
21	20151.53	42.31	1044.97
22	20930.72	64.71	1345.71
23	22833.52	51.03	1191.52
24	23784.91	44.80	1119.88
25	11621.06	87.12	1367.22
26	11621.06	87.12	1367.22
27	12573.61	74.67	1195.06
28	18030.32	59.74	1253.23
29	19090.93	49.78	1144.60
30	20858.60	38.58	982.42
31	22357.82	54.76	1229.07
32	22833.52	51.03	1191.52
33	23309.21	47.29	1154.88
34	11621.06	87.12	1367.22
35	12573.61	74.67	1195.06
36	12764.12	73.43	1163.49

Table E-10. Dhanmondi site retrieved data sensitivity all cases (Configuration)

Case no.	Discount Rate (%)	Turbine Lifetime (years)	Turbine Hub Height (m)	Turbine	Battery	Converter (kW)
1	10	10	100	26	24	3.46
2	10	15	100	26	22	3.18
3	10	25	100	27	20	3.31
4	10	10	150	24	20	3.62
5	10	15	150	24	20	3.62
6	10	25	150	24	20	3.62
7	10	10	32	30	29	3.31
8	10	15	32	32	24	3.85
9	10	25	32	33	22	3.60
10	12	10	100	26	24	3.46
11	12	15	100	26	22	3.18
12	12	25	100	26	22	3.19
13	12	10	150	23	23	3.32
14	12	15	150	24	20	3.62
15	12	25	150	24	20	3.62
16	12	10	32	30	29	3.31
17	12	15	32	32	24	4.14
18	12	25	32	33	22	3.56
19	14	10	100	26	24	3.46
20	14	15	100	25	25	3.30
21	14	25	100	26	22	3.18
22	14	10	150	24	20	3.62
23	14	15	150	24	20	3.62
24	14	25	150	24	20	3.62
25	14	10	32	30	29	3.31
26	14	15	32	32	24	4.14
27	14	25	32	32	24	3.78
28	8	10	100	26	24	3.46
29	8	15	100	26	22	3.18
30	8	25	100	27	20	3.31
31	8	10	150	24	20	3.62
32	8	15	150	24	20	3.62

33	8	25	150	24	20	3.63
34	8	10	32	30	29	3.31
35	8	15	32	32	24	4.71
36	8	25	32	31	24	3.45

Table E-11. Dhanmondi site retrieved data sensitivity all cases (Cost)

Case no.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	5159221	78.51	211746.9	1948785	1300000	52000
2	4440158	69.30	164957.9	1939122	1300000	52000
3	3891613	60.74	126983.9	1966327	1350000	54000
4	4764490	74.39	194102.9	1821567	1200000	48000
5	4166773	65.06	154680.5	1821560	1200000	48000
6	3667388	57.26	121743.1	1821560	1200000	48000
7	5931006	92.59	244181.9	2228801	1500000	60000
8	5140029	78.22	190250.7	2255512	1600000	64000
9	4445869	67.64	143100.6	2276226	1650000	66000
10	4572933	83.96	208827.5	1948785	1300000	52000
11	3983853	75.02	162718.1	1939120	1300000	52000
12	3552047	66.89	128350.6	1939180	1300000	52000
13	4223547	79.54	192554.0	1803893	1150000	46000
14	3738804	70.43	152572.1	1821567	1200000	48000
15	3340038	62.92	120839.3	1821560	1200000	48000
16	5255197	98.98	240838.0	2228801	1500000	60000
17	4627778	84.97	188394.7	2260390	1600000	64000
18	4061056	74.55	142090.4	2275533	1650000	66000
19	4117344	89.57	204492.1	1948785	1300000	52000
20	3658225	81.64	163105.5	1928554	1250000	50000
21	3285153	73.31	126928.8	1939122	1300000	52000
22	3807902	85.00	187317.6	1821471	1200000	48000
23	3405413	76.02	149354.5	1821567	1200000	48000
24	3088518	68.94	119472.4	1821560	1200000	48000
25	4730116	105.57	235870.4	2228801	1500000	60000
26	4216678	91.74	184475.1	2260390	1600000	64000
27	3778949	82.22	143769.5	2254329	1600000	64000
28	5920668	73.20	212851.9	1948785	1300000	52000
29	5029835	63.79	165630.3	1939122	1300000	52000
30	4341897	55.06	127306.1	1966327	1350000	54000
31	5462874	69.30	195136.5	1821567	1200000	48000
32	4719811	59.87	155316.4	1821560	1200000	48000
33	4099745	52.01	122081.7	1821663	1200000	48000
34	6808927	86.36	245447.5	2228801	1500000	60000
35	5873978	72.63	193129.2	2270128	1600000	64000
36	4922342	62.44	144890.6	2218639	1550000	62000

