Operation Cost Minimization Planning in South Eastern PGCB Grid with Solar PV Energy.

By

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Candidate's Declaration

It is therefore stated that the work included in this thesis has never before been submitted to fulfill the requirements for an award at this or any other university. To the best of my knowledge and belief, the thesis does not contain any previously published or written content by anybody else, with the exception of the places where appropriate citations are included.

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Dedication

To my beloved Parents

List of Publications

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Approval by the Supervisor

This is to certify that **Farhana Hossain** completed this work under my supervision and that she complied with the relevant Academic Ordinance of the Chittagong University of Engineering and Technology, thereby qualifying her to submit the following thesis in application for the MASTER of SCIENCE in Energy Technology.

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Abstract

Although the demand for power is growing rapidly, it is not being met at the same rate. Even though the generation capacity has reached 20 GW still, significant power crisis is being observed due to unreliable power system operation. Delivering power and energy at a lower cost is inevitable for efficient operation of the electric power system. Increased energy consumption has aggravated the issue of energy security, necessitating the usage of renewable resources. Solar photovoltaic technology is one of the best strategies for encouraging electricity generation from sources of renewable power in Bangladesh. Grid-connected solar photovoltaic systems are becoming more and more popular every day because of the growing amount of solar energy and the declining ancillary prices of solar PV modules. Due to industrialization and fourth industrial revolution electric demand is soaring high. As a result, thereby a gap between demand and supply exist to solve this problem. This research proposes technoeconomic operation of solar PV power integrated power system optimization to optimise operation cost and selling price. A model for solar PV integration has considered with south eastern PGCB grid. We have analysed the techno economic benefit comprises of operational cost and selling price. A grid power system with seven buses is tested using an ideal power flow method. The prospect of injecting renewable power into one of the test bus systems is being investigated. Conventional power plants use seven different kinds of fuel to provide the load. Nine transmission lines connected each of these facilities. To determine the system's optimality conditions, the Lagrangian technique and Karush Kuhn Tucker (KKT) criteria are applied. To evaluate upcoming operational costs and selling prices, a number of prospective case studies have been simulated. Both with and without solar energy, the optimal power source,

operational costs, and selling price were evaluated. Despite a 60% increase in load, a considerable amount of operating cost was decreased in 2041, accounting for 72.22%.

বিমূর্ত

বিদ্যুতের চাহিদা দ্রুত বাড়লেও একই হারে পূরণ হচ্ছে না। যদিও উৎপাদন ক্ষমতা এখনও 20 গিগাওয়াটে পৌঁছেছে, তবুও অবিশ্বাস্য বিদ্যুৎ ব্যবস্থা পরিচালনার কারণে উল্লেখযোগ্য বিদ্যুৎ সংকট পরিলক্ষিত হচ্ছে। বৈদ্যুতিক পাওয়ার সিস্টেমের দক্ষ পরিচালনার জন্য কম খরচে শক্তি এবং শক্তি সরবরাহ করা অনিবার্য। বর্ধিত শক্তি খরচ জ্বালানি নিরাপত্তার সমস্যাকে আরও বাড়িয়ে তুলেছে, নবায়নযোগ্য সম্পদের ব্যবহার প্রয়োজন। সৌর ফোটোভোলটাইক প্রযুক্তি বাংলাদেশে নবায়নযোগ্য বিদ্যুতের উৎস থেকে বিদ্যুৎ উৎপাদনকে উৎসাহিত করার জন্য একটি সেরা কৌশল। সৌর শক্তির ক্রমবর্ধমান পরিমাণ এবং সৌর PV মডিউলগুলির ক্রমহ্রাসমান আনুষঙ্গিক দামের কারণে গ্রিড-সংযুক্ত সৌর ফটোভোলটাইক সিস্টেমগুলি প্রতিদিন আরও বেশি জনপ্রিয় হয়ে উঠছে। শিল্পায়ন এবং চতুর্থ শিল্প বিপ্লবের কারণে বৈদ্যুতিক চাহিদা বাড়ছে। ফলস্বরূপ, এই সমস্যা সমাধানের জন্য চাহিদা এবং সরবরাহের মধ্যে একটি ব্যবধান বিদ্যমান। এই গবেষণাটি সৌর পিভি পাওয়ার ইন্টিগ্রেটেড পাওয়ার সিস্টেম অপ্টিমাইজেশানের প্রযুক্তিগত অপারেশনের প্রস্তাব করে যাতে অপারেশন খরচ এবং বিক্রয় মূল্য অপ্টিমাইজ করা যায়। সৌর PV একীকরণের জন্য একটি মডেল দক্ষিণ পূর্ব PGCB গ্রিডের সাথে বিবেচনা করা হয়েছে। আমরা পরিচালন ব্যয় এবং বিক্রয় মূল্যের সমন্বয়ে প্রযুক্তিগত অর্থনৈতিক সুবিধা বিশ্লেষণ করেছি। সাতটি বাস সহ একটি গ্রিড পাওয়ার সিস্টেম একটি আদর্শ পাওয়ার প্রবাহ পদ্ধতি ব্যবহার করে পরীক্ষা করা হয়। পরীক্ষামূলক বাস সিস্টেমগুলির মধ্যে একটিতে পুনর্নবীকরণযোগ্য শক্তি ইনজেকশনের সম্ভাবনা তদন্ত করা হচ্ছে। প্রচলিত বিদ্যুৎ কেন্দ্রগুলি লোড সরবরাহ করতে সাতটি বিভিন্ন ধরণের জ্বালানী ব্যবহার করে। নয়টি ট্রান্সমিশন লাইন এই প্রতিটি সুবিধাকে সংযুক্ত করেছে। সিস্টেমের সর্বোত্তম অবস্থা নির্ধারণ করতে, ল্যাগ্রাঞ্জিয়ান কৌশল এবং কারুশ কুহন টাকার (কেকেটি) মানদণ্ড প্রয়োগ করা হয়। আসন্ন কর্মক্ষম খরচ এবং বিক্রয় মূল্য মূল্যায়ন করতে, সম্ভাব্য কেস স্টাডির একটি সংখ্যা সিমুলেট করা হয়েছে। সৌর শক্তির সাথে এবং ছাড়া উভয়ই, সর্বোত্তম বিদ্যুতের উত্স, কার্যক্ষম খরচ এবং বিক্রয় মূল্য মূল্যায়ন করা হয়েছিল। লোডের 60% বৃদ্ধি সত্ত্বেও, 2041 সালে উল্লেখযোগ্য পরিমাণে পরিচালন ব্যয় হ্রাস পেয়েছে, যা 72.22% ছিল।

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Nomenclature

List of Abbreviations and Acronyms

AC	Alternating Current
ACSR	Aluminium Conductor Steel Reinforced
ASEAN	Association of Southeast Asian Nations
BCM	Billion cubic meters
BPDB	Bangladesh Power Development Board
BREB	Bangladesh Rural Electrification Board
BTS	Base Transceiver Station
BOO	Build Own Operate
COD	Commercial Operation Date
CPGCBL	Coal Power Generation Company Bangladesh Limited
DR	Demand Response
EGCB	Electricity Generation Company of Bangladesh Ltd.
ELD	Economic Load Dispatch
GDP	Gross domestic product
GW	Gigawatt
HFO	Heavy Fuel Oil
IDCOL	Infrastructure Development Company Limited
IPP	Independent Power Producer
JICA	Japan International Cooperation Agency
JPL	Joules Power Limited
KKT	Karush Kuhn Tucker
KWH	Kilowatt Hour
LCOE	Levelised Cost of Electricity
LMP	Locational Marginal Price
LNG	Liquified Natural Gas
LP	Linear Programming

LOI	Letter of Internet
MCM	Million cubic meters
MODMR	Ministry of Disaster Management and Relief
MPEMR	Ministry of Power, Energy and Mineral Resources
MW	Megawatt
MVA	Mega Volt Ampere
NENP	No Electricity No Payment
NEM	National Electricity Market
OPF	Optimal Power Flow
PPA	Power Purchase Agreement
PDPP	Project Development Proposal
PGCB	Power Grid Company Bangladesh
PPP	Public Power Plant
PSMP	Power System Master Plan
PV	Photovoltaic
RDCD	Rural Development and Cooperative Division
REN21	Renewable Energy Policy Network for the 21^{st} Century
SDG	Sustainable Development Goals
SOE	State-owned Enterprise
SREDA	Sustainable and Renewable Energy Development Authority
TSEL	Technaf SolarTech Energy Limited
VPP	Virtual Power Plant

Chapter 1

1 Introduction

In the preceding section, I discussed the background information (section1.1) and importance of the study (section 1.2) of my research. I stated the main objectives (section1.3) of my work. Along with that, the significance and scope (section1.4) of my research in the practical field are discussed. Additional definitions of the key concepts are also provided in that section. This chapter also includes generation planning and study sites for solar PV. Finally, I gave a summary (section 1.7) of the remaining chapters.

1.1 BACKGROUND

In our everyday life, electricity is essential for many things, including transportation, manufacturing, agriculture, and homework. The GDP's annual growth rate serves as a gauge of the socioeconomic progress of any given nation. A nation's long-term energy supply security, especially its close ties to its energy market, has a significant impact on its GDP [1]. Despite having a high population density of 1118 persons per square kilometer, Bangladesh was categorized by the World Bank in 2018 as a nation with lower middle incomes [2] . With 162 million inhabitants, the nation is seventh in the globe among those with the densest populations [3]. With the aim of reaching high income status by 2041, it has sustained an overall economic expansion rate of over 6% since 1998 [1]. With an installed capacity of 24,911MW, Bangladesh's overall power consumption during peak hours is around 15,500MW. At a growth rate of only 1.26 percent, it is anticipated that the amount of electricity produced per person would reach 570 kilowatt hours, with a potential peak generation of 15,648 MW [4] . By 2041, demand for net power is anticipated to climb 61 GW in order to achieve this development target. Bangladesh must import energy supplies, including gas, oil, and occasionally direct power, to meet its electrical requirements. In Bangladesh, coal is a significant source of power generation when compared to other energy sources. Figure 1.1 illustrates that natural gas accounts for approximately 44.97% of the world's electrical production, with the other sources being coal, solar photovoltaics, hydropower, imported energy, and imported liquid fuel[4]. The country's primary source of power, fossil fuel reserves are expected to be exhausted within the next decade [5]. Bangladesh needs implement alternative energy technologies such as solar PV to fulfill rising demand. Even so, there are possible drawbacks because the production of RE is inconsistent and weather-dependent. From a technological, economical, and environmental standpoint, it has recently been proved that the most desirable and viable approach is to combine energy from renewable sources into both interconnected with the grid and off-grid power sources [6]. By using this green power approach, current demand on non-renewable resources and various imported fossil fuels may be reduced [1].

In order to alleviate this energy dilemma, grid integration of solar power is suggested as a prevailing power source in this research. The target of this work is to develop a data-driven analysis of the PGCB grid in the South East, which includes a seven-bus system, nine transmission lines, and seven busbars with various levels of solar photovoltaic (PV) power supply.

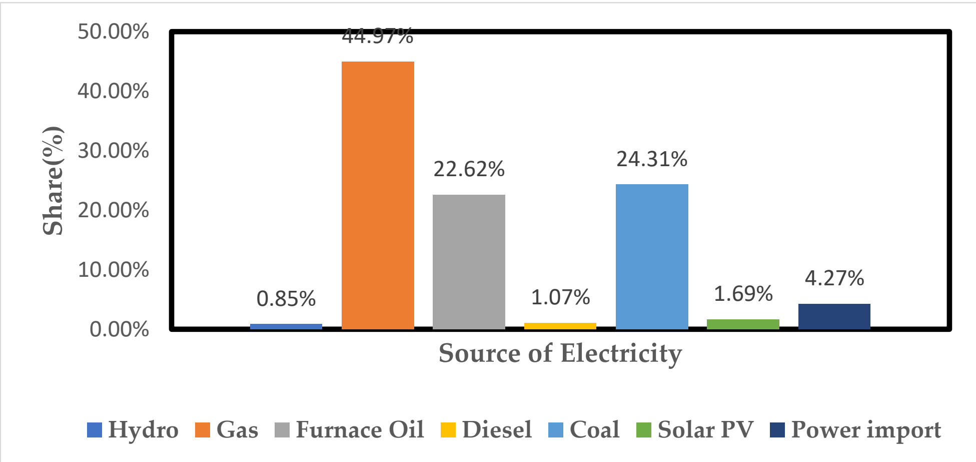

Figure 1.1: Bangladesh's electricity production by fuel type (June,2024)

Between 2010 and 2023, utility-scale photovoltaic facilities' the average weighted levelized cost of electricity around the world (LCOE) fallen by 90%, from USD 0.460/kWh to USD 0.044/kWh. In 2023, there was a 12% decrease over the previous year. More than 1411 GW of solar PV systems have been built worldwide by the end of 2023. When compared to 2010, this indicated a 35-fold increase in the technology's deployment. About 346 GW of newly installed systems were put into service in 2023. This was the largest annual gain in yearly-commissioned capacity since 2011 and was 73% higher than in 2022. Since 2016, solar PV has been the technology with the highest annual new capacity additions among all renewable technologies [7].When accounting for health risks, environmental issues, and cheaper operational costs, solar energy may be made economically feasible even if the initial investment expenses are frequently greater compared to energy sources like coal. Figure 1.2 displays the worldwide weighted average LCOEs for utility-scale photovoltaic from 2010 to 2023.

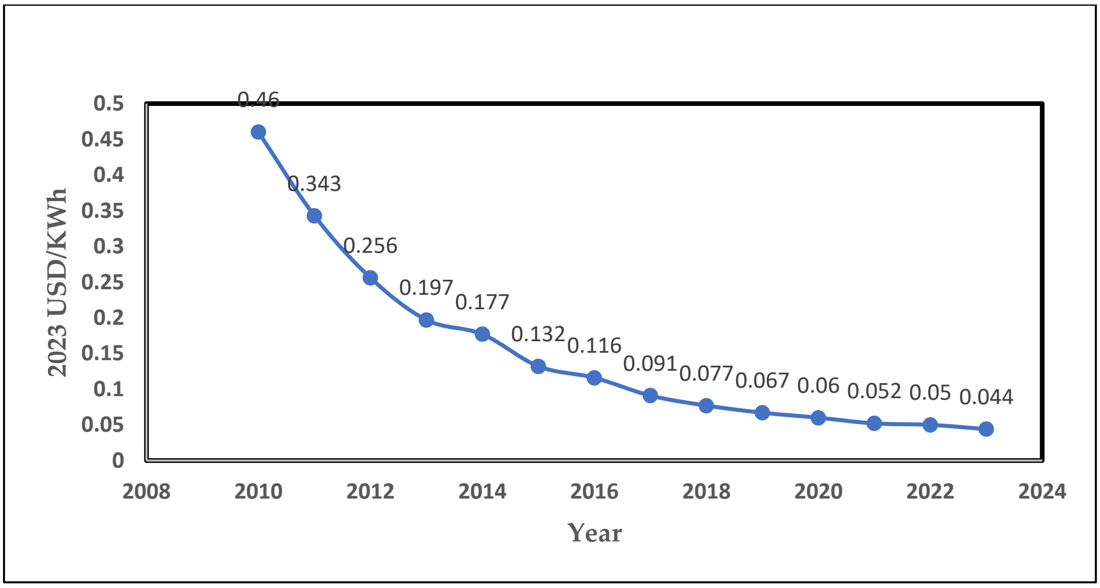

Figure 1.2: Utility-scale solar PV weighted average LCOEs worldwide, 2010–2023

With the aim of accomplishing missions of the Sustainable Development Goals' (SDGs) plans, contemporary, reasonably priced, and trustworthy, sustainable, and easily used energy is needed[8]. In addition to ecologically sustainable power sources such as, hydro, solar, tidal, nuclear and wind power, it may be generated by burning coal, gas, or oil [9]. Non-renewable energy generation emits greenhouse gasses, negatively impacting the environment. Because of their little environmental effect, sources of environmentally friendly power are considered a clean substitute for natural gas. It is estimated that almost eighty percent of the main energy produced worldwide originates from natural gas [10]. In the mid-1980s of the previous century, 10 billion metric tons of coal were burned annually. By 2025, the world's coal usage is predicted to exceed 55 billion metric tons. Because of the massive use of fossil fuels, fossil fuel-based resources would be depleted, putting the planet at greater risk of catastrophic climate change and global warming as well as resource scarcity. To accomplish economic development without negatively impacting the environment, it's important to use fossil fuels effectively and create alternative clean energy sources simultaneously [11]. In recent years, energy consumption has increased across all aspects of life worldwide. From 2010 to 2030, it is expected to rise by 33%, with an average growth rate of 2.3% through 2015 and 2040 [12, 8].

1.2 IMPORTANCE OF THE STUDY

By taking into consideration changes in generation, load, and the physical boundaries of the system of transmission, locational marginal pricing (LMP) allows costs for large-scale electric energy to represent how much electric energy is worth at various places. So, it is crucial to calculate marginal electricity price in case of renewable energy penetrated grid, Transmission line capacity limit and congestion management.