Table E-12. Dhanmondi site retrieved data sensitivity all cases (Performance)

Case no.	Turbine Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	27320.82	29.11	981.28
2	27320.82	27.38	913.34
3	28371.62	24.89	866.68
4	36318.55	24.89	724.43
5	36318.55	24.89	724.43
6	36318.55	24.89	724.43
7	11762.13	36.09	1580.90
8	12546.27	29.11	1560.11
9	12938.34	26.69	1501.17
10	27320.82	29.11	981.28
11	27320.82	27.38	913.34
12	27320.82	27.38	913.36
13	34805.28	28.62	769.30
14	36318.55	24.89	724.43
15	36318.55	24.89	724.43
16	11762.13	36.09	1580.90
17	12546.27	29.11	1560.11
18	12938.34	26.69	1501.17
19	27320.82	29.11	981.28
20	26270.02	31.11	961.48
21	27320.82	27.38	913.34
22	36318.55	24.89	724.43
23	36318.55	24.89	724.43
24	36318.55	24.89	724.43
25	11762.13	36.09	1580.90
26	12546.27	29.11	1560.11

27	12546.27	29.11	1560.11
28	27320.82	29.11	981.28
29	27320.82	27.38	913.34
30	28371.62	24.89	866.68
31	36318.55	24.89	724.43
32	36318.55	24.89	724.43
33	36318.55	24.89	724.43
34	11762.13	36.09	1580.90
35	12546.27	29.11	1560.11
36	12154.20	29.87	1518.06

Table E-13. City Centre site sensitivity all cases (Configuration)

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine	Battery	Converter (kW)
1	10	10	23	20	3.59
2	10	15	23	20	3.59
3	10	25	23	20	3.59
4	12	10	23	20	3.60
5	12	15	23	20	3.59
6	12	25	23	20	3.59
7	14	10	22	22	3.57
8	14	15	23	20	3.59
9	14	25	23	20	3.59
10	8	10	23	20	3.59
11	8	15	23	20	3.59
12	8	25	23	20	3.59

Table E-14. City Centre site sensitivity all cases (Cost)

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	4636991	72.40	189021.6	1771109	1150000	46000
2	4064201	63.45	151242.7	1771109	1150000	46000
3	3585624	55.98	119677.8	1771109	1150000	46000
4	4113199	77.48	186377.9	1771154	1150000	46000
5	3645772	68.68	149184.1	1771109	1150000	46000
6	3263640	61.48	118774.4	1771109	1150000	46000
7	3676563	82.07	182074.5	1745734	1100000	44000
8	3319852	74.11	146044.2	1771109	1150000	46000
9	3016177	67.33	117408.1	1771109	1150000	46000
10	5317043	67.45	190025.5	1771109	1150000	46000
11	4604966	58.42	151865.5	1771109	1150000	46000
12	4010369	50.87	120001.2	1771109	1150000	46000

Table E-15. City Centre site sensitivity all cases (Performance)

Case No.	Turbine Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	40494.88	24.89	659.48
2	40494.88	24.89	659.48
3	40494.88	24.89	659.48
4	40494.88	24.89	659.48
5	40494.88	24.89	659.48
6	40494.88	24.89	659.48
7	38734.23	27.38	699.76
8	40494.88	24.89	659.48
9	40494.88	24.89	659.48
10	40494.88	24.89	659.48
11	40494.88	24.89	659.48
12	40494.88	24.89	659.48

Table E-16. Hilton Dhaka site sensitivity all cases (Configuration)

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine	Battery	Converter (kW)
1	10	10	24	20	3.35
2	10	15	23	22	3.26
3	10	25	24	20	3.36
4	12	10	23	22	3.29
5	12	15	23	22	3.26
6	12	25	24	20	3.33

7	14	10	22	25	3.41
8	14	15	24	20	3.33
9	14	25	23	22	3.26
10	8	10	24	20	3.35
11	8	15	23	22	3.26
12	8	25	24	20	3.33

Table E-17. Hilton Dhaka site sensitivity all cases (Cost)

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	4749577	74.14352	193426.7	1816906	1200000	48000
2	4141001	64.6409	155032.8	1790446	1150000	46000
3	3653357	57.03092	121106.9	1817175	1200000	48000
4	4180846	78.74257	190191.9	1790875	1150000	46000
5	3712383	69.91991	152945.0	1790461	1150000	46000
6	3326274	62.65021	120133.6	1816663	1200000	48000
7	3778976	84.3483	188456.0	1780473	1100000	44000
8	3392975	75.72704	148648.5	1816614	1200000	48000
9	3074850	68.62432	121117.5	1790446	1150000	46000
10	5445572	69.07006	194459.0	1816906	1200000	48000
11	4695231	59.55072	155666.5	1790446	1150000	46000
12	4081057	51.76294	121350.0	1816629	1200000	48000

Table E-18. Hilton Dhaka site sensitivity all cases (Performance)

Case No.	Turbine Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	38563.27	24.89	683.99
2	36956.46	27.38	725.18
3	38563.27	24.89	683.99
4	36956.46	27.38	725.21
5	36956.46	27.38	725.18
6	38563.27	24.89	683.99
7	35349.66	31.11	768.10
8	38563.27	24.89	683.99
9	36956.46	27.38	725.18
10	38563.27	24.89	683.99
11	36956.46	27.38	725.18
12	38563.27	24.89	683.99

Table E-19. Bangladesh Bank site sensitivity all cases (Configuration)

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine	Battery	Converter (kW)
1	10	10	25	19	3.50
2	10	15	25	19	3.50
3	10	25	25	19	3.50
4	12	10	25	19	3.50
5	12	15	25	19	3.50
6	12	25	25	19	3.50
7	14	10	25	19	3.49
8	14	15	25	19	3.50
9	14	25	25	19	3.50
10	8	10	25	19	3.50
11	8	15	25	19	3.50
12	8	25	25	19	3.52

Table E-20. Bangladesh Bank site sensitivity all cases (Cost)

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	4836394	75.51	196509.5	1856983	1250000	50000
2	4213796	65.79	155445.5	1856983	1250000	50000
3	3693603	57.66	121135.8	1856983	1250000	50000
4	4291616	80.84	193739.6	1857065	1250000	50000
5	3783450	71.27	153306.6	1856983	1250000	50000
6	3368089	63.44	120252.6	1856983	1250000	50000
7	3867451	86.33	189591.9	1856903	1250000	50000
8	3448142	76.97	150044.1	1856983	1250000	50000
9	3118061	69.60	118917.9	1856983	1250000	50000
10	5543624	70.32	197565.9	1856983	1250000	50000

11	4769628	60.50	156087.7	1856983	1250000	50000
12	4124698	52.32	121506.4	1857352	1250000	50000

Table E-21. Bangladesh Bank site sensitivity all cases (Performance)