In order to maximize the utilization of transmission capacity, a limited resource, the energy market uses the LMP mechanism to reflect grid limits at different locations on the electrical network. If there is adequate transmission capacity, electricity costs in two distinct places will be the same. However, if a disruption to the grid occurs among the two places, locational power prices change, causing the market to divide. The LMP system can be predicated on a zonal or node analysis pricing scheme, depending on how precisely grid restrictions are described [13]. In the electrical system, nodal pricing takes into account the distribution system's capacity for transmission at each node. On the other hand, zonal pricing ignores the boundaries within each price zone and only considers the capacity of the interconnector within two distinct offering zones.

1.3 OBJECTIVES

The major purpose of the research is to reduce operation costs at the planning level for the South Eastern PGCB Grid by boosting solar PV penetration. The specific objectives are:

a) To develop a data-driven execution system of the South Eastern (PGCB) network having different level of PV solar penetration.
b) To determine optimal power delivery from different generation plants to minimize selling price and operating expenses.
c) To analyze its techno-economic performance on the extended South Eastern (PGCB) grid and compare with it existing market, price and practice.

1.4 LIMITATIONS AND SCOPE OF THE STUDY

Bangladesh has been graced with a variety of fossil fuel sources. The primary fuel applied to deliver power is natural gas. Generation of power is additionally aided by furnace oil, diesel, gas, nuclear, hydro and coal. Solar, wind, and biomass are examples of small-scale sources of green energy that are being employed, especially for an off-grid energy source. Given the growing need for energy and the depletion of fossil resources, the impending energy crisis is a troubling issue. The strain is increasing due to environmental degradation. Bangladesh's location near the Bay of Bengal means that if sea levels rise significantly as a result of global warming, there is still a significant chance that the southern parts will be submerged under water. Rising sea levels threaten homes, livelihoods, and eventually life. As sea levels continue to rise due to the climate catastrophe, up to 410 million people may be at risk of coastal flooding by the year 2100. Over nine lakh people from southern Bangladesh might be displaced by sea level rise by 2050, endangering their homes and means of subsistence. This will have catastrophic effects for important food crops, forcing more people to flee their homes.

Leaning toward renewable energy sources can be a suitable choice because they are endless and rarely harm the environment. The country's geographical position and geological structure provide enormous potential for a variety of RE resources. These include, micro-hydro, wind, solar, biogas, biomass, and geothermal. The estimated expense of establishing the use of RE plants is high right now, hence these sources of information aren't given much consideration. To properly establish the pattern, operational costs must be reduced, which will be less expensive than conventional electricity costs in the long term. Thereby this study focuses on investigating operation cost and price for future demand. The following are some definitions associated with this research:

1.4.1 Optimal power flow (OPF): OPF [14] model reflects the challenge of establishing the appropriate electric power plant operating levels in order to fulfill request supplied throughout a network of transmission, often in an effort to reduce cost of operation [15].

1.4.2 Operation Cost in power system planning: The running cost notion is rather straightforward. It is entirely dependent on how many units are generated across the electrical grid. The cost of fuel used per unit of electrical energy generated is the primary operating expense of power-producing plants. Primary energy sources include conventional energy, fossil fuels (like natural gas, coal, and oil), and alternative forms of energies like hydroelectric, geothermal, wind, and sun. The price of fuel is nil for many renewable energy sources, modest for nuclear, and costly for fossil fuels and biomass. Throughout the life of the generating machinery, fuel prices may fluctuate somewhat owing to political and other variables.

1.4.3 Objective function in power system: The purpose of the function is commonly used to address optimization issues in linear programming. The primary goals of optimum power flow are to reduce fuel costs, pollution, actual power losses, and voltage variation while meeting operational restrictions in power systems. An objective function is a number that should be optimized. Businesses, for example, attempt to maximize profit while minimizing costs, both of which are determined by the company's level of output or sales.

1.4.4 Equality and Inequality Constraints in power system: There are two broad categories of constraints: inequality and equality are used to solve constrained optimization problems like the OPF. Conditions that must always be adhered to are equality constraints. In other words, they are "binding" at all times. For instance, the area MW exchange limits and reactive and actual power balancing system bus equations in the OPF always have to be fulfilled, at least to the extent that the user specifies a tolerance. On the other hand, limitations on inequality could or might not be legally obligatory. For instance, the actual power output of a generator might or might not be at its maximum while a line's MW flow may or may not be at its limit.

1.4.5 Linear Programming (LP): This approach optimizes an objective function in linear form, taking linear equality and linear inequality constraints into account [16]. With many obstacles, the best possible flow of power issue is a massive and challenging quadratic optimization problem in power system reproduction, structure, consideration, and maintenance.

1.4.6 Locational Marginal Price: Locational marginal pricing is a technique used in retail electric energy pricing to account for technological constraints in the transmission, generating, and load systems while representing the value of power at different locations.

1.4.7 Lagrange Multiplier: The Lagrange multiplier method is a technique used in mathematical optimization to determine a function's local maxima and minima while adhering to equality requirements, or the need that certain equations be precisely satisfied by the variables' selected values. This method's main benefit is that it makes it possible to solve the optimization without explicitly parameterizing the restrictions. Consequently, the Lagrange multiplier approach is frequently employed to resolve difficult restricted optimization issues [17].

1.4.8 Economic dispatch: It is a method for identifying the most dependable, economical, and efficient functioning of a power system by allocating accessible electrical generating resources for serve the system's load in the absence of a network. Reducing the overall cost of generating while meeting the demands for operation of readily available generation supplies is the main goal of economic dispatch [18].

1.5 PLANNING FOR GENERATION

The planning of generation is the most essential aspect of the electrical mechanism, and the dependability of the energy-producing structure has a considerable effect on the overall availability of the electrical system. The primary fuels taken into account for generation planning include hydro resources, coal, nuclear, cross-border commerce, and indigenous natural gas. When it comes to power plants, regional balance is given the proper consideration. Additional considerations for plant seating include the accessibility of fuel, cooling water, heavy equipment transportation, proximity to the grid network and load centre, etc.

1.6 STUDY SITE ON SOLAR PV

A significant amount of research has been undertaken on the functioning of the grid-wise electrical system in order to determine the most cost-effective technique of transporting energy from diverse producing resources[19, 20, 21, 22]. The authors of [23] proposed a reduction of costs strategy for a power system that included a necessary contribution from wind power and dispersed production from solar photovoltaics [24]. In order to reduce operational expenses and preserve supply and demand balance, authors in [23] also looked at market clearing as a potential option for electricity networks that incorporate energy from plants. Furthermore, utilizing the optimal power flow technique, the authors in [25] and [26] suggested a bi-level optimization that took into account the numerous entities found in the existing market structure. In addition, the authors in [27] have increased electrical transmission proficiency by pinpointing the specific network nodes. Additionally, utilizing data from seven electricity-powered zones in Bangladesh, the study referenced in [28] developed a system for producing utilizing the cheapest likely generation expenditures. However, there hasn't been enough research done on how capacity for transmission affects a real power system network's running costs and energy selling price. From the viewpoint of power system operation, this study explores into this topic. The OPF problem is resolved, and the power system is constructed using the Lagrangian technique.

Linear optimization is a robust program is used for analysing the power system's network's optimum power flow and load flow. Recognizing the ideal conditions of the current power grid and developing the next-generation grid both of them rely upon optimal power flow. The amount of energy price and billing are calculated on actual power use. Due to AC optimum power flow reactive power flow is ignored in this research. When developing a model of electrical power that serves Bangladesh's southern area, all of these aspects were taken into account. It included nine transmission lines, seven bus-bar, and seven generating units.

1.7 THESIS OUTLINE

This research's outline is divided into five chapters. The contents of these chapters are briefly discussed as follows.

- Chapter 1, the introduction chapter, contains research motivation, objective and thesis outline. Motivation for the research, objective for the study and how this thesis paper is organized are concisely described in the chapter.
- Theoretical background in line with literature review associated with the study is organized in chapter 2. It will present a quick summary of the ideas, equations, and literature necessary for the audience to get interested in and comprehend the topic.
- Chapter 3 systematically organizes the methodological framework followed in the study. A comprehensive flowchart for the methodological framework is illustrated for providing a concise understanding on how the study is performed.
- Chapter 4 includes simulation results, performance analysis, and comparative study. Details on designing and modeling of various power plant in simulation along with design parameters and figures are included in the chapter. Data and output figures are included as seem appropriate.
- Finally, chapter 5 summarizes overall study method, results and findings. Challenges and limitations are discussed. Future recommendations and conclusion finish the thesis paper.

A number of problems facing conventional power plants in Bangladesh, including the currency crisis, rising fuel prices, and fuel shortages, were discussed in the introduction chapter. Electricity generation that uses energy sources such as coal are harmful to the environment. However, grid-connected microgrids of distributed solar in addition to extensive solar PV plants may be considered a practical and suitable approach for introducing dispersed renewable energy into the electric grid. At the moment in Bangladesh, of all the environmentally friendly energy sources, solar photovoltaics offer the most promise. One of the primary purposes of the research is to lessen operation costs at the planning level for the South Eastern PGCB Grid using Solar PV Energy in the Chittagong area.

Chapter 2

2 Literature Review

The relevance and influence of grid-connected microgrids have significantly risen due to the expanding usage of environmentally friendly energy-based generation in microgrids. Its design and operation have been thoroughly investigated in the literature. This chapter addresses the present state of energy from renewable sources integrated power plants, which includes the global status of renewable energy, namely solar energy, and how they compare. The research gap, as well as the merits and downsides of previous work, have been evaluated. These dissertations gave rise to the notion of grid-connected microgrids with renewables of low operation costs.

2.1 INTRODUCTION

Rapid economic development is increasing the demand for power worldwide. The constant demand for power is included most significant components for the growth. Future financial expansion will depend heavily on the availability of an inexpensive, dependable, and sustainable electrical source. The Bangladeshi government aims to develop a variety of master plans for power systems that focus on boosting the ability to generate electricity to meet future demands [29, 30, 31]. Because of its endless supply and lack of environmental impact, energy from renewable sources is an essential factor in the emergence of sustainable electricity [32]. Additionally, RES technologies are continuously being developed, and enhanced RES producing devices are now available for purchase on the market [33]. Among the most noteworthy resources are biomass, solar thermal systems, wind energy, and solar photovoltaics (PV). Several investigations [34, 35, 36] are being carried out to ascertain the optimal design and functionality of such facilities. According to the most recent study, load reduction has been happening often at the time, even if the real capacity currently in place exceeds current demand. Gas, coal, diesel, furnace oil, hydro, and HFO comprises the majority of the current total generation capacity of above 24,911 MW [30]. The majority of Bangladesh's current power plants are gas-powered. The system adds a substantial quantity of sustainable solar energy each year. Furthermore, energy is provided by the nation adjacent to it [37]. Specifically due to a lack of transmission line capacity, the BPDB is unable to meet marketplace demand even with this capacity.

2.2 PRESENT STATUS OF RE INTREGRATED POWER PLANT

2.3 PRESENT SITUATION OF GLOBAL RENEWABLE ENERGY SECTOR

Sources of REs are readily replenishable and really inexhaustible; thus, they never run out. These sources can be created using natural resources such as wind, sunlight, tides in the ocean, waves from the sea, flowing water, the heat within the earth, biomass, and renewable fuels such as the growth of plants. These forms of energy might be transformed into electricity, which would then be stored and sent to our homes, workplaces, or manufacturing facilities. This type of energy is known as renewable energy. The utilization of alternative energy sources has helped to mitigate the dependence on energy sources like coal and may be vital for Bangladesh's energy security in the future[38]. Sources of renewable energy can provide fuels for heating, power generation, and transportation[39].

According to Ref. [40] ,Global energy usage is growing faster than population growth. By 2030, the world community hopes to have achieved the SDG plans, which would need around 30% more energy consumption due to business advancement and population growth (Division P, 2016). In order to overcome this obstacle, renewable energy can be really helpful. In 2017, renewable energy sources produced over 25% of global electricity [41].

Global renewable power capacity reached 3,372 GW by the end of 2022. With a capacity of 1,256 GW, hydropower that is renewable was responsible for the majority of the world's total. The bulk of the remaining capacities was supplied by solar and wind energy, which had an aggregate capacity of 1053 GW and 899 GW. 15 GW of geothermal energy, 524 MW of marine energy, and 149 GW of biofuel made up the renewable capacity [42].

In 2022, solar and wind energy comprised 90% of all net renewable additions, retaining its power to increase renewable capacity. This increase in solar and wind power resulted in the largest yearly gain in alternative energy production and the following highest percentage rise on record. [42].

2.3.1 Renewable generation capacity by region

In 2022, Asia continued to account for around 60% of newly installed capacity, with its renewable energy capabilities increasing by 174.9 GW to 1.63 TW (48% of the global total). China was mostly responsible for this rise (+141 GW). North American and European capacity increased by 29.1 GW (+6.3%) and 57.3 GW (+8.8%), respectively. Africa's GDP grew by 2.7 GW (+4.8%), which was marginally higher than the year before, as the continent kept growing gradually. While South America persisted to move upward with a projected rise of 18.2 GW (+7.4%), Oceania maintained strong growth rates with an increase of 5.2 GW (+10.6%), mostly owing to development in Australia. Additionally, with 3.2 GW of new capacity coming through the web in 2022 (+12.8%), the Middle East had its largest growth ever. Following table represent the step-by-step renewable generation capacity by region.

Table 2.1: Geographical capability for renewable energy

North America Capacity 489 GW Global Share 15% Change +29.1 GW Growth + 6.3%	**Europe** Capacity 709 GW Global share 21% Change +57.3 GW Growth +8.8%	**Eurasia** Capacity 119 GW Global share 4% Change +3.4 GW Growth +3.0%
Central America and the Caribbean Capacity 18 GW Global share 1% Change +0.4 GW Growth +2.3%	**Middle East** Capacity 29 GW Global share 1% Change +3.2 GW Growth +12.8%	**Asia** Capacity 1 630 GW Global share 48% Change +174.9 GW Growth +12.0%
South America Capacity 265 GW Global share 8% Change +18.2 GW Growth +7.4%	**Africa** Capacity 59 GW Global share 2% Change +2.7 GW Growth +4.8%	**Oceania** Capacity 55 GW Global share 2% Change +5.2 GW Growth +10.6%

Source: IRENA (2023), The Specific information of Renewable Capacity 2023, available at: www.irena.org/publications.

In comparison to 2021, the growth of renewable generating capacity increased in 2022 and stayed much above the pattern over the past decade. As in past decades, China and the United States were mostly responsible for this increase. But in contrast to 2021, a large number of other nations also expanded the growth of their renewable capacity in 2022.

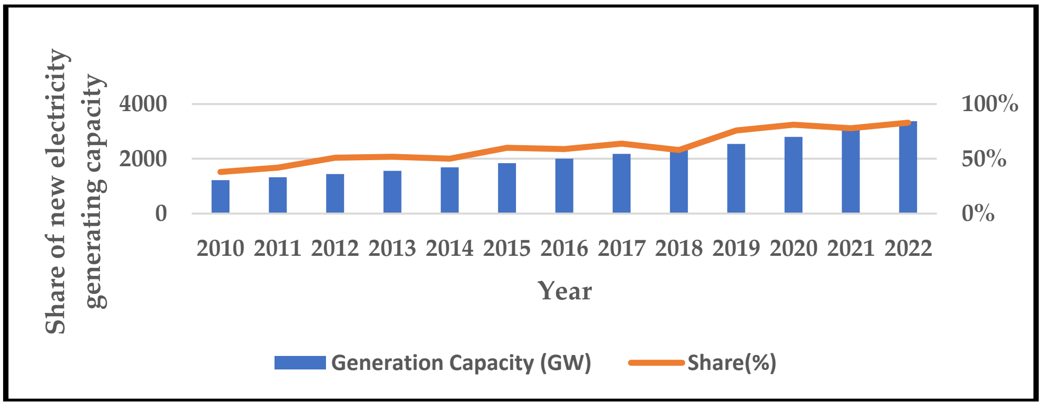

Figure 2.1: Annual increases in power capacity as a proportion of energy from nature.

Renewable energy accounted for 83% of total capacity additions in 2022, up from 78% in 2021. Additionally, from 38.3% in 2021 to 40.2% in 2022, there was a roughly two percentage point rise in the broad amount of sustainable energy generation capacity. The higher trend in these shares is indicative of the growing and fast utilization of renewable energy potential.

2.3.2 Global solar energy scenario

The demand for solar photovoltaics is always expanding since solar energy is a viable and economical alternative to numerous popular alternative energy sources for power generation. Figure 2.2 shows the historical worldwide supply with annual solar PV additions from 2010 to 2021, while Figure 2.3 shows the top ten nations for solar power expansions in 2021. Around 25% of the world's solar PV market, or 175 GW, was added in 2021; by contrast, in 2010, only 11 years earlier, only 23 GW of solar PV, including on- as well as off-grid were deployed globally.