Case No.	Turbine Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	36947.86	23.65	700.56
2	36947.86	23.65	700.56
3	36947.86	23.65	700.56
4	36947.86	23.65	700.56
5	36947.86	23.65	700.56
6	36947.86	23.65	700.56
7	36947.86	23.65	700.56
8	36947.86	23.65	700.56
9	36947.86	23.65	700.56
10	36947.86	23.65	700.56
11	36947.86	23.65	700.56
12	36947.86	23.65	700.56

Table E-22. Section Seven site measured data sensitivity all cases (Configuration)

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine Hub Height (m)	Turbine	Battery	Converter (kW)
1	10	10	100	30	47	6.76
2	10	15	100	32	35	3.66
3	10	25	100	35	25	3.52
4	10	10	150	31	29	3.68
5	10	15	150	33	24	3.61
6	10	25	150	33	24	3.61
7	10	10	40	34	61	3.57
8	10	15	40	42	29	3.91
9	10	25	40	43	28	3.46
10	12	10	100	30	47	6.77
11	12	15	100	32	35	3.66
12	12	25	100	35	25	3.52
13	12	10	150	31	29	4.68
14	12	15	150	33	24	3.61
15	12	25	150	33	24	3.61
16	12	10	40	34	61	3.57
17	12	15	40	42	29	3.77
18	12	25	40	43	28	3.46
19	14	10	100	29	54	3.51
20	14	15	100	32	35	3.66
21	14	25	100	33	30	3.50
22	14	10	150	31	29	4.68
23	14	15	150	33	24	3.61
24	14	25	150	33	24	3.61
25	14	10	40	34	61	3.57
26	14	15	40	40	36	3.79
27	14	25	40	43	28	3.53
28	8	10	100	30	47	6.76
29	8	15	100	32	35	3.66
30	8	25	100	35	25	3.52
31	8	10	150	31	29	3.68
32	8	15	150	33	24	3.61
33	8	25	150	33	24	3.61
34	8	10	40	34	61	3.57
35	8	15	40	42	29	3.82
36	8	25	40	42	29	3.75

Table E-23. Section Seven site measured data sensitivity all cases (Cost)

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	8337527	130.18	384197.8	2512448	1500000	150000
2	7145407	111.55	312345.5	2409729	1600000	160000
3	6374669	99.52	260020.7	2432323	1750000	175000
4	7486884	116.90	343095.1	2284992	1550000	155000
5	6767324	105.65	293233.9	2321410	1650000	165000
6	6080670	94.93	247945.1	2321410	1650000	165000
7	9514500	148.55	440670.3	2833206	1700000	170000
8	8302095	126.34	361643.8	2818974	2100000	210000

9	7482012	113.84	305586.3	2848815	2150000	215000
10	7293771	137.41	380482.0	2512594	1500000	150000
11	6299633	118.66	309555.3	2409729	1600000	160000
12	5687268	107.13	259025.8	2432323	1750000	175000
13	6601380	124.36	342133.5	2302096	1550000	155000
14	5973100	112.52	290598.4	2321410	1650000	165000
15	5424824	102.19	246967.1	2321410	1650000	165000
16	8317358	156.69	436424.3	2833206	1700000	170000
17	7317130	134.35	358147.8	2816608	2100000	210000
18	6676037	122.56	304567.1	2848815	2150000	215000
19	6471111	144.46	374976.5	2494630	1450000	145000
20	5647154	126.05	305284.7	2409729	1600000	160000
21	5138600	114.71	258763.8	2394510	1650000	165000
22	5876045	131.17	337018.4	2302096	1550000	155000
23	5360384	119.65	286571.0	2321410	1650000	165000
24	4924677	109.93	245484.4	2321410	1650000	165000
25	7393988	165.06	430075.4	2833206	1700000	170000
26	6587012	143.31	356689.8	2804455	2000000	200000
27	6065199	131.94	303187.6	2850012	2150000	215000
28	9707683	123.16	385590.4	2512448	1500000	150000
29	8253742	104.70	313178.8	2409729	1600000	160000
30	7290998	92.48	260374.9	2432323	1750000	175000
31	8711449	110.51	344391.8	2284992	1550000	155000
32	7807760	99.04	294011.7	2321410	1650000	165000
33	6954642	88.22	248293.4	2321410	1650000	165000
34	11085800	140.64	442253.9	2833206	1700000	170000
35	9578438	118.43	362324.2	2817357	2100000	210000
36	8488455	104.95	303973.0	2816226	2100000	210000