China installed the largest amount of solar energy capacity, around 54.9 GW (31%), while the US added the second-highest amount, 26.9 GW (15%). India added over 13 GW (7%)—the third most in the world and the second highest in Asia—after Japan at 6.5 MW (4%), Brazil at 5.5 GW (3%), Germany at 5.3 GW (3%), Spain at 4.9 GW (3%), Australia at 4.6 GW (3%), Korea at 4.2 GW (2%), and France at 3.4 GW (3%). The remaining nations contributed around 45.8 GW (20%). The top 10 nations' 2021 solar PV capacity increases are displayed in Figure 2.3.

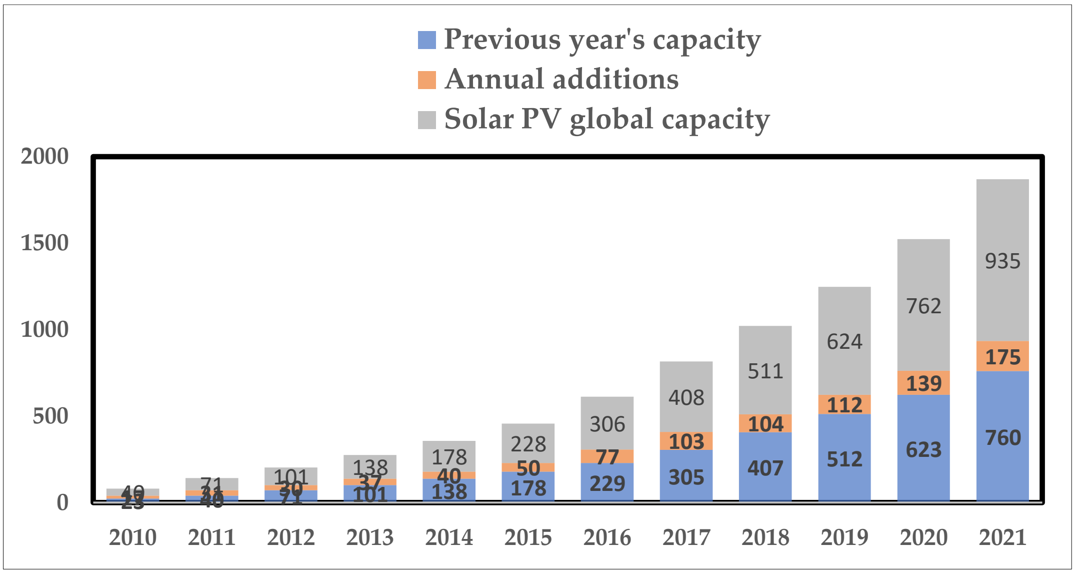

Figure 2.2: Solar PV worldwide capacity and per year additions (2010–2021)

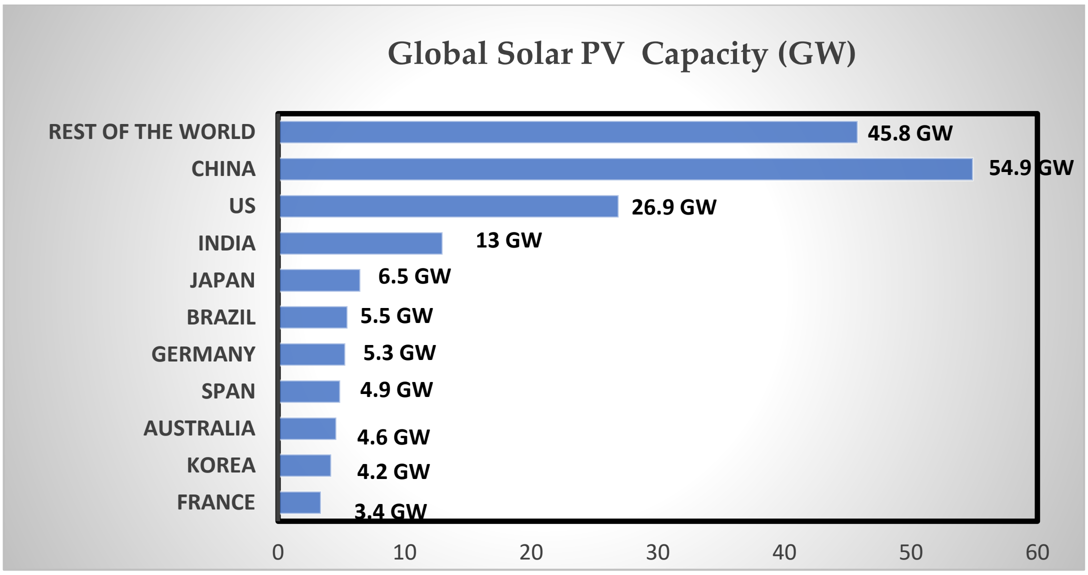

Figure 2.3: Growth in solar PV capacity worldwide in 2021: the top ten countries

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2.3.3 Power generation in Bangladesh

According to the BPDB, energy consumption is now growing at a pace of around 10% annually, but future increases in population, social, financial, technical, and GDP growth will cause it to rise [43]. During the fiscal year 2020–2021, 80,423 GWh of energy were produced, 12.61% more than the net production of 71,419 GWh the year preceding. In 2020–2021, the amount of power generated per capita was 560 KWh [44]. In fiscal year 2021–2022, 85,607 GWh of electricity were generated overall, a 6.45% increase over the overall production of 80,423 GWh in the prior year. BPDB launched on a determined effort due to improve the nation's power environment in fiscal year 2022–2023. With unwavering commitment and a plan of action, 3,149 MW of additional electricity production has been installed this fiscal year, increasing aggregate production capacity to 24,911 MW and the annual increase to 10.8%. BPDB installed 220 MW and contracted 2,033 MW from Adani Power Ltd., while B-R Powergen Ltd., BIFPCL, and APSCL erected the remaining 896 MW. With a total energy output of 88,450 GWh (including REB purchases from SIPP), the largest generation was 15,648 MW [45].

There were 24,911 megawatts of installed generating capacity as of June 30, 2023. The BPDB contributed 6,233 MW, the public sector contributed 10,479 MW, joint ventures (JVs) contributed 1,861 MW, IPP/SIPP contributed 8,494 MW, rental and NENP (No Energy No Payment) energy plants contributed 1,170 MW, REB contributed 251 MW (for PBS), and 2,656 MW of electricity was imported from India.

Compared to the requirement for 14,500 MW, 27,400 MW, and 51,000 MW for electricity generation in 2021, 2030, and 2041, respectively, the amended PSMP-2016 claims that the required capacity will be 21,000 MW, 31,000 MW, and 57,000 MW [46, 47, 48]. The nation's historical total power generation is displayed in Figure 2.4.

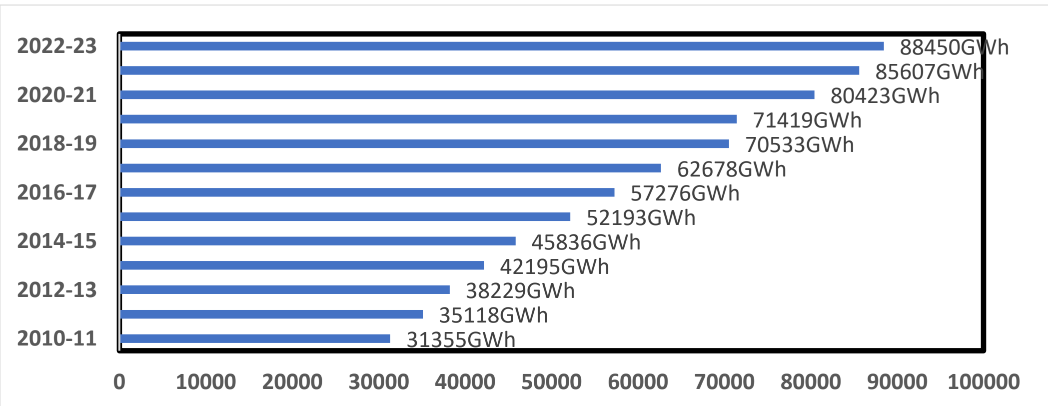

Figure 2.4: Total power output in Bangladesh for fiscal years 2010-2022.

Bangladesh is the eighth largest economy in the world, with 168.25 million inhabitants. Its population growth rate is 1265 individuals per square kilometer, or 3277 persons per square mile. [49, 50]. Bangladesh is a nation in south Asia. In the previous decade, Bangladesh has seen a stunning insufficient energy supply to satisfy the nation's boosting consumption [51, 52, 53].While 90.1% of the population used electricity to illuminate their houses in 2018, only 93.5% of users did so in 2019 [54], meaning that 60% of users face load shedding and 79% of users experience low voltage supply. Low voltage supplies, load reduction, inadequate energy and all prevent output, decrease in exports, and limit financial progress. Therefore, without RE, there is no alternative way to handle the energy situation.

The GDP growth rate for 2024 in Bangladesh's economic history was 5.7%, up 6.03% from 2023 [55]. In essence, long-term economic growth relies on whether energy or electricity is available. Consequently, meeting the Sustainable Development Goals requires enough energy production and proper energy utilization.

2.3.4 Current state of renewable energy in Bangladesh

The government has put in place a range of programs to promote and expand the field of green energy in addition to conventional non-renewable energy sources because fossil fuel reserves are quickly running out. Ref. [56], states that the use of RE resources can fulfill everyone's energy demands, with the percentage of renewable generation capacity rising to 5% by 2015, 10% by 2021, and 100% by 2050, respectively [57, 56]. The government has already put in place a number of investment programs in both sectors of society and business are working to achieve the goal [58, 59].

Currently, renewable energy accounts for just 4.5% of net national power output. The net power producing capacity from renewables was 1373.81 MW in mid-April 2024, with solar accounting for 373.82 MW, hydro for 230 MW, others for 4.23 MW, wind for 2 MW, biogas for 0.69 MW, and biomass for 0.4 MW [60]. Nowadays, biomass, sun, wind, and hydropower are Bangladesh's main sources of renewable energy.

2.3.4.1 Solar Energy

The energy from the sun is the greenest, polished and ecologically benign all-around renewable energy sources, and it serves as a significant material of alleviating Bangladesh's electricity problem. The earth's surface is constantly generating sufficient solar energy to cover the planet's energy requirements all year round [61, 62]. The sun generates around 99.99% of all energy, while the planet provides only 0.01%. An estimated 450 EJ of energy will be released by the sun, which is 7500 times higher than the world's present energy requirements [63]. PV systems are being used by an increasing number of nations to produce over 20 percent of their own electricity [64].

2.3.4.2 Current state of solar energy in Bangladesh

Solar roofs, parks, irrigation, charging stations, solar-powered BTS, mini- and nano-grids, street lighting and home systems are just a few of the ways that solar energy is utilized in Bangladesh [39]. The following table provides solar RE generation details.

Table 2.2: Technology wise RE (Solar) Generation Statistics [60].

RE Source	Technology	Quantity	Off-grid MWp	On-grid MWp	Total MWp
Solar	Solar Park	11	0	536	536
	Rooftop Solar Except NEM	238	29.879	51.301	81.18
	Net Metering Rooftop Solar	2394	0	110.128	110.128
	Solar Irrigation	3381	54.616	2.742	57.359
	Solar Home System	6037689	263.793	0	263.793

	Solar Mini-grid	28	5.805	0	5.805
	Solar Microgrid	0	0	0	0
	Solar Nano-grid	2	0.001	0	0.001
	Solar Charging Station	15	0.275	0.016	0.291
	Solar Street Light	297691	17.104	0	17.104
	Solar Powered Telecom BTS	1933	8.06	0	8.06
	Solar Drinking Water System	82	0.095	0	0.095

Source: Development Authority for Renewable and Sustainable Energy.

Figure 2.5 provides an in-depth analysis of Bangladesh's multiple solar energy programs.

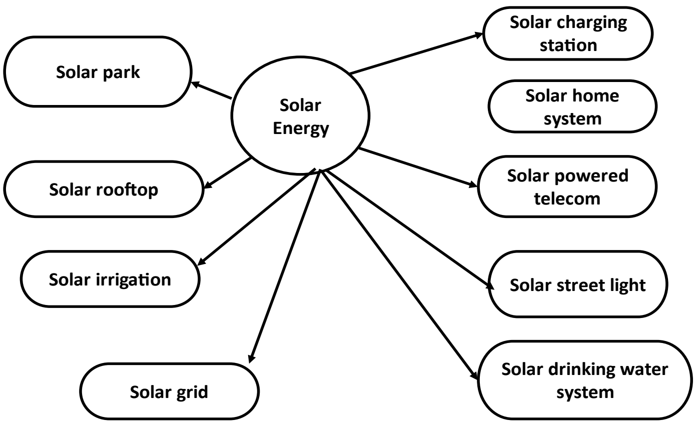

Figure 2.5: Variation of solar energy methods utilized in Bangladesh.

However, more than 42% of rural communities continue to lack access to power [50].

2.3.5 Solar power plant projects in Bangladesh

Bangladesh is currently proposing several solar projects in Chittagong region,some of which are already under construction. Solar PV Power Plant by Consortium of Kai Bangladesh Aluminium Ltd. and ALTECH Aluminium

Industries Ltd 100 MW (AC) Grid-Tied power station will have the greatest capacity of solar in our country.Another (AC) Grid-Tied high-capacity solar PV plant with a capacity of 100MWp is being built in Cox's Bazar Sadar Upazila, Cox's Bazar by Consortium of Ditrolic SA International Pte. Ltd. and Powernetic Energy Ltd. The table below lists upcoming renewable projects (solar) in Bangladesh.

Table 2.3: List of Bangladeshi Solar Power Plant Projects

Sl No.	Project Name	Capacity	Location	Agency	Present Status	Grid Status
1	Joules Power Limited's 20MW (AC) Solar Park (JPL).	20 MWp	Teknaf Upazila, Cox's Bazar	BPDB	Completed & in operation.	On Grid
2	Grid-connected 7.4 MWp (6.63 MW AC) Solar PV Power Plant Kaptai	7.4 MWp	Kaptai Upazila, Rangamati	BPDB	Completed & in operation.	On Grid
3	50 MW Grid Tied Solar Power Plant Project Matarbari	50 MWp	Maheshkhali Upazila, Cox's Bazar	CPGCBL	Under Planning	On Grid
4	Rangunia Grid-Tied 45–55 MW (AC) Solar Power Project on a BOO Basis	55 MWp	Rangunia Upazila, Chittagong	BPDB	Under Planning	On Grid
5	50 MW Grid-tied Solar Power Plant near Baroiyerhat 132,33 KV Grid Substation	50 MWp	Mirsharai Upazila, Chittagong	BPDB	Under Planning	On Grid
6	100 MW (AC) Grid-Tied Solar PV Power Plant by Consortium of Kai Bangladesh Aluminium Ltd. and ALTECH Aluminium Industries Ltd.	100 MWp	Cox's Bazar Sadar Upazila, Cox's Bazar	BPDB	Under Planning	On Grid
7	100 MW (AC) Grid-Tied Solar PV Power Plant by Consortium of Ditrolic SA International Pte. Ltd. and Powernetic Energy Ltd.	100 MWp	Cox's Bazar Sadar Upazila, Cox's Bazar	BPDB	Under Planning	On Grid

8	50 MW (AC) Grid-Tied Solar PV Power Plant by Joules Power Limited	50 MWp	Cox's Bazar Sadar Upazila, Cox's Bazar	BPDB	Under Planning	On Grid
9	30 MW (AC) Grid-Tied Solar PV Power Plant By Consortium of NewTech Solar Energy BD Limited and D.H. Euro Hitech Co. Ltd. (South Korea)	30 MWp	Chakaria Upazila, Cox's Bazar	BPDB	Under Planning	On Grid

2.3.5.1 20MW Joules Power Limited (JPL) Solar Park (AC)

Technaf Solartech Energy Limited (TSEL) operates a 20 MW countrywide grid-tied solar power plant on 116 acres of property along the Naf River in Teknaf. A majority owned subsidiary of Joules Power Limited, TSEL is a solar IPP. It is now the biggest solar power facility in Bangladesh, having begun commercial operations on September 15, 2018. It is anticipated that TSEL will save over 400,000 tons of carbon emissions throughout this time. Technaf Solartech Energy Limited (TSEL), a division of Joules Power Limited (JPL) under Expo Group, is the power plant's sponsor. TSEL functions as an Independent Power Producer (IPP) in the private sector [65].Solar panels will be used by Technaf Solartech Energy Limited to produce electricity. A backup generator that is used in case of an after-sunset power outage is supplied by a small amount of diesel [66].With 87,500 solar panels and a total capacity of 27.69 MW, it annually produces an estimated 43,794,720 KWh of electricity [65]. The plant, featuring five sub-stations, stores generated power and transmits it to the Palli Bidyut substation in the Leda area of Hinla union.