Table E-24. Section Seven site measured data sensitivity all cases (Performance)

Case No.	Turbine Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	12766.66	58.49	1842.19
2	13617.77	43.56	1733.84
3	14894.43	31.11	1578.30
4	19625.21	36.09	1511.02
5	20891.36	29.87	1410.09
6	20891.36	29.87	1410.09
7	7599.11	75.92	2213.36
8	9387.14	35.18	1896.06
9	9610.64	33.97	1846.38
10	12766.66	58.49	1842.19
11	13617.77	43.56	1733.84
12	14894.43	31.11	1578.30
13	19625.21	36.09	1511.02
14	20891.36	29.87	1410.09
15	20891.36	29.87	1410.09
16	7599.11	75.92	2213.36
17	9387.14	35.18	1896.06
18	9610.64	33.97	1846.38
19	12341.10	67.20	1898.19
20	13617.77	43.56	1733.84
21	14043.32	37.34	1680.63
22	19625.21	36.09	1511.02
23	20891.36	29.87	1410.09
24	20891.36	29.87	1410.09
25	7599.11	75.92	2213.36
26	8940.13	43.67	1999.07
27	9610.64	33.97	1846.41
28	12766.66	58.49	1842.19
29	13617.77	43.56	1733.84
30	14894.43	31.11	1578.30
31	19625.21	36.09	1511.02
32	20891.36	29.87	1410.09
33	20891.36	29.87	1410.09
34	7599.11	75.92	2213.36
35	9387.14	35.18	1896.06
36	9387.14	35.18	1896.06

Table E-25. Section Seven site retrieved data sensitivity all cases (Configuration)

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine Hub Height (m)	Turbine	Battery	Converter (kW)
1	10	10	100	18	26	3.50
2	10	15	100	20	20	3.26

3	10	25	100	20	20	3.26
4	10	10	150	15	23	3.57
5	10	15	150	15	23	3.57
6	10	25	150	15	23	3.57
7	10	10	40	24	29	3.32
8	10	15	40	24	29	3.32
9	10	25	40	24	29	3.32
10	12	10	100	18	26	3.50
11	12	15	100	20	20	3.26
12	12	25	100	20	20	3.26
13	12	10	150	15	23	3.57
14	12	15	150	15	23	3.57
15	12	25	150	15	23	3.57
16	12	10	40	24	29	3.32
17	12	15	40	24	29	3.32
18	12	25	40	24	29	3.32
19	14	10	100	18	26	3.50
20	14	15	100	20	20	3.26
21	14	25	100	20	20	3.26
22	14	10	150	15	23	3.57
23	14	15	150	15	23	3.57
24	14	25	150	15	23	3.57
25	14	10	40	24	29	3.32
26	14	15	40	24	29	3.32
27	14	25	40	24	29	3.32
28	8	10	100	18	26	3.50
29	8	15	100	20	20	3.26
30	8	25	100	20	20	3.26
31	8	10	150	15	23	3.57
32	8	15	150	15	23	3.57
33	8	25	150	15	23	3.57
34	8	10	40	24	29	3.32
35	8	15	40	24	29	3.32
36	8	25	40	24	29	3.32

Table E-26. Section Seven site retrieved data sensitivity all cases (Cost)

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	5066674	77.10	230333.5	1574435	900000	90000
2	4652473	72.62	200307.8	1615473	1000000	100000
3	4236319	66.13	172860.0	1615473	1000000	100000
4	4451964	69.51	200756.0	1408170	750000	75000
5	4078717	63.68	176131.7	1408267	750000	75000
6	3766601	58.81	155545.9	1408267	750000	75000
7	6266908	97.83	286113.7	1928949	1200000	120000
8	5669214	88.50	246692.3	1928949	1200000	120000
9	5169829	80.71	213754.9	1928949	1200000	120000
10	4439303	81.51	227983.8	1574435	900000	90000
11	4108657	77.38	198405.5	1615473	1000000	100000
12	3776369	71.12	171962.3	1615473	1000000	100000
13	3904529	73.55	198658.2	1408170	750000	75000
14	3600041	67.81	174419.5	1408267	750000	75000
15	3350825	63.12	154587.1	1408267	750000	75000
16	5487987	103.37	283225.3	1928949	1200000	120000
17	5000369	94.19	244421.0	1928949	1200000	120000
18	4601623	86.68	212689.1	1928949	1200000	120000
19	3954981	86.04	224482.1	1574435	900000	90000
20	3688735	82.32	195505.7	1615473	1000000	100000
21	3424671	76.43	170604.8	1615473	1000000	100000
22	3481708	77.72	195531.8	1408170	750000	75000
23	3230247	72.10	171810.1	1408267	750000	75000
24	3032198	67.68	153134.4	1408267	750000	75000
25	4886862	109.07	278927.0	1928949	1200000	120000
26	4483931	100.08	240938.8	1928869	1200000	120000
27	4167054	93.01	211057.7	1928869	1200000	120000
28	5888967	72.81	231214.4	1574435	900000	90000
29	5364144	68.03	200890.1	1615473	1000000	100000
30	4847103	61.47	173182.0	1615473	1000000	100000
31	5169000	65.57	201541.7	1408170	750000	75000
32	4704963	59.68	176668.9	1408267	750000	75000
33	4317183	54.76	155887.9	1408267	750000	75000
34	7288223	92.45	287201.8	1928949	1200000	120000
35	6545186	83.02	247382.7	1928949	1200000	120000
36	5924464	75.15	214122.3	1928876	1200000	120000

Table E-27. Section Seven site retrieved data sensitivity all cases (Performance)

Case No.	Turbine Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	37871.09	31.54	681.66
2	42078.99	24.89	552.32
3	42078.99	24.89	552.32
4	43516.15	28.62	537.13
5	43516.15	28.62	537.13
6	43516.15	28.62	537.13
7	19681.86	36.09	1158.42
8	19681.86	36.09	1158.42
9	19681.86	36.09	1158.42
10	37871.09	31.54	681.66
11	42078.99	24.89	552.32
12	42078.99	24.89	552.32
13	43516.15	28.62	537.13
14	43516.15	28.62	537.13
15	43516.15	28.62	537.13
16	19681.86	36.09	1158.42
17	19681.86	36.09	1158.42
18	19681.86	36.09	1158.42
19	37871.09	31.54	681.66
20	42078.99	24.89	552.32
21	42078.99	24.89	552.32
22	43516.15	28.62	537.13
23	43516.15	28.62	537.13
24	43516.15	28.62	537.13
25	19681.86	36.09	1158.42
26	19681.86	36.09	1158.42
27	19681.86	36.09	1158.42
28	37871.09	31.54	681.66
29	42078.99	24.89	552.32
30	42078.99	24.89	552.32
31	43516.15	28.62	537.13
32	43516.15	28.62	537.13
33	43516.15	28.62	537.13
34	19681.86	36.09	1158.42
35	19681.86	36.09	1158.42
36	19681.86	36.09	1158.42

Table E-28. Aziz Court Imperial sensitivity all cases (Configuration)

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine	Battery	Converter (kW)
1	10	10	19	26	3.3
2	10	15	20	23	3.22
3	10	25	20	23	3.22
4	12	10	19	26	3.3
5	12	15	20	23	3.22
6	12	25	20	23	3.22
7	14	10	19	26	3.3
8	14	15	20	23	3.22
9	14	25	20	23	3.22
10	8	10	19	26	3.3
11	8	15	20	23	3.22
12	8	25	20	23	3.22