2.3.5.2 Kaptai 7.4 MW Solar Power Plant

In 2019, a 7.4 MW solar-power-plant will be built close to the Karnaphuli Hydropower Station in Kaptai. This project is an essential part of Bangladesh's ambitious aim to diversify electricity sources. Being the first solar power plant in the nation to be associated directly to the national-grid, this solar facility is rather remarkable. This effort was prompted by the government's pledge to produce 10% of the nation's electricity from renewable sources, including solar, hydropower, and wind, by 2025. The solar-power-plant's overall energy output is expected to exceed 161 gigawatt-hours (GWh) throughout the plant's lifetime. This anticipated total electrical output is expected to be generated over its functioning life [67].The project's costs were more than those of any other Bangladeshi solar power facility. Each megawatt required installation at a cost of BDT 14.08 crore (USD 1.81 million).

2.3.5.3 Matarbari 50MW (CPGCBL) Solar Power Plant

A proposed solar photovoltaic (PV) power project, the Matarbari 50 MW Solar-power-project, also called CPGCBL Matarbari Solar-Park, would be located on the island of Matarbari in the Maheshkhali Upazila in Bangladesh's Cox's Bazar district. The Coal Power Generation Company Bangladesh Limited, a State-owned Enterprise (SOE) under the Power Division, plans to build a 20-year Public Power Plant (PPP) [68]. It is still unknown how much land the facility has bought. It is a solar-powered power plant that uses solar radiation for its operation. The plant has not yet reached generation. The Matarbari Coal Plant is Bangladesh's largest planned energy development project. It is being developed with more than $2.4 billion in climate change funding from Japan. In 2014 and 2015, the government allocated Tk 360 billion (US$4.2 billion) for two 600 MW plants. The cost was updated in November 2021 to Tk 510.7 billion (US$6 billion), and in October 2021 to Tk 51,854.88 crore, which includes the cost of creating a deep-sea port.

When opposed to rooftop installations, ground-mounted solar panels have a number of advantages. These panels boost energy generation when positioned on the ground to maximize sunshine exposure. Because of their positional versatility, they may be placed in open spaces with little shade, giving you additional options for where to put them. Notwithstanding these advantages, it's important to understand that the installation of solar panels might result in habitat disturbance, disagreements over land use, and possible aesthetic effects. Ground-mounted solar projects require thorough design and ecological aspect evaluation in order to overcome these obstacles and optimize beneficial environmental effects.

2.3.5.4 Grid Tied 45-55MW(AC) Solar Power Project in Rangunia on a BOO Basis

Rangunia 55MW electric AC grid-tied solar-power-plant project has been granted by the Bangladeshi government to a consortium headed by the Metito Group, Jinko Power, and AlJomaih Group.

In keeping with the government's goal of securing a more balanced energy mix and a decrease in environmental pollution in Bangladesh, the infrastructure project will be built on a Build Own Operate (BOO) basis, with a 20-year bargain time period. Following approval by the Power Division of the Ministry of Power, Energy, and Mineral Resources (MPEMR), the BPDB awarded the project to the consortium. With a competitive pricing of $0.0748/kWh, the lowest tariff ever recorded in Bangladesh, BPDB has already declared the consortium to be the lowest bidder. The group is prepared to put the power plant into service by the second half of 2021 and will construct it on land donated by BPDB in Rangunia, Chattogram. A single circuit (ckt) 132KV line will connect the power plant to the 132/33KV Chandraghona grid substation. BPDB has set aside 149.259 acres of land for the power project.

Metito has over 60 years of expertise in three business areas: utilities, specialized chemicals, and design and construction. It is a leading global provider of comprehensive intelligent water management systems. With an emphasis on creating solar, wind, and waste-to-energy power projects, Metito has lately expanded its experience creating public-private partnership projects (PPPs) in the water sector to include the alternative energy sector.

With the goal of making solar energy a sustainable and reasonably priced energy source globally, one of the leading independent solar-power producers, Jinko Power plans, builds, finances, owns, and operates solar power facilities worldwide. The 1.77GW Sweihan solar PV facility, the biggest in the world, is also owned and operated by Jinko. The firm gives the Consortium practical technical and operational knowledge that will guarantee the facility runs smoothly and sustainably.

Water and energy division of AlJomaih Holding Company, among the most well-known companies in Saudi Arabia, is called AlJomaih Energy and Water (AEW). Its operations include everything from the sale of automobiles to maintenance, repairs, and lubricants. It is a developer of extensive water and electricity resources in the Middle East, Africa, and Asia.

2.3.5.5 Baraiyarhat 50MW(SOSPL) Solar Power

Sometimes referred to as Baraiyarhat Solar PV Park, the Baraiyarhat 50 MW (SOSPL) solar power project is a BPDB solar PV power project that would be situated in Baroyer Hat, Bangladesh's Chattogram District, within Banshkhali Upazila.

IB Vogt, a joint venture between a Bangladeshi and a German company, had won a contract to build a 50-megawatt solar power plant in Chittagong. On October 02, 2019, the Bangladeshi government's Cabinet Committee on Public Procurement authorized the accord to build this solar-project next to the 32/33 kV substation in Baraiyarhat. A 20-year contract has been signed by the government to buy the power produced by the plant for USD 0.1094 per kWh, or BDT 8.75 per kWh, with the stipulation that "no electricity, no payment." The anticipated cost of the Baraiyarhat 50 MW (SOSPL) Solar Power Plant is about 547.306 crore, or $49.8 million, in BDT.

On December 15, 2019, BPDB made a preliminary commitment to build the power plant by issuing a Letter of Intent (LOI) [69]. The project will be developed in a single construction phase and is now in the permitting process [70]. The LOI specifies that the power plant's Commercial Operation Date (COD) will be June 30, 2023, however, the corresponding Power Purchase Agreement has not yet been completed [69]. It is anticipated that the power plant's construction would begin in 2023 and that it will be ready for commercial usage in 2024 [70]. However, according to the most current BPDB progression report, the power plant is scheduled to start up in June 2025 [71]. The power plant will be powered by sunlight. An impending ground-mounted solar power project called the Baraiyarhat Solar PV Park would span 207 hectares [70]. An estimated $49.8 million, or BDT 547.306 crore, would be spent on the project. One TWh of energy is anticipated to be generated [72].

When compared to rooftop installations, ground-mounted solar panels have many benefits. In order to maximize solar exposure and boost energy generation, they are placed on the ground. Because of their location versatility, they may be positioned in open spaces with little shade, giving site selection more options. By lowering greenhouse gas emissions, creating clean, renewable energy, and slowing down climate change, ground-mounted solar panels assist the environment. By making use of unusable or non-arable land, they also preserve land. Their installation, however, may occasionally result in disagreements over land use, disturbance of the environment, and possible aesthetic effects. For ground-mounted solar projects to avoid these problems and optimize their beneficial environmental effects, careful planning and ecological consideration are crucial. The following was included in the PV installation cost comparison table for Bangladesh:

Table 2.4: Cost comparison based on PV project in Bangladesh

Sl No.	Project Name	Cost per kwh
1	Joules Power Limited's 20MW (AC) Solar Park (JPL).	$0.1069/kWh
2	Grid-connected 7.4 MWp (6.63 MW AC) Solar PV Power Plant Kaptai	$0.024/kWh
3	50 MW Grid-Tied Solar Power Plant Project in Matarbari	$0.1094/kwh
4	Rangunia Grid-Tied 45–55 MW (AC) Solar Power Project on a BOO Basis	$0.0749/kWh
5	50 MW Grid-tied Solar Power Plant in Baroiyerhat with 132.33 KV Grid Substation	$0.1094/kwh
6	100 MW (AC) Grid-Tied Solar PV Power Plant by Consortium of Kai Bangladesh Aluminium Ltd. and ALTECH Aluminium Industries Ltd.	$0.092/kwh
7	100 MW (AC) Grid-Tied Solar PV Power Plant by Consortium of Ditrolic SA International Pte. Ltd. and Powernetic Energy Ltd.	$0.092/kwh
8	Joules Power Limited's 50 MW (AC) Grid-Tied Solar PV Power Plant	$0.1094/kwh
9	30 MW (AC) Grid-Tied Solar PV Power Plant By Consortium of NewTech Solar Energy BD Limited and D.H. Euro Hitech Co. Ltd. (South Korea)	$0.092/kwh

2.3.6 Power scenario in Bangladesh

Table 2.5: Overview of the Power Plants in Bangladesh

Type of Plant	Name of Power Plant	Type of Fuel	Generation Capacity Installed (As of 30 June 2023) MW
Public	Karnafuli Hydro	Hydro	230
	Rauzan 210 MW/ST (1st)	Gas	210
	Rauzan 210 MW/ST (2nd)	Gas	210
	Shikalbaha 150 MW Peaking PP	Gas	150
		HSD	
	Shikalbaha 225 MW PS	Gas	225
		HSD	
	Hathazari 100 MW Peaking PP	F.oil	98
	Sangu, Dohazari-kaliaish 100 MW PPP	F.oil	102
	RPCL Raozan 25 MW	F.oil	25
	Mirsarai 150MW Ecconomic Zone	Gas	163
		F.oil	

	Matarbari 2*600 MW U-1 PS	Imported Coal	
	Sonagazi 1 MW Wind PP	Wind	0
	Kutubdia 900KW Wind PP	Wind	0
	Kaptai Solar	Solar	7
IPP	Rural Power Company Ltd. (RPCL)	Gas	210
	Baraka Patenga	F.oil	50
	ECPV Chattogram Limited 108 MW	F.oil	108
	Juldha Acorn 100 MW Unit-3	F.oil	100
	Baraka Shikalbaha 105MW PS	F.oil	105
	United Anwara 300MW PS	F.oil	300
	Potia Jodiac Power	F.oil	54
	Shikolbaha Karnaphuli Power Ltd.	F.oil	110
	Julda 100 MW Unit - 2 (Acorn)	F.oil	100
	20 MW Solar Teknaf	Solar	20
	US-DK Wind PP 60 MW, Cox's Bazar	Wind	
RENTAL	Shikalbaha 55 MW Rental Power Plant	F.oil	51
	Julda Acorn Infra.service Ltd.100MW	F.oil	100

Table 2.6: Plan for Generation of Power

Year	Planned Generation (MW)
2021	24,000
2030	40,000
2041	60,000

(Source: Power System Master Plan 2016)

Numerous generating projects have been planned and executed across the country. Until now, gas generation has been significantly higher than that from other fuels such as hydro and coal. Because of this, the government has decided to diversify the main fuel source for the production of power. This plan asks for the utilization of LNG, nuclear power, limited local gas, imported electricity from neighboring countries, coal (either domestic or imported), and renewable energy sources.

As of October 2023, the current generation expansion plan aims to add around 11,079 MW of generating up to 2025. This comprises 3,684 MW in the commercial sector, 1,861 MW from joint ventures, and 5,534 MW of extra capacity in the public sector. The following table shows the capacity increase plan for the years 2023 through 2025:

Table 2.7: Plan for Additional Power Generation by Year

Year	Public Sector (MW)	Private Sector (MW)	Joint Venture (MW)	Total
2023	50	2,015	617	2,682
2024	2,774	1,492	1,244	5,510
2025	2,740	1,77	0	2,917
Total	5,534	3,684	1,861	11,109

(Source: BPDB Annual Report 2022-2023)

27 projects with a 9,334 MW capacity are currently under construction, 14 projects with a 659 MW capacity are in the contract signing phase (LOI and NOA have been provided), and 7 projects with a 628 MW capacity are presently in the tendering process, according to the above-mentioned plan.

However, this study focuses on the Chattogram area. The year-by-year commissioning status of power projects in the Chattogram region for the preceding fourteen years, commencing in 2010, has been produced using the BPDB Annual Reports 2022-2023.

Table 2.8: Commissioning Status of Generation Projects in Chattogram

Year	Plant	Capacity (MW)	Ownership	Fuel Type
2010	Shikalbaha 150 MW	150	BPDB	Gas

	Shikalbaha 55 MW Rental Power Plant	55	Rental (BPDB)	HFO
2011	Hathazari 100 MW Peaking PP	98	BPDB	HFO
	Sangu, Dohazari 100 MW Peaking PP	102	BPDB	HFO
2012	Julda, Chattogram Power Plant	100	Rental (BPDB)	HFO
2013	Raujan 25 MW P	25	RPCL	Gas/HFO
2014	Baraka-Patenga Chattogram 50 MW PP	50	IPP	HFO
2015	Potiya, Chattogram 108 MW Power Plant	108	IPP	HFO
2017	Shikalbaha 225 MW CCPP	225	BPDB	Gas/HSD
2018	Teknaf, Coxs bazar 20 MW Solar Park	20	IPP	Solar
	Julda, CTG 100 MW PP (Unit-3	100	IPP	HFO
2019	Kaptai Solar Power Plant	7	BPDB	Solar
	Shikalbaha 105 MW PP	105	IPP	HFO
	Anowara, Chattogram 300 MW PP	300	IPP	HFO
	Shikalbaha 110 MW PP	110	IPP	HFO
	Shikalbaha, Chattogram 54 MW PP	54	IPP	HFO
2020	Julda, Chattogram 100 MW PP (Accorn Inf) (Unit-2	100	IPP	HFO
2021	Potiya, Chattogram 116 MW PP (Unlima Energy	116	IPP	HFO
2023(up to June)	Mirsorai, Chittagong 150 MW PP	163	BR Power Gen	HFO/Gas

2.4 PREVIOUS WORKS

There are loads in the neighborhood that the proposed grid-connected microgrid can handle. The simulation included planning for cost savings in order to optimize operations. Figure 2.6 depicts a schematic of various significant studies' research gaps.

N. Mohammad and D.K. Chowdhury studied grid-wise power system operation to discover the best power distribution from various generating units to save money. A model for minimizing costs in a power system that incorporates a significant proportion of energy from wind as well as spread solar PV generation. A bi-level-optimization suggested making use of the most effective flow of power approach while incorporating distinct things in the present market structure [73].

Baky et al. offered an analysis of the existing state and future potentials of Bangladesh's renewable energy sector, as well as upcoming developments [74]. Using locational marginal cost pricing encourages effective virtual network and generation investment [75].

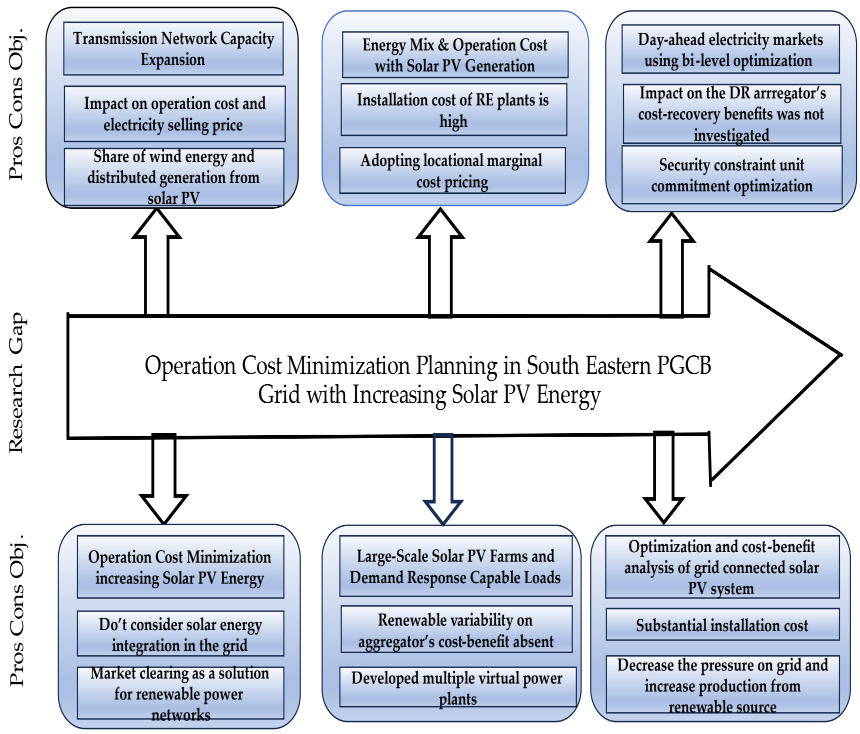

Figure 2.6: A research gap is identified by evaluating a few significant studies of operation cost minimization.

In their investigation of competition-driven supply strategies to satisfy a particular demand in day-ahead power markets, Nur Mohammad et al. found that a framework devoid of transmission limitations and lower demand leads to Nash equilibrium in terms of generating reward [76].

A pool-based DRX for day-ahead scheduling using energy from renewable sources was presented by Wu et al.[77] .Participants' bids are collected by a DRX operator (DRXO). Lower locational marginal pricing (LMP) during peak hours was brought about by the DRX settlement, which reduced operating and overloading costs. In order to reduce operational costs, DR was given priority over renewables, and the relationship between supply of energy and deferrable demand was not examined. The security constraint unit commitment optimization factored in renewables' variability, resulting in a lower market clearing price. In [78], the coupon-based DR system was utilized to decrease operating costs, with the top-level maximizing income for load-serving enterprises (LSEs) and the lower-level minimizing operation costs for the energy market operator. In order to lower operating costs, marketing clearance systems with renewable uncertainties were studied in [79, 80, 81]. To assess the financial effect of wind-power uncertainty, a risk measure was included in the model. The effect on the advantages of recovering costs of the DR aggregator was not examined, though.

Farhana et al. [82] investigated the grid-wise functioning of power-systems to determine the best affordable method of transferring electricity from a number of power plants. In the meantime, in order to lower operating costs and preserve supply and demand balance, the authors looked at market clearing is an approach to integrated power networks powered by renewable energy and suggested a bi-level-optimization method using the optimum power-flow method, taking into account multiple entities in the current market framework. They did not, however, take grid integration of solar energy into account.

In order to reduce operating costs, Y. Wang et al. [83] created a collaborative proposals approach for multiple virtual power plants (VPPs) in the form of renewable energy sources and interruptible loads, neglecting the link between VPPs and the retail energy pool. T. Sadamoto et al. [84] and H. Hao et al. [85] provide an optimization technique for scheduling home loads and storages with the goal of lowering overall electricity consumption costs while leaving connection to the grid power system. A coupon-based DR scheme was part of the bi-level optimization and MCM that X. Fang et al. [78] provided in order to reduce operational expenses and boost revenue for the load-serving entity.

Bangladesh's energy mix is evaluated and an energy future is presented by N.K. Das et al. [86]. Bangladesh's potential for solar and renewable energy was investigated and documented in reference [87]. Additionally, Ganesan et al. [88] built a method using a PV system and found that incorporating the operational cost of DG is decreased using RE resources.. In order to lower power prices and greenhouse gas emissions, Bangladesh will implement solar photovoltaic systems connected to the grid which are less expensive and beneficial to the environment.

This chapter looked at the current state of a hurdle to Bangladesh's progress in renewable energy. Section 2.1 discusses the current situation of renewable energy integrated power plants, including sector-wise generation capacity. This chapter compares the renewable energy trends in Bangladesh and throughout the world. In the preceding work part, various prior studies and discovered a research gap in selecting an acceptable operating cost reduction strategy for grid-connected microgrids were analysed. As a result, the proposed microgrid focused on measures for reducing operating costs.

Chapter 3

3 Research Methodology

This chapter describes the design and techniques of this investigation. The detail modelling of the grid and its operation cost is developed the solution technique. Karush-Kuhn-Tucker (KKT) optimality conditions and Lambda Iteration Method are used for the studied grid model. This chapter also covers specific criteria for transmission line parameters and transmission line reactance. The per unit values are considered during computations. Flowcharts of the algorithm is explained in this section.

3.1 MODELLING OF POWER PLANT

3.1.1 Hydro power plant

One of the most practical ways to generate electricity is through hydropower facilities, which have been modelled taking into account a wide range of application factors. They additionally happen to be quite effective, with some plants exceeding 90% efficiency. The cost per unit of electricity generated by a hydropower plant varies according to the project's size, location, and other factors. The cost of constructing a large hydropower plant with storage can range from $1,050-$7,650 per kilowatt, whereas small hydropower projects can cost between $1,300 and $8,000. The LCOE for large-scale hydropower projects at good sites can be as low as $0.02 per kilowatt-hour (kWh), at an average price of about $0.05 per kWh. The LCOE for hydropower varies by region, with lower costs in Asia and South America and higher costs in Europe and Central America and the Caribbean. Hydropower is generally the cheapest source of electricity globally, and is a mature technology with limited potential for cost reduction. However, adding capacity to existing dams or hydropower schemes can be much cheaper than building new plants.

3.1.2 Solar power plant

Solar photovoltaics, a clean and green energy technology, are essential to renewable power generation in order to meet any nation's electricity needs. Before installing a photovoltaic system anywhere, It is necessary to model, simulate, and analyse the generator to better understand its behaviour and features in actual climatic circumstances. Solar power plants use either photovoltaics or concentrated solar power to convert sunlight into electricity. Light is transformed into an electric current by solar panels using the photovoltaic effect. With a 275 MW capacity, it's the largest solar photovoltaic power capacity in Bangladesh. It's located in Sundarganj, Gaibandha, and was completed in January 2023. The unit used to measure the generation of solar power is the kilowatt hour (kWh). For large solar energy systems, the unit used is the megawatt hour, which is equivalent to 1,000 kWh. The price per unit of solar power in Bangladesh varies depending on the plant. With a production cost of Tk14.30 per unit, the Tetulia 8 MW solar power plant is the most affordable in the nation. One of the most expensive solar power plants is the Kaptai 7 MW, which costs Tk22.38 per unit to produce.

3.1.3 Natural gas

Natural gas power plants, often referred to as gas-fired power stations, are a form of thermal power plant that uses natural gas to generate electricity. Building a natural-gas-power plant is rapid and affordable. Emissions from natural gas power stations are lower than those from other fossil fuels but higher than those from nuclear-power-plants. Natural gas-fired power plants employ a variety of methods to generate electricity, including steam turbines (ST), simple-cycle gas turbines (SCGT), internal combustion engines (ICE), and combined-cycle gas turbines (CCGT). Heat rate, or the quantity of British thermal units (Btu) needed to produce one kWh of electricity, is a measure of a generator's efficiency. As of February 2024, the cost of natural gas for power-plants in Bangladesh is Tk

14.75 per cubic meter for rental power plants, privately held independent power producers (IPPs), and government-owned gas-fired power plants. The cost per cubic meter for commercial, small, and captive power plants is Tk 30.75. The government raised the price of gas for power plants per unit, by 0.75 taka ($0.0068).

3.1.4 Heavy fuel oil (HFO)

HFO, a hydrocarbon fuel or petroleum distillate, is used to produce lighter hydrocarbon products like gasoline and diesel, is made from crude oil. Long-term dependable operation, long-life duration, reduced operating and maintenance expenses, and low noise benefits are all provided by HFO power plants—all essential components for a 24/7 operation. Power plants using hydrocarbon fuels, such as HFO fuel will continue to be a major source of power generation till their prices are equal to or above those of renewable energy technologies, even as it continues to become more affordable. Diesel and HFO generators are two of the many generating units used in heavy fuel oil (HFO) power facilities. The power output of these generators ranges from 120 kW to 3000 kW. They might be employed in power plants or as land generators. Compared to diesel generators of the same size, HFO generators may be more dependable and operate more economically. Electricity produced using furnace oil or heavy fuel oil (HFO) costs Tk 17 per unit in Bangladesh. Since the cost of producing energy from HFO is three times greater than that of other fuels, the government employs HFO-powered facilities to produce electricity. The electricity industry has significant arrears. HFO imports cost US dollars.

3.2 OPTIMAL POWER FLOW

The general theory statement of the issue was that the power flow complies with the basic equality criterion of supply and demand. Power flow generally complies with the basic rules of electricity and network theory, those are commonly referred to as the load flow equations and are founded on Kirchhoff's laws. A collection of factors for making decisions that satisfy the essential principles of electricity flow and achieve the desired outcomes of cost and loss minimization are the outcome of the optimal solution generated by incorporating these load flow equations into the Economic Load Dispatch (ELD) system of supply and demand patterns balance constraints [89, 90, 91, 92, 93]. OPF formulation is a stable, quadratic, issue of optimization with constraints.

Economic dispatch is framed by the best power flow strategy. The OPF must then be made linear. For the sake of accessibility, every unit is considered to provide an identical selling prices estimate. The aim of the function [94] sometimes referred to as the cost function, is constructed by multiplying the unique price offer of each unit by its MW of generation. Assuming S_1, S_2, and S_3 as the individual pricing offers, the resulting generation amounts would be Pg_1, Pg_2, and Pg_3, respectively. The entire idea is graphically shown in Figure 3.1. The purpose of the objective

$$Z(X) = \sum S_j P_j^g \tag{3.1}$$

Where, j = 1,2,3……….. to n;

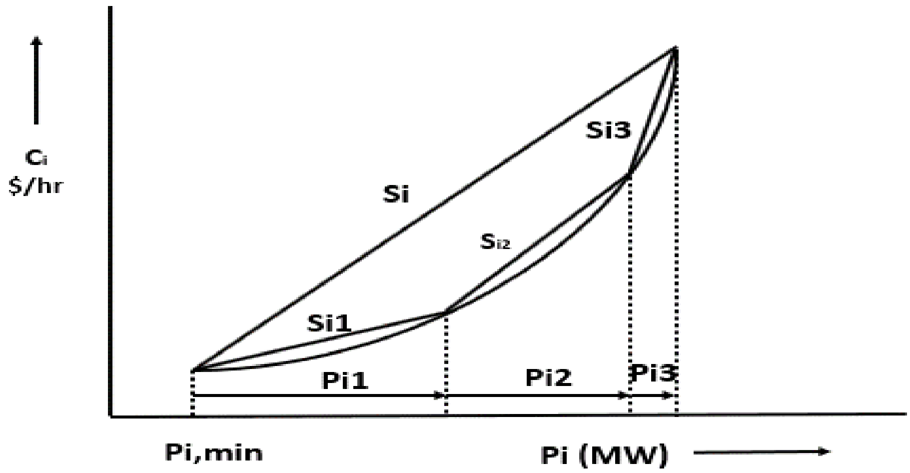

Figure 3.1: Graphical representation of the cost function.

S_1 across Sn is the cost of producing energy for each and every producing system, where n is the overall amount of power-generating units in the whole method. In order to achieve all of the necessary constraint equations (3.3 to 3.4), it must be done to optimize this objective function (3.1). Each bus's LMP of electrical energy must be calculated using the Lagrange multiplier [95]. It is employed to rapidly determine a restricted function's extrema. Since all of the equality and inequality constraints [96] are provided in an approach that makes this feasible, this problem can be resolved using linear programming. All of the variables that remain undefined are included in a single vector known as the solution vector, which describes these limitations. The recommended problem's solution vector is defined as follows:

$$X= \begin{pmatrix} \underline{P_g} \\ \underline{P_B} \\ \underline{\theta} \end{pmatrix} \tag{3.2}$$

Subject to:

$$\underline{P} = \underline{B'}\ \underline{\theta} \tag{3.3}$$

$$- \underline{P_B} + (\underline{D} \times \underline{A}) \times \underline{\theta} = \underline{0} \tag{3.4}$$

The system's transmission line flows are the cause of equality constraint (3.4), whereas injections are the cause of constraint (3.3).

Here,

- Pg represents the vector of generation increments $[P_{gk}\ldots\ldots\ldots]^T$ for all buses with generator.
- P_B represents the vector of line flows $[P_{B1}\ P_{B2}\ldots\ldots P_{BM}]^T$, M is a set of branches.
- θ represents the vector of bus angles in radians $[\theta_1\ \theta_2 \ldots\ \theta_N]$, where N is the number of buses.

Equation (3.3) yields the Lagrange multiplier, which is in charge of maintaining supply and demand equilibrium. It illustrates how adding 1 MW to the system's output reduces its cost by 1 MW. A vector Pg, or $[Pg_1, Pg_2,\ldots Pg_x]^T$, is the output of every generating unit on every bus. $[P_{B1}, P_{B2},\ldots P_{BY}]^T$ is the vector P_B, which contains the line flows for each branch. A vector of the form [θ_1, θ_2, θ_3,... θ_m] in radians is used to express bus angles. The idea of a solution vector may be used to derive inequality restrictions. The angle limits are the only thing remaining to figure out. Every angle needs to be precisely radians positive or negative. The specification of the solution vector yields inequality restrictions. Finding the angle constraints is the main obstacle here. The range of each angle must be between -π and +π radians. Thus, constraints on inequality are:

$$\begin{bmatrix} \underline{P_g}, min \\ -\underline{P_{B,max}} \\ -\underline{\pi} \end{bmatrix} \leq \begin{bmatrix} \underline{P_g} \\ \underline{P_B} \\ \underline{\theta} \end{bmatrix} \leq \begin{bmatrix} \underline{P_g}, max \\ \underline{P_{B,max}} \\ \underline{\pi} \end{bmatrix} \tag{3.5}$$

Equation (3.5) illustrates these inequalities, which enable any network to have its line flow, generation, and power-angle adjusted while still achieving cost and generation aims. Network modifications can be used to accomplish any distribution of load. Finally, a bus system with optimum strength distribution will be constructed.

3.2.1 Formulation of DC OPF

OPF approach is widely used by engineers, scientists and the electrical regulatory body to lower the running costs of producing units. The heat rate, input-output, fuel cost and curves of incremental costs are frequently used to show the operational costs of generators [31]. The DC OPF method is used to determine the test system's purchase price of energy and operating expenses. The power-flow technique is used to ascertain the impact of electrical power flow on a grid-connected system. The per unit system and the one-line diagram serve as the foundation for this method. This technique is used to calculate voltage angles and reactive power when voltage values and active power are already known on the generator side. Despite this, the power-flow approach is used to calculate voltage angles and voltage at the load when reactive and active power values are known.

DC OPF may be taken into consideration for the transmission system constraint. DC power flow is frequently employed in many kinds of research. It offers a highly realistic approximation of AC OPF and is incredibly rapid and simple to sort out.

The standard form of the power flow equation (PF) is as follows:

$$P_c = \sum_{d=1}^{K} V_c V_d (G_{cd} \cos(\theta_c - \theta_d) + (B_{cd} \sin(\theta_c - \theta_d)) \tag{3.6}$$

$$Q_c = \sum_{d=1}^{K} V_c V_d (G_{cd} \sin(\theta_c - \theta_d) - (B_{cd} \cos(\theta_c - \theta_d)) \tag{3.7}$$

However, the conventional method to DC OPF equations includes various assumptions about the power system network. The following presumptions are taken into consideration:

- All transmission resistance is thought to be almost 0 (zero). Stated differently, a lossless transmission network is required. For this reason, $G_{cd}=0$.
- It is assumed that there is very little angle of change in bus voltage. Consequently, $\sin(\theta_m - \theta_n) \approx \theta_m - \theta_n$
- The bus voltages are taken to be 1.0 (p. u.).
- DC OPF ignores the flow of reactive power.

Given the preceding assumptions, equation (3.6) might be expressed as the DC OPF equation:

$$P_c = \sum_{d=1}^{K} B_{cd}(\theta_c - \theta_d) \tag{3.8}$$

Karush-Kuhn Tucker (KKT) circumstances do not provide an actual optimum value since the study's producing units and transmission flow were constrained. Consequently, the quadratic function is suggested as a solution to the DC OPF [37].

The cost function of the generator's units may be represented as a quadratic function:

$$C_i(P_{Gi})=c_i+b_i.P_{Gi}+a_i.P_{Gi}^2 \tag{3.9}$$

Where a_i, b_i, c_i are cost coefficients of i^{th} generator and C_i (P_{Gi}) is the generation cost of i^{th} generator. The cost is determined using the Lagrangian multiplier.

3.2.2 Lagrangian incorporating into DC OPF

Surprisingly, when a continuous-time horizon is used, the nonconvex problem in this study is demonstrated to have no duality gap. This makes it possible to exhaust the Lagrangian approach while still keeping the generation scheduling problem optimum.

Upon adding a line flow limit to the system, it may be represented as an equation, as shown in this example:

$$\frac{100}{x_{cd}}(\theta_c-\theta_d)=\alpha \tag{3.10}$$

where, x_{cd} represents the transmission line reactance, while α denotes the line flow limit's numerical value.

The Lagrangian of the DC OPF equation becomes if equation (3.10) is included

$$L=\sum_{i=1}^{N} c_i+b_iP_{Gi}+a_iP_{Gi}^2+\lambda_1(100Bx_{11}\theta_1+100Bx_{12}\theta_2+\ldots+100Bx_{1n}\theta_n \ldots-P_{G1}+P_{ld})+\ldots+\lambda_i(\frac{100}{x_{cd}}\theta_c-\frac{100}{x_{cd}}\theta_d-k) \tag{3.11}$$

The set of linear equations is derived by calculating the Lagrangian's (L) derivative with respect to zero variables. The Lagrangian multipliers indicate the system's marginal values, often known as shadow prices. The change in system cost for a one-unit (MWh) rise in demand is represented by the multiplier, λ_(i).

This is known as the system's added cost. The marginal costs of the system are the same whether line flow is set to infinite. When the line flow is constrained, however, the system experiences various marginal prices. These prices are sometimes referred to as the Locational Marginal Price (LMP).

Karusk-Khun-Tucker (KKT) criteria were applied in an attempt to find the best power flow in this case.

3.2.3 Karusk-Khun-Tucker (KKT) conditions

The optimality requirements for a confined local optimum are known as the Karush Kuhn Tucker (KKT) criteria, and they are essential to the theory and advancement of constrained optimization algorithms. The KKT criteria for optimality are a set of conditions that must be met for a solution to be optimal in a mathematical optimization problem. They are both adequate and needed conditions for a local minimum in problems requiring nonlinear programming. The following components comprise the KKT conditions:

Regarding an optimization problem:

$$\min_{x} f(x) \tag{3.12}$$

Subject to

$$g_i(x) - b_i \geq 0 \quad i = 1\ldots\ldots, k \tag{3.13}$$

$$g_i(x) - b_i = 0 \quad i= k+1\ldots\ldots, m \tag{3.14}$$

The ideal primal (x) and dual (λ) variables have four KKT criteria. Optimal values are indicated with the asterisk (*).