Table E-29. Aziz Court Imperial sensitivity all cases (Cost)

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	5265941	82.2	239076.60	1641142	950000	95000
2	4792757	74.81	207130.30	1652317	1000000	100000
3	4376603	68.32	179682.60	1652317	1000000	100000
4	4614661	86.91	236627.90	1641170	950000	95000
5	4230542	79.68	205173.00	1652317	1000000	100000
6	3898254	73.42	178729.80	1652317	1000000	100000
7	4111780	91.77	232975.10	1641170	950000	95000
8	3796434	84.73	202187.20	1652317	1000000	100000
9	3532369	78.83	177286.30	1652317	1000000	100000
10	6119727	77.62	240003.80	1641182	950000	95000
11	5528642	70.12	207731.00	1652317	1000000	100000
12	5011601	63.56	180023.00	1652317	1000000	100000

Table E-30. Aziz Court Imperial sensitivity all cases (Performance)

Case No.	Turbine Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	33304.03	32.36	747.99
2	35056.88	28.62	702.46
3	35056.88	28.62	702.46
4	33304.03	32.36	747.99
5	35056.88	28.62	702.46
6	35056.88	28.62	702.46
7	33304.03	32.36	747.99
8	35056.88	28.62	702.46
9	35056.88	28.62	702.46
10	33304.03	32.36	747.99
11	35056.88	28.62	702.46
12	35056.88	28.62	702.46

Table E-31. Courtyard Marriot sensitivity all cases (Configuration)

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine	Battery	Converter (kW)
1	10	10	20	26	3.76
2	10	15	19	29	3.59
3	10	25	22	20	3.30
4	12	10	20	26	3.76
5	12	15	19	29	3.59
6	12	25	22	20	3.31
7	14	10	20	26	3.76
8	14	15	19	29	3.59
9	14	25	20	24	3.22
10	8	10	19	29	3.59
11	8	15	20	24	3.22
12	8	25	22	20	3.30

Table E-32. Courtyard Marriot sensitivity all cases (Cost)

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Initial capital (BDT)	Turbine Capital Cost (BDT)	Turbine O&M Cost (BDT)
1	5423804	82.54	247002.30	1678838	1000000	100000
2	4950969	77.30	215503.00	1683585	950000	95000
3	4490170	70.08	182961.30	1716172	1100000	110000
4	4751204	87.24	244496.30	1678838	1000000	100000
5	4366174	82.25	213478.20	1683585	950000	95000
6	4004450	75.41	182086.30	1716334	1100000	110000
7	4232054	92.08	240764.60	1678838	1000000	100000
8	3914645	87.39	210385.80	1683585	950000	95000
9	3568532	79.64	179528.40	1664703	1000000	100000
10	6304866	79.98	247653.00	1683585	950000	95000
11	5583703	70.82	210020.30	1664660	1000000	100000
12	5136298	65.14	183283.50	1716172	1100000	110000

Table E-33. Courtyard Marriot sensitivity all cases (Performance)

Case No.	Turbine Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	33067.16	31.54	801.85
2	31413.80	36.09	794.91
3	36373.88	24.89	660.35
4	33067.16	31.54	801.85
5	31413.80	36.09	794.91
6	36373.88	24.89	660.35
7	33067.16	31.54	801.85
8	31413.80	36.09	794.91
9	33067.16	29.87	748.05
10	31413.80	36.09	794.91
11	33067.16	29.87	748.05
12	36373.88	24.89	660.35

Table E-34. Tower-71 sensitivity all cases (Configuration)

Case No.	Discount Rate (%)	Turbine Lifetime (years)	Turbine	Battery	Converter (kW)
1	10	10	21	24	3.30
2	10	15	21	24	3.28
3	10	25	21	24	3.29
4	12	10	21	24	3.30
5	12	15	21	24	3.28
6	12	25	21	24	3.29
7	14	10	21	24	3.30
8	14	15	21	24	3.29
9	14	25	21	24	3.29
10	8	10	21	24	3.30
11	8	15	21	24	3.29
12	8	25	21	24	3.29