1.Primal Feasibility**:** All constraints must be fulfilled.

$$g_i(x^*) - b_i \text{ is feasible} \tag{3.15}$$

2. No Feasible Descent**:** There is no objective way to enhance the solution.

$$\nabla f(x^*) - \sum_{i=1}^{m} \lambda_i^* \nabla_{gi}(x^*) = 0 \qquad (3.16)$$

3.Complementarity: The product of the Lagrange multipliers and the corresponding variables must be zero

$$\lambda_i^*(g_i(x^*) - b_i) = 0 \qquad (3.17)$$

4.Dual Feasibility**:** The Lagrange multipliers associated with constraints have to be non-negative (zero or positive).

$$\lambda_i^x \geq o \qquad (3.18)$$

For both equality and inequality constraints, the feasibility criterion (3.15) only states that under ideal circumstances, the constraints cannot be overcome. There is no practical path that may possibly enhance the goal function, according to the gradient condition (3.16). The latter two conditions (3.17 and 3.18), which impose a positive Lagrange multiplier when the constraint is active and a zero Lagrange multiplier when it is not, are only required for inequality constraints.

3.2.4 Proposed method

An effective and precise iterative optimization technique for resolving limited optimization issues, such as economic dispatch, is the Lambda iteration approach. It converts the restrictions of the issue into Lagrange multipliers, which serve as objective function penalty terms. In order to discover the best option that minimizes fuel consumption costs while meeting power demand and plant restrictions, the algorithm iteratively adjusts the Lagrange multiplier and power generation values.

The Lambda iteration approach, which incorporates the Lagrange multiplier and limitations, guarantees that the power-generating plan reduces fuel costs while fulfilling demand. The Lambda iteration approach is useful because it takes into account factors such as plant capacity, fuel prices,and operational restrictions. By iteratively updating the power generation values, Lagrange multiplier and power system operators may make more informed judgments about power allocation. This robust technique allows for the effective optimization of economic dispatch issues, balancing the trade-off between fuel consumption costs and power demand fulfillment while accounting for each power plant's limits[97].

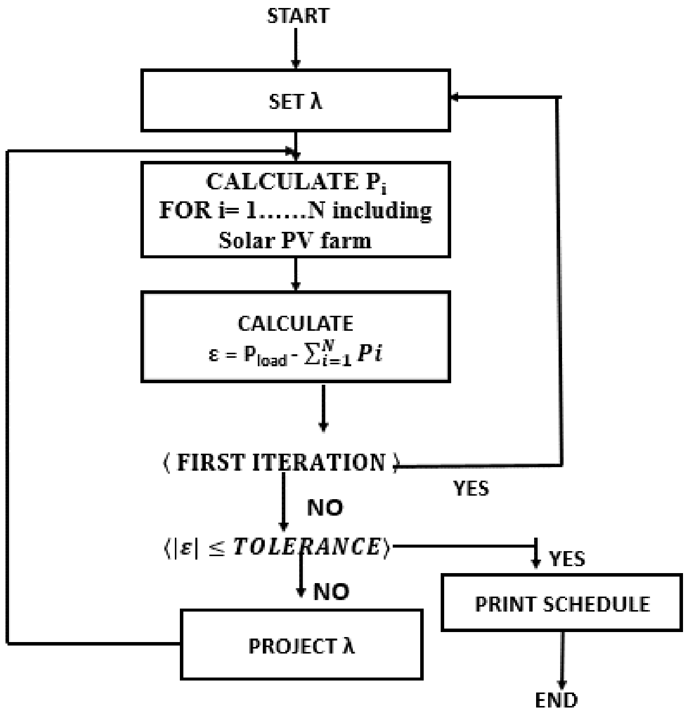

Figure 3.2: Flowchart of the suggested approach for generating utility-scale solar PV.

The lambda iteration strategy, which addresses the carelessness of losses in all-thermal dispatching, is depicted in a block diagram in Figure 3.2. We must first ascertain λ in order to compute Pi, which includes solar PV activities. The ideal economic operating point to cut expenses is then found by calculating the epsilon value, which is the difference between supply and demand. Check the epsilon value following the conclusion of the first iteration. The system either modifies to λ or keeps updating the Pi value until the tolerance threshold is reached if the value is within the range. Lastly, quantity, price, and cost are generated by the system's print schedule [98, 99] .

3.3 TRANSMISSION LINE PARAMETERS

In this case, Aluminum Conductor Composite Core, Grosbeak Low Loss Finch Quad Conductor and Aluminum Conductor Steel Reinforced (ACSR) were used. Transmission lines' inductive reactance may be calculated using the following formula for both double and single circuit lines:

$$L = 0.2 \ln \frac{D_m}{D_s} \text{ mH/km} \tag{3.19}$$

$$X_L = 2\pi f L \ \Omega/\text{km} \tag{3.20}$$

$$GMR = \sqrt{\left(D_S \times d \times d \times d \times \sqrt{2}\right)^4} \tag{3.21}$$

Where D_s = GMR or self-GMD = 0.7788r and

D_m = Mutual GMD = $(d_1 d_2 d_3)^{1/3}$ [100]

Positive sequence impedance (X_1) multiplied by substation length yielded the transmission line's impedance value. These impedances are transformed into per-unit values using the following formulas:

$$Z_{pu} = Z_{\Omega} \times \frac{S_b}{V_b^2} \tag{3.22}$$

The purpose of a conductor is to move electric current with the least amount of resistance from one place to another. When an alternating electricity passes through a conducting substance, the current density is maximum near its surface and the current distribution varies along the conductor's cross-sectional area. As a result, the AC resistance is somewhat greater than the DC resistance. Conductor resistance increases with temperature. This change may be computed from and is thought to be linear over the typical temperature range.

$$R_2 = R_1 \frac{T + t_2}{T + t_1} \tag{3.23}$$

Where R_2 and R_1 are conductor resistances at t_2 and t_1-C^0, respectively. T is a temperature constant that varies with the conductivity material. The manufacturer's specs are the best way to calculate the conductor resistance due to the aforementioned effects.

3.4 TRANSMISSION LINE INFORMATION

Table 3.1 displays the transmission line length, voltage level, and positive sequence impedance of the substation as calculated by the PGCB network. In this scenario, PGCB data indicates that buses 1 through 2, 4 through 3, 1 through 4,4 through 5, 4 through 6, 5 through 6, 1 through 3 and 3 through 7 are all 132 KV, whereas buses 2–3 are 230 KV.

Table 3.1: Transmission line information [100]

Name of Substation		Length(km)	Positive Sequence impedances (ohm/km)		Name of the conductor
From	To		R_1	X_1	
Kaptai to Chandraghona (132kv Double circuit)		11.50	0.08868	0.389301	Grosbeak
Chandraghona to Madunaghat (132 kv Double circuit)		30.80	0.10123961	0.385162987	Grosbeak
Madunaghat to Shikalbaha (132 kv single circuit)		16.10	0.067	0.367	ACCC
Shikalbaha to Hathazari (230 kv Double circuit)		28.35	0.016	0.234	Quad
Hathazari to Kaptai (132 kv Double circuit)		38	0.100852632	0.392866842	Grosbeak
Shikalbaha to Dohazari (132 kv Double circuit)		32	0.067	0.367	ACCC
Dohazari to Cox's Bazar (132 kv double circuit)		87.70	0.0751	0.394	ACCC`
Dohazari to Matarbari		48	0.101090155	0.384954	Grosbeak

(132 kv single circuit)				
Matarbari to Cox's Bazar (132 kv single circuit)	18	0.101090155	0.384954921	Grosbeak
Hathazari to Raozan (132 kv double circuit)	22.50	0.0529	0.30164755	Twin300 sq.mm

3.4.1 Transmission line reactance calculations

For ACCC conductor Madunaghat to Shikalbaha, Shikalbaha to Dohazari and Dohazari to Cox's Bazar transmission line reactance are calculated.

Here, single circuit horizontal spacing = 8m

ACCC conductor diameter = 25. 159mm

For single circuit, Inductance per phase per kilometre length is

$$L = 0.2 \ln \frac{D}{D_s}\ mH/km$$

Here, $D_s = 0.7788r$

$$r = \frac{25.159 \times 10^{-3}}{2}\ m$$

$= 0.0125795$ m

$D_s = 0.7788r \times 0.0125795$ m

$= 9.7969 \times 10^{-3}$ m

D = Geometric Mean Distance (GMD)

$= \sqrt[3]{D_{12}D_{23}D_{31}}$

$= \sqrt[3]{8 \times 8 \times 16}$

$= 10.056$ m

Finally, $L = 0.2 \ln \frac{D}{D_s}\ mH/km$

$= 0.2 \ln \frac{10.056}{9.7969 \times 10^{-3}}$ mH/km

$= 1.38677$ mH/km

$= 1.3867 \times 10^{-3}$ H/ km

Inductive reactance, $X_L = 2\pi fL$

$$= 2\pi \times 50 \times 1.3867 \times 10^{-3}$$

$$= 0.4356\ \Omega/\text{km}$$

So, calculated value for inductive reactance is equal to 0.4356 Ω/km and measured value is equal to approximately 0.367 Ω/km.

Similarly, For Grosbeak ACSR conductor Kaptai to Chandraghona, Chandraghona to Madunaghat, Hathazari to Kaptai, Dohazari to Matarbari and Matarbari to Cox's Bazar transmission line reactance are calculated. These are calculated value for inductive reactance is equal to 0.4356 Ω/km and measured value is equal to approximately 0.367 Ω/km.

For Quad conductor, Shikalbaha to Hathazari double circuit transmission line reactance is calculated using following formula

$$GMR = \sqrt{\left(D_s \times d \times d \times d \times \sqrt{2}\right)^4}$$

Where GMR or self GMD = 0.7788r

For Twin 300sq.mm.calculated value for Hathazari to Raozan double circuit transmission line reactance is equal to 0.30164 Ω/km.

3.4.2 Per unit value calculations for transmission line reactance

In PGCB network, Kaptai to Shikalbaha transmission line is not directly connected. It is connected to Kaptai to Chandraghona, Chandraghona to Madunaghat and Madunaghat to Shikalbaha transmission line. The following table are represented here:

Table 3.2: Data table for Kaptai-Shikalbaha transmission line reactance.

Name of Substation	Length (km)	Positive Sequence reactance(ohm/km)
Kaptai to Chandraghona	11.50	0.389301
Chandraghona to Madunaghat	30.80	0.385162987
Madunaghat to Shikalbaha	16.10	0.367

Total	58.4	1.141463987

The reactance value of the transmission line was determined by multiplying the substation length by the positive sequence reactance (X_1). So, Kaptai to Shikalbaha total transmission line reactance is

$X_1 = 58.4 \times 1.141463987$

$= 66.6614\ \Omega$

Assume S_{base} 100 KVA per unit value of Kaptai to Shikalbaha line is

$$Z_{pu} = 66.66 \times \frac{100}{132^2}$$

$= 0.382$ pu

Per unit admittance

$$y_{pu} = \frac{1}{Z_{pu}} = \frac{1}{0.382} = 2.618\ pu$$

Table 3.3: Data table for the Shikalbaha - Hathazari transmission line reactance

Name of Substation	Length (km)	Positive Sequence reactance (ohm/km)
Shikalbaha to Hathazari	28.35	0.234

Shikalbaha to Hathazari transmission line reactance is

$X_2 = 28.35 \times 0.234$

$= 6.6339\ \Omega$

Per unit value of Shikalbaha to Hathazari line is

$$Z_{pu} = 6.63 \times \frac{100}{230^2}$$

$= 0.012$ pu

Per unit admittance

$$y_{pu} = \frac{1}{Z_{pu}} = \frac{1}{0.012} = 83.33\ pu$$

In PGCB network, Hathazari to Dohazari transmission line is not directly connected. It is connected Hathazari to Kaptai, Kaptai to Chandraghona, Chandraghona to Madunaghat, Madunaghat to Shikalbaha and Shikalbaha to Dohazari transmission line. The following table are represented here:

Table 3.4: Data table for the Hathazari - Dohazari transmission line reactance

Name of Substation	Length (km)	Positive Sequence reactance (ohm/km)
Hathazari to Kaptai	38	0.392866842
Kaptai to Chandraghona	11.50	0.389301
Chandraghona to Madunaghat	30.80	0.385162987
Madunaghat to Shikalbaha	16.10	0.367
Shikalbaha to Dohazari	32.20	0.367
Total	128.6	1.901330829

Hathazari to Dohazari total transmission line reactance is

$X_3 = 128.6 \times 1.901330829$

$= 244.5111\Omega$

Per unit value of Hathazari to Dohazari line is

$$Z_{pu} = 244.511 \times \frac{100}{132^2}$$

$$= 1.403 \text{ pu}$$

Per unit admittance

$$y_{pu} = \frac{1}{Z_{pu}} = \frac{1}{1.403} = 0.7127\ pu$$

Dohazari to Kaptai transmission line is not directly connected. It is connected to Kaptai to Chandraghona, Chandraghona to Madunaghat, Madunaghat to Shikalbaha and Shikalbaha to Dohazari transmission line. Data table for Dohazari to Kaptai transmission line reactance is

Table 3.5: Data table for the Dohazari - Kaptai transmission line reactance

Name of Substation	Length (km)	Positive Sequence reactance(ohm/km)
Kaptai to Chandraghona	11.50	0.389301
Chandraghona to Madunaghat	30.80	0.385162987
Madunaghat to Shikalbaha	16.10	0.367
Shikalbaha to Dohazari	32.20	0.367
Total	90.6	1.508463987

Dohazari to Kaptai total transmission line reactance is

$X_4 = 90.6 \times 1.508463987$

$= 136.6668\ \Omega$

Per unit value of Dohazari to Kaptai line is

$$Z_{pu} = 136.6668 \times \frac{100}{132^2}$$

$= 0.784$ pu

Per unit admittance

$$y_{pu} = \frac{1}{Z_{pu}} = \frac{1}{0.784} = 1.2755\ pu$$

Table 3.6: Data table for the Kaptai - Hathazari transmission line reactance

Name of Substation	Length (km)	Positive Sequence reactance (ohm/km)
Kaptai to Hathazari	38	0.392866842

Kaptai to Hathazari transmission line reactance is

$X_5 = 38 \times 0.392866842$

$= 14.928944\ \Omega$

Per unit value of Kaptai to Hathazari line is

$Z_{pu} = 14.928 \times \frac{100}{132^2}$

$= 0.085$ pu

Per unit admittance

$$y_{pu} = \frac{1}{Z_{pu}} = \frac{1}{0.085} = 11.764\ pu$$

Data table for Dohazari to Cox's Bazar transmission line reactance is

Table 3.7: Data table for the Dohazari - Cox's Bazar transmission line reactance

Name of Substation	Length (km)	Positive Sequence reactance (ohm/km)
Dohazari to Cox's Bazar	87.70	0.394

Dohazari to Cox's Bazar transmission line reactance is

$X_6 = 87.70 \times 0.394$

$= 34.5538\ \Omega$

Per unit value of Dohazari to Cox's Bazar line is

$Z_{pu} = 34.55 \times \frac{100}{132^2}$

$= 0.1983$ pu

Per unit admittance

$$y_{pu} = \frac{1}{Z_{pu}} = \frac{1}{0.1983} = 5.0428\ pu$$

Table 3.8: Data table for the Dohazari - Matarbari transmission line reactance

Name of Substation	Length (km)	Positive Sequence reactance(ohm/km)
Dohazari to Matarbari	48	0.384954

Dohazari to Matarbari transmission line reactance is

$X_7 = 48 \times 0.384954$

= 18.4777 Ω

Per unit value of Dohazari to Matarbari line is

$$Z_{pu} = 18.477 \times \frac{100}{132^2}$$

= 0.10604 pu

Per unit admittance

$$y_{pu} = \frac{1}{Z_{pu}} = \frac{1}{0.10604} = 9.4304\ pu$$

Table 3.9: Data table for the Cox's Bazar - Matarbari transmission line reactance

Name of Substation	Length (km)	Positive Sequence reactance(ohm/km)
Cox's Bazar to Matarbari	18	0.3849549

Cox's Bazar to Matarbari transmission line reactance is

X_8 = 18 × 0.3849549

= 6.929 Ω

Per unit value of Cox's Bazar to Matarbari line is

$Z_{pu} = 6.929 \times \frac{100}{132^2}$

= 0.039768 pu

Per unit admittance

$$y_{pu} = \frac{1}{Z_{pu}} = \frac{1}{0.039768} = 25.1458\ pu$$

Table 3.10: Data table for the Hathazari - Raozan transmission line reactance

Name of Substation	Length (km)	Positive Sequence reactance(ohm/km)
Hathazari to Raozan	22.50	0.3016475

Hathazari to Raozan transmission line reactance is

$X_9 = 22.50 \times 0.3016475$

$= 6.78706\ \Omega$

Per unit value of Hathazari to Raozan line is

$Z_{pu} = 6.78706 \times \frac{100}{132^2}$

$= 0.03895$ pu

Per unit admittance

$$y_{pu} = \frac{1}{Z_{pu}} = \frac{1}{0.03895} = 25.6739\ pu$$

Table 3.11: Amount of transmission line reactance per unit [100]

Name of Substation		Reactance (ohm)	Reactance (pu)	Admittance (y)
From	To			
Kaptai	Shikalbaha	66.6614	0.382	2.617
Shikalbaha	Hathazari	6.63	0.012	83.33
Hathazari	Dohazari	244.5111	1.403	0.712
Dohazari	Kaptai	136.6668	0.784	1.275
Kaptai	Hathazari	14.928	0.085	11.764
Dohazari	Cox's Bazar	34.5538	0.1983	5.0428
Dohazari	Matarbari	18.4777	0.10604	9.4304
Cox's Bazar	Matarbari	6.929	0.039768	25.1458
Hathazari	Raozan	6.78706	0.03895	25.6739

The theoretical and mathematical model for every component of the suggested study has been explained in the methodology chapter. In section 3.1.1 and section 3.1.2, formulation of DC optimum power flow, Lagrangian of DC OPF has been described with several equations. Karush Kuhn Tucker (KKT) conditions for both equality and inequality constraints stated in section 3.1.3. A flowchart of the Lambda iteration technique, which is the suggested approach for determining a utility-scale solar PV system, is also presented in section 3.1.4. As a part of financial optimization, section 3.2 covered a variety of transmission line issues, including substation positive sequence impedance, conductor kinds, transmission line reactance calculation, per unit value computation, and more.

Chapter 4

4 Results & Discussion

The performance of several power plants in the Chattogram region under supply profile is examined in this chapter, both with and without solar electricity. It has two networks separated from it. Regardless of the amount of solar electricity, the PGCB grid's southern testing zone in network one examined a four-bus system; network two examined a seven-bus system. In order to save operating costs, compare the two networks using separate data tables for the years 2023, 2025, 2030, 2035, and 2041.

Linear programming solver is used to carry out the simulation. In addition to comparing the performance of the networks, the suggested network's performance is compared to an already-existing network in order to construct the whole network with the PV model under all solar irradiance situations. A table with specifics about their performance is shown.

4.1 RESEARCH MODEL

This study has investigated two networks for the Chattogram area as part of my study. This research work makes every effort to optimize such networks so that they may serve as the foundation for the whole Chattogram area, and potentially the entire country in the future.

4.1.1 Research design

In this study, optimum power flow is used to tackle a real-world problem. Figures 4.1 and 4.5 show two simplified PGCB networks for the Chattogram area. Each attempt includes a network solution modified to the Chattogram region, and those models may be expanded to accommodate the power system in Bangladesh. Five scenarios, including those for the years 2023,2025,2030,2035 and

2041 were suggested for the solar plant in both models. Certain regions have been chosen to offer the best statewide coverage. Every place is sketched by the bus. The names of all the generators and their total generating quantities have been gathered and examined in order to determine which generators are most suited to be part of the fundamental model [27] [28].

4.1.1.1 Selection of generator and required parameter

It has been thought that some areas should conceal the entire city as much as possible. The bus defines each zone. To select the most appropriate generators to be addressed under the basic method, the list of all the generators and their generation levels was gathered from the BPDB website. Included are generators that run on all fuel types, including hydro, solar, gas, and oil. Heavy fuel oil (HFO) is also covered under oil-based generators. The primary determinant of a power plant's generation cost is the fuel type. The least expensive plants are hydro-based. The oil-based plants are the most expensive. Moreover, gas-based plants are less expensive. Both the selling price to the government and the cost of generating are influenced by other factors. Fuel availability is one of the key concerns. Once more, fuel delivery to the facility has a significant impact on the price.

Numerous reports and statistical data from BPDB websites and other sources have been compiled. Then, fuel cost and availability were investigated. After gathering all of the data, the generation parameters for the units in the operational network have been determined.

Table 4.1 summarizes the electricity generation and profile of the unit of the southeast PGCB grid. With an emphasis on the southern zone, the Energy Corporation of Bangladesh, sometimes referred to as PGCB, is assessing the operation of its national grid. Transmission lines owned by PGCB cover 2190 circuit kilometers at 400 kV, 4236 circuit kilometers at 230 KV, and 8317 circuit kilometers at 132 KV. Bangladesh's infrastructure is connected to 291 grid substations as of 2023. The voltage of 170 substations is 132/33 kV, whereas the voltage of 31 substations is 230/132 kV. The system consists of five loads, seven buses, and seven generators.

Table 4.1: Overview of Power Plants in Chattogram

SL No.	Power Plant	Generator No.	Capacity MW	Types of Fuel	Cost of Generation ($/puMWhr)	Maximum demand P_{dmax} (pu)
1	Kaptai Hydro Power Plant	P_{KH}	230	Hydro	4.7	0.46
2	Kaptai Solar Power Plant	P_{KS}	250	Solar	14.1	0.04
3	Shikalbaha Power Plant	P_S	225	Natural gas	53.298	1.5
4	Hathazari Power Plant	P_H	100	HFO	178.6	0.32
5	Dohazari Power Plant	P_D	100	HFO	178.6	0.51
6	Cox's bazar Power Plant	P_C	300	Solar	14.1	0.03
7	Raozan Power Plant	P_R	570	Natural gas	53.298	0
8	Dohazari & Cox's bazar Power Plant (with Matarbari load)	$P_D + P_C$	100 +300	HFO + Solar	178.6 + 14.1	3.56

Source: Bangladesh Power Development Board (BPDB)

4.2 4 BUS PGCB NETWORK

Following that, a bus network system was established to connect the various regions based on their locations. Lines from bus to bus were guided based on credible assumptions. It does not, however, affect the direction in which the line is drawn. Except for the potential of adding a negative sign, the values would stay unchanged. Thus, the required bus diagram was obtained.

The slack bus, often referred to as the reference bus, is the power source interfaced with the first bus. The grids' total capacity for generation analysed in this study is 905 MW, according to grid data supplied by the PGCB. In relation to the overall power generation, the total amount of power used is 233 MW. The cost function of the generator in this system is quadratic. 4.7 $/puMWhr, 14.1

$/puMWhr, 53.29 $/puMWhr, 178.6 $/puMWhr and 178.6 $/puMWhr are each power plant's specific generating costs. The planned electrical system, which consists of 132/33 KV substations from Kaptai to Shikalbaha, Hathazari to Dohazari, Dohazari to Kaptai, and Kaptai to Hathazari, is shown in a single-line schematic in Figure 4.1. The substation from Shikalbaha to Hathazari is 230/132 KV.

Four PGCB buses link the system, which is made up of loads, power plants, and power lines. Buses 2, 3, and 4 are connected to the network loads in that order. Each of the buses is equipped with five generators.

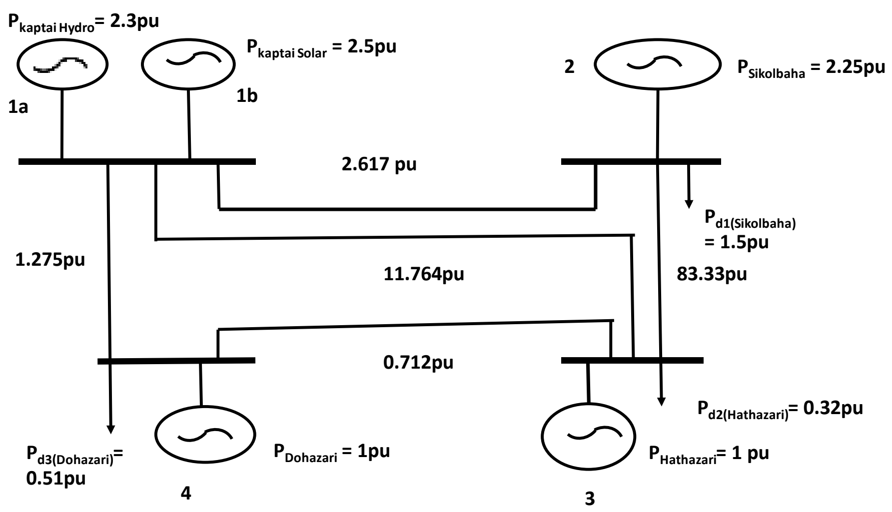

Figure 4.1: PGCB Network at 4 Bus System.

4.2.1 Assumptions and considerations at 4 bus system

4.2.1.1 Generation profile for conventional power plant (Base case)

According to Table 4.2, An operational cost measurement for traditional power plants is included in the supply profile. In such circumstances, the symbols K_{HG}, S_G, H_G and D_G stand for Kaptai-hydro, Sikolbaha , Hathazari and Dohazari generation of power respectively. Each generating plant's capacity is set up to analyze the different circumstances of the energy transportation units.

Table 4.2: Generation delivers for conventional power plant

Case	Year	Case definition/ plant status	Load demand (MW)	Load demand (pu)
1.	2025	K_{HG}=230(15%) =264.5MW = 2.645 pu, S_G =225 MW, H_G=100MW, D_G=100 MW	165	1.65
			35.2	0.35
			56.1	0.56
2.	2030	K_{HG}=230MW,S_G=225(30%)=292.5MW=2.92pu, H_G = 100 MW, D_G= 100 MW	206.25	2.06
			44	0.44
			70.13	0.70
3.	2035	K_{HG} = 230 MW, S_G = 225MW, H_G = 100(45%) =101.45 MW = 1.0145 pu, D_G= 100 MW	257.8	2.58
			55	0.55
			87.656	0.88
4.	2041	K_{HG} =230 MW, SG = 225 MW, HG =100 MW, D_G= 100(60%) =160 MW = 1.60 pu	335.14	3.35
			71.5	0.72
			113.95	1.14

4.2.1.2 Generation profile for solar power plant

A supply profile for a solar power plant is shown in Table 4.3. To maintain an investigation of the various infrastructure issues around the power dissemination range, the solar-powered system has gradually grown its delivering efficiency (to 250 MW) as baseline capacity. In certain instances, Kaptai Solar, Kaptai Hydro, Sikolbaha, Hathazari and Dohazari generation of power are represented by the symbols K_{SG}, K_{HG}, S_G, H_G and D_G respectively.

Table 4.3: Generation dispatch for solar power plant

No. of Case	Year	Case definition	Demand for load (MW)	Load demand (pu)
1	2023 (7%)	K_{SG}=250(7%) =267.5MW=2.675pu, K_{HG}=230MW, S_G=225MW, H_G=100MW, D_G=100MW	150	1.5
			32	0.32
			51	0.51
2	2025 (15%)	K_{SG}=267.5(15%)=307.625MW=3.076 pu, K_{HG}= 230MW, S_G= 225MW H_G=100MW, D_G= 100MW	165	1.65
			35.2	0.35
			56.1	0.56

3	2030 (30%)	K_{SG}=307.625(30%) =399.91M=3.999 pu, K_{HG}=230MW, S_G=225MW, H_G=100MW D_G= 100 MW.	206.25	2.06
			44	0.44
			70.13	0.70
4	2035 (45%)	K_{SG}=399.91(45%) =579.86MW=5.798 pu, K_{HG}=230MW, S_G=225MW, H_G=100MW, D_G=100 MW	257.8	2.58
			55	0.55
			87.66	0.88
5.	2041 (60%)	K_{SG}=399.91(60%) = 927.776MW = 9.277pu, K_{HG}=230MW, S_G=225MW, H_G=100MW D_G= 100 MW	335.14	3.35
			71.5	0.72
			113..95	1.14

4.3 CASE STUDIES FOR COVENTIONAL POWER PLANT

4.3.1 Scenario 1 (For the year of 2025)

In the basic scenario, the load profile for a typical power plant in 2025 was considered. Table 4.2, supply profile for conventional power plant, provides the required information. The load capabilities of buses 2, 3 and 4 in this basic situation are 165MW, 35.2MW and 56.1 MW, respectively. With a 10% load demand and no solar network connectivity in bus one, Kaptai-hydropower output rose 15% more, or 264.5 MW, while the other power plants' conditions stayed the same.

4.3.2 Scenario 2 (For the year of 2030)

With a 25% load in 2030, Sikalbaha's-power output rose by 30% in scenario 2, while the plant's additional features remained same.

4.3.3 Scenario 3 (For the year of 2035)

In the third scenario for 2035, other plant output stayed unchanged, while Hathazari-power production climbed by 45% at a 25% load.

4.3.4 Scenario 4 (For the year of 2041)

Even if the other plants' circumstances were same, Dohazari's-power plant would eventually grow approximately 60%, with a load increase of 30% by 2041.

4.4 CASE STUDIES FOR SOLAR POWER PLANT

4.4.1 Scenario 1 (Base case):

At proceed, the ideal scenario for a network of four buses were introduced. It has been assumed that all transmission lines have an infinite line capacity (500) and that there is no transmission line cost. Before the trial began, the whole weight was then divided evenly among all of the buses. The generation upper bounds are set up to the maximum rating of every single unit and lower bounds are assumed with values more than half of the respective rated capacity.

In the basic case, the load profile for 2023 was considered. Figure 4.1 displays the network. The required information is provided in Table 4.3, solar-powered supply profile. In the preceding instance, buses 2, 3, and 4 have been assigned the 150 MW, 32 MW, and 51 MW load capabilities, respectively. Solar grid-penetration in bus one accounts for 267.5 MW, or 7% of total supply, while other electricity sources remain unchanged.

4.4.2 Scenario 2 (For the year of 2025)

With line limitations, this scenario approaches a somewhat more realistic state. It is anticipated that the load would have grown to 10% by 2025. There would have been a 15% expansion in the solar supply. The ability to produce solar energy increases to at least 267.5 MW and up to 307.63 MW.

4.4.3 Scenario 3 (For the year of 2030)

For plants with greater generation costs, linear programming always aims to achieve the minimal generation level. The station was capable of generating at least 307.63 MW and up to 399.91 MW of solar energy by 2030. The load would have increased by 25%, while the solar supply would have increased by 30%.

4.4.4 Scenario 4 (For the year of 2035)

At this point, the next purpose—line modification—will be approached. Transmission losses may be reduced and line limitations can be strengthened, according to research. Instead of discussing how to increase line capacity, the emphasis will be on how much more capacity should be added in order to maximize a network's overall production costs. Due to a 25% rise in demand and a 45% increase in solar power, the network's solar output increased from 399.91 MW (lowest) to 579.86 MW (highest) between 2035 and 2036.

4.4.5 Scenario 5 (For the year of 2041)

The station's solar-generating-dispatch at 2041 was 579.86 MW (minimum) and 927.78 MW (maximum), assuming a 60% increase in supply of solar and an additional 30% load.

4.5 GENERATION MIXING

Table 4.4: Generation Mixing at 4 Bus System

Case Status	Capacity of Generation (MW)
2023	K_{SG} =267.5, K_{HG}= 213.9, S_G= 209.25, H_G= 93, D_G= 93
2025	K_{SG} =307.63, K_{HG}=179.12, S_G=177.86, H_G= 79.05, D_G= 79.05
2030	K_{SG}=399.91, K_{HG}=125.38, S_G=124.50, H_G=55.34, D_G=55.34
2035	K_{SG} =579.87, K_{HG}= 68.96, S_G= 68.48, H_G= 30.43, D_G= 30.43
2041	K_{SG}=927.78, K_{HG}=27.58, S_G= 27.39, H_G=12.17, D_G= 12.17

The generating mixing of different case statuses is displayed in Table 4.4. In 2023, the solar supply rose by 7%, and the resisting plants were scaled down by an identical number to decrease upkeep expenses. To ensure price stability, the quantity of additional resources would fall by the same proportion as the amount of solar energy generated per year rose by 15% in 2025, 30% in 2030, 45% in 2035, and 60% in 2041. A graphical depiction of generations mixing with years is seen in figure 4.2.

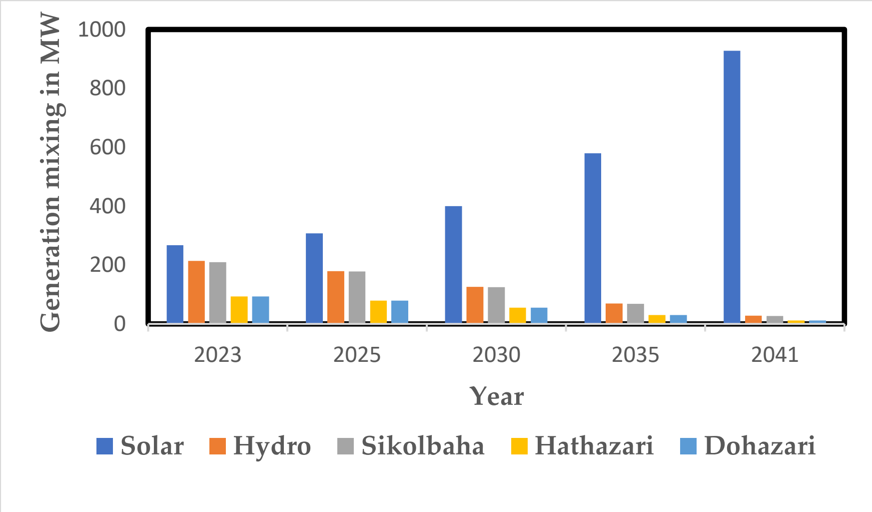

Figure 4.2: Power generation of various locations with solar

Here hydropower generation can be reduced by a number of factors, including erratic rainfall caused by climate change can disrupt hydro production. Development of hydropower projects in China, Latin America, and Europe has slowed down. Large-scale hydropower projects can have significant environmental impacts, such as displacing communities, disrupting natural river ecosystems, damaging local flora and fauna, increasing earthquake risk, causing greenhouse gas emissions. Aging facilities require investment to maintain and operate. It's possible that outdated business models and market systems don't fully account for the variety of services that hydropower offers. However, hydropower can be more widely used than most people realize.