Table E-35. Tower-71 sensitivity all cases (Cost)

Case No.	NPC (BDT)	COE (BDT)	Operating cost (BDT/yr)	Turbine O&M Cost (BDT)	Initial capital (BDT)	Turbine Capital Cost (BDT)
1	5513944	86.06	250489.50	105000	1716106	1050000
2	4989981	77.89	215951.30	105000	1715800	1050000
3	4553469	71.07	187151.50	105000	1715941	1050000
4	4831521	90.99	247922.00	105000	1716106	1050000
5	4403971	82.94	213923.00	105000	1715792	1050000
6	4055486	76.37	186179.00	105000	1715941	1050000
7	4304736	96.06	244104.10	105000	1716106	1050000
8	3951829	88.19	210845.00	105000	1715900	1050000
9	3674695	82.00	184706.60	105000	1715953	1050000
10	6408385	81.27	251457.70	105000	1716106	1050000
11	5757288	73.01	216579.20	105000	1715853	1050000
12	5214719	66.13	187498.40	105000	1715941	1050000

Table E-36. Tower-71 sensitivity all cases (Performance)

Case No.	Turbine Production (kWh/yr)	Battery Autonomy (hr)	Battery Annual Throughput (kWh/yr)
1	30354.42	29.87	811.63
2	30354.42	29.87	811.61
3	30354.42	29.87	811.62
4	30354.42	29.87	811.63
5	30354.42	29.87	811.61
6	30354.42	29.87	811.62
7	30354.42	29.87	811.63
8	30354.42	29.87	811.62
9	30354.42	29.87	811.62
10	30354.42	29.87	811.63
11	30354.42	29.87	811.61
12	30354.42	29.87	811.62

Appendix F

Table F-1. Gas volume conversion (Ambient to STP)

Ambient to STP Conversion
PV = nRT
P is the pressure (atm)
V is the volume (liter)
n is the amount of gas (in moles)
R is the gas constant
T is the temperature (in Kelvin)
At STP (standard temperature and pressure), the pressure is 1 atm and the temperature is 273 K.
At STP 1 mole gas volume 22.4 L

Table F-2. Gas volume conversion calculation (Ambient to STP)

P1=1 atm	P1	1
T1 = 28 + 273.15 = 301.15 K	T1	301.15
V1 = 227 mL = 0.227 L	V1	0.227
Calculating the number of moles of hydrogen using the ideal gas law:	n = PV/RT	
R is the gas constant (0.0821 L·atm/mol·K) as we are uing pressure in atm and volume in liter	R	0.0821
n = (1 atm)(0.227 L)/(0.0821 L·atm/mol·K)(301 K) = 0.00908 mol	n	0.00918
Using the molar volume of a gas at STP (22.4 L/mol) to calculate the volume of hydrogen at STP:V2 = n × 22.4 L/mol = 0.00908 mol × 22.4 L/mol = 0.203 L	V2	0.206
V2: 206mL	V2	206

Table F-3. kg to Nm^3 conversion

PV = nRT
P is the pressure (in Pascal)
V is the volume (m3)
n is the amount of gas (in moles)
R is the gas constant
T is the temperature (in Kelvin)
M is the Hydrogen molecular weight
m is the produced weight of Hydrogen
At STP (standard temperature and pressure), the pressure is 1 atm and the temperature is 273 K.

Table F-4. kg to Nm^3 conversion calculation

P=101325 pa	P	101325
R=8.314 J/(mol K)	R	8.315
T=273.15 K	T	273.15
M=2.016X10-3 kg/mol	M	0.002016
m=0.001104 kg/hour	m	0.001104
n=(m/M)	n	0.547619048
PV=nRT		
or, PV=(m/M)RT		1243.775518
or, V=((m/M)RT)/P		0.0123