4.6 LINE FLOW

Figure 4.3 shows a graphic representation of line flow with regard to the year. The power flow was acquired for various case statuses. Power flow was symbolized by an opposing sign, suggesting that it would flow in just the opposite direction as the required paths. However, none of the lines flow surpasses its maximum capacity.

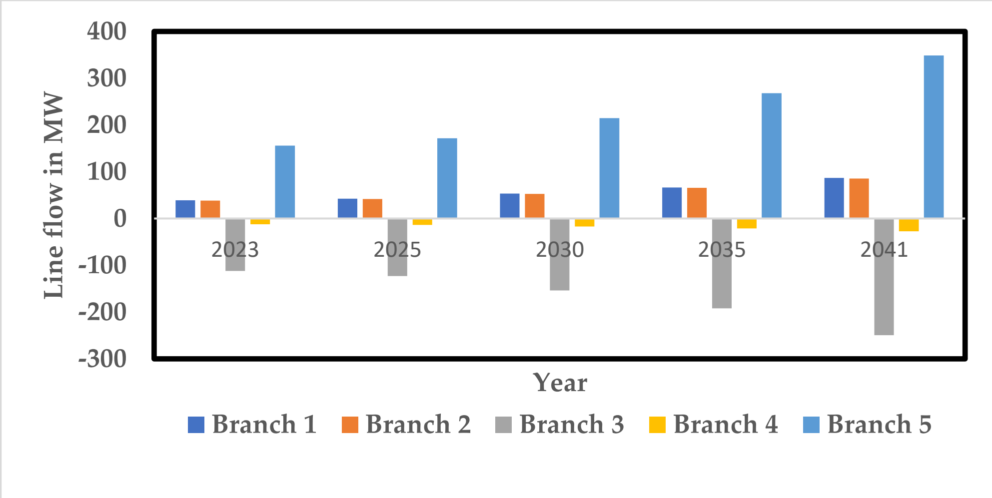

Figure 4.3: Line flow from different places using solar.

4.7 SOLAR PENETRATION IN GRID

It was concluded from the description above that the supply profile for conventional power plants has higher operating expenses than the supply profile for solar power plants. In instance 2, the operational cost differences began at $11.23/hour in 2023 and grew to 20.52% by 2025. The difference in operating expenses in scenario 3, 4, and 5 shows a discernible rising trend. In Figure 4.4, the grid's operating costs for solar and conventional power are shown visually. When compared to solar supply, conventional power plants' operational costs have increased significantly.

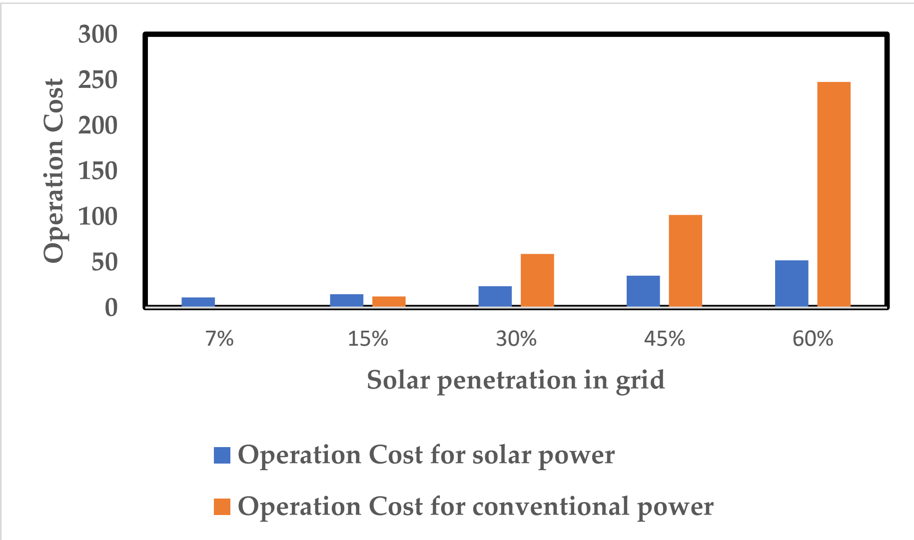

Figure 4.4: Operational costs of varying solar penetration in grid

4.7.1 PGCB network scenario at 4 bus system

Table 4.5 depicts the PGCB network scenario for a 4-bus system. This chart compares the operating costs and prices of conventional and solar power plants for the years 2023, 2025, 2030, 2035, and 2041 using MATLAB simulation. It has been noted that the running costs of solar-power-plants are progressively growing, but when compared to conventional power plants, the increase is greater. The price of solar power plants is virtually stable, but conventional power plants' prices are progressively growing, as is the difference in running costs. Based on the simulation results, the exit flag was verified to ensure that the problem was optimum.

Table 4.5: PGCB Network Scenario at 4 Bus System

Year	Operating cost (fuel) for conventional power FVAL($/hr)	Operating cost(fuel) for solar power FVAL($/hr)	Difference in operating cost	Price for conventional power λ($/MW-hr)	Price for solar power λ($/MW-hr)
2023	0	11.23	11.23%	0	14.1
2025	12.05	14.52	20.52%	4.7	14.1
2030	58.98	23.56	60.06%	53.3	14.1
2035	101.66	34.84	65.72%	53.3	14.1
2041	247.63	51.76	79.09%	178.6	14.1

4.8 MODIFIED PGCB NETWORK AT SEVEN BUS SYSTEM

In modified 7 bus system in figure. 4.5 two extra loads of 3MW and 356MW are connected to bus 5 and 6. Additional branches are linked to buses 4,5, 6, and 7. Since generator P_C produces 300MW and generator P_R produces 570MW, the generators' generation limits have been adjusted. The branches 4-5, 4-6, 5-6, and 3-7 are subject to transmission flow constraints.

The overall generating size of the networks examined in this investigation is 1545 MW, based on PGCB grid data. In comparison to the overall power generation, the total power use is 592 MW. The generator cost function in this system is quadratic. Individual producing costs for each power plant are as follows: 4.7 $/puMWhr, 14.1 $/puMWhr, 53.298 $/puMWhr, 178.6 $/puMWhr, 178.0 $/puMWhr, 14.1 $/puMWhr and 53.298 $/puMWhr. Figure 4.5 represents the projected electrical system's single line diagram, which includes 132/33 KV substations from Kaptai to Shikalbaha, Hathazari to Dohazari, Dohazari to Kaptai, Kaptai to Hathazari, Dohazari to Cox's Bazar, Dohazari to Matarbari, Cox's Bazar to Matarbari, and Hathazari to Raozan. Shikalbaha-Hathazari is a 230/132 KV substation.

A seven-bus system is included in the southern testing region of the PGCB grid inside network two. The mechanism is made from with power plants, loads and electrical cables in order connected by seven PGCB bus lines. The corresponding bus numbers 2, 3, 4, 5, and 6 are linked to the network loads. Each of their different buses is equipped with seven generators.

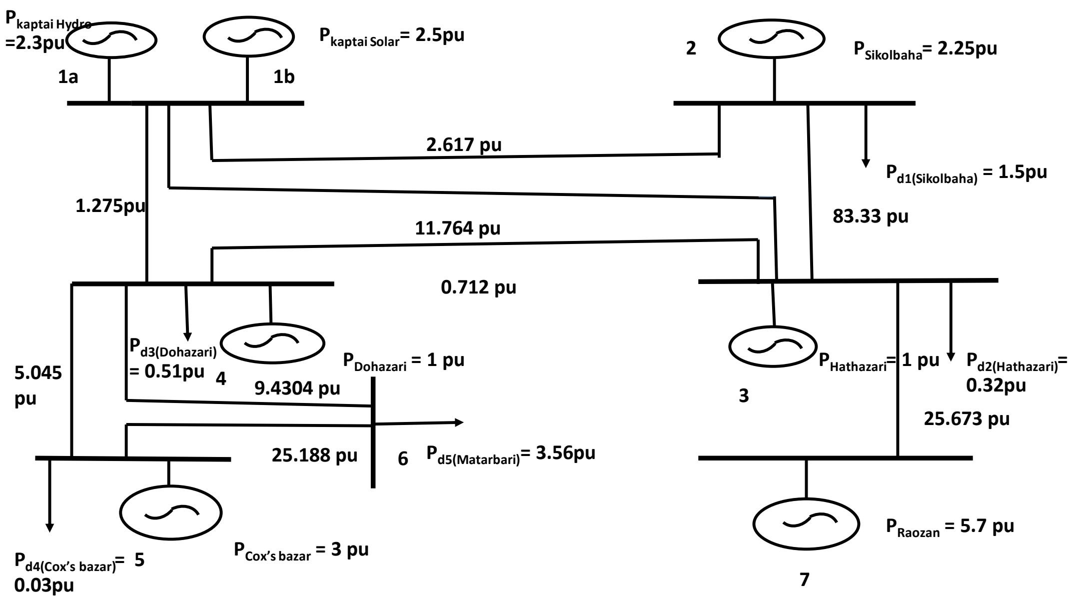

Figure 4.5: PGCB Network of Modified 7 Bus System

4.8.1 Assumptions and considerations at seven bus system

4.8.1.1 Generation profile for conventional power plant:

Table 4.6 shows that the operational cost measurement for conventional power is included in the supply profile. The symbols K_{SG}, K_{HG}, S_G, H_G, D_G, C_G, and R_G indicate the power generation assets of Kaptai Solar Generation of Power, Hydro Generation of Power, Sikolbaha Generation of Power, Hathazari Generation of Power, Dohazari Generation of Power, Cox's Bazar Generation of Power, and Raozan Generation of Power, respectively.

Table 4.6: Generation dispatch for conventional power plant at 7 bus system

Case No.	Year	Plant status	Load demand (MW)	Load demand (pu)
1.	2023	K_{HG}=230(7%) =246.1MW= 2.461 pu, S_G =225 MW, H_G = 100 MW, D_G= 100 MW, R_G =570MW	150	1.5
			32	0.32
			51	0.51
			3	0.03
			356	3.56
2.	2025	K_{HG}=230 MW, S_G=225(15%) =258.75MW =2.58pu, H_G = 100 MW, D_G= 100 MW, R_G =570MW	165	1.65
			35.2	0.35
			56.1	0.56
			3.3	0.03
			391.6	3.92
3.	2030	K_{HG} = 230 MW, S_G = 225MW, H_G = 100(30%) =130MW = 1.3 pu, D_G= 100 MW, R_G =570MW	206.25	2.06
			44	0.44
			70.13	0.70
			4.13	0.04
			489.5	4.88
4.	2035	K_{HG} =230 MW, S_G = 225 MW, H_G =100 MW, D_G= 100(45%) =145MW = 1.45 pu, R_G=570MW	257.8	2.58
			55	0.55
			87.66	0.88
			5.16	0.05
			611.88	6.12

			257.8	2.58
5.	2041	K_{HG} =230 MW, S_G = 225 MW, H_G =100 MW, D_G=100MW, R_G=570(60%) =912MW=9.12pu	335.14	3.35
			71.5	0.72
			113..95	1.14
			6.70	0.07
			795.44	7.95

4.8.1.2 Generation profile for solar power plant:

Table 4.7 also shows a detailed summary of the solar supply in various plant statuses. To allow for the monitoring of different plant conditions along the energy production line, the solar grid boosted its base capacity by 250 MW. Each generating plant's capacity is evaluated in order to track the energy transmission line's different operating statuses.

Table 4.7: Generation dispatch/delivers with solar penetration at 7 bus system

Case	Year	Case definition/ Plant Status	Load demand (MW)	Load demand (pu)
1.	2023	K_{SG}=250(7%) =267.5MW=2.675pu, K_{HG}=230MW, S_G=225MW, H_G=100MW, D_G=100MW, C_G=300(7%) =321MW, R_G = 570MW	150	1.5
			32	0.32
			51	0.51
			3	0.03
			356	3.56
2.	2025	K_{SG}=267.5(15%) =307.625MW=3.076pu, K_{HG}=230MW, S_G=225MW, H_G=100MW, D_G=100MW, C_G=321(15%) =369.15MW, R_G= 570MW	165	1.65
			35.2	0.35
			56.1	0.56
			3.3	0.03
			391.6	3.92
3.	2030	K_{SG}=307.625(30%) =399.91MW=3.999pu, K_{HG}=230MW, S_G=225MW, H_G=100MWD_G=100MWC_G=369.15(30%) =479.89MW, R_G = 570MW	206.25	2.06
			44	0.44
			70.13	0.70
			4.13	0.04
			489.5	4.88

4.	2035	K_{SG}=399.91(45%) =579.86MW=5.798pu, K_{HG}=230MW, S_G=225MW, H_G=100MW, D_G=100MW, C_G=479.89(45%) = 695.84MW, R_G = 570MW	257.8	2.58
			55	0.55
			87.66	0.88
			5.16	0.05
			611.88	6.12
5.	2041	K_{SG}=399.91(60%) =927.776 MW = 9.277 pu, K_{HG}=230MW, S_G=225MW, H_G=100MW, D_G=100MW, C_G=695.84(60%) = 1113.34MW, R_G= 570MW	335.14	3.35
			71.5	0.72
			113.95	1.14
			6.70	0.08
			795.44	7.95

4.9 CASE STUDIES FOR CONVENTIONAL POWER PLANT OF MODIFIED SEVEN BUS SYSTEM

4.9.1 Scenario 1 (For the year of 2023)

In the basic scenario, the typical electricity load profile in 2023 had been taken into account. Table 4.8, Supply Profile for Conventional Power, gives the necessary information. The load capabilities of buses 2, 3, 4, 5, and 6 in this basic situation are 150 MW, 32 MW, 51 MW, 3 MW, and 356 MW, respectively. It was determined that 7% of the overall supply for conventional power grid penetration in bus one was provided by the 246.1 MW of hydropower produced by Kaptai, while the other power plant supply quantities remained constant.

4.9.2 Scenario 2 (For the year of 2025)

In scenario 2, Sikalbaha's generation of electricity increased by 15% in 2025 with a 10% load. All other features of the plant remained same.

4.9.3 Scenario 3 (For the year of 2030)

In the third simulation for 2030, other plant output remained constant but Hathazari power production increased by 30% at a 25% load.

4.9.4 Scenario 4 (For the year of 2035)

In fourth case, despite the other plants' continued stability, Dohazari's power plant increased by 45% in 2035 with a 25% increase in demand.

4.9.5 Scenario 5 (For the year of 2041)

Ultimately, in 2041, the Raozan power plant experienced a 60% expansion and successfully handled a 30% surge in demand, totalling 912 MW, notwithstanding the condition of the other power plants.

4.10 CASE STUDIES FOR SOLAR POWER PLANT OF MODIFIED SEVEN BUS SYSTEM

4.10.1 Scenario 1 (Base case)

Similarly, all transmission lines in network 2 had an unlimited line capacity of 500 and no transmission line charge. Then, distribute the total load evenly across each bus and begin the model. Each plant's rated capacity serves as the upper constraint for generation, whereas values more than half of each plant's rated capacity were assumed for the lower bounds.

In the basic case, consideration was given to the load profile for 2023. One might see that in figure 4.5. Table 4.7, Supply Profile with solar Power, contained the necessary details. The load capacity of buses 2, 3, 4,5, and 6 in this basic scenario are 150 MW, 32 MW, 51 MW, 3 MW, and 356 MW, respectively. Bus 1's & bus 5’s solar grid penetration was 7% of the overall supply, which includes 321 MW from Cox's Bazar and 267.5 MW from Kaptai solar output. The supply quantities from the other power plants keep the same.

4.10.2 Scenario 2 (For the year of 2025)

This instance approaches a somewhat more realistic scenario with line limits. This is the total of the costs for a certain transmission line. To get the best optimization outcomes, the values of these line charges might be changed. It was anticipated that the load will have increased to 10% by 2025. There would have been a 15% increase in the solar supply. Solar power in Cox's Bazar has climbed from 321 MW (minimum) to 369 MW, while Kaptai has increased from 267.5 MW (minimum) to 307.63 MW.

4.10.3 Scenario 3 (For the year of 2030)

When used plants with greater generation cost, linear programming always tried to get the least generation level. By 2030, the station had been able to generate up to 399. 91 MW of solar power from Kaptai and 479 MW of solar power from cox's bazar, with a minimum of 367 MW and a maximum of 479 MW. While the load had gone up by 25%, the solar supply had expanded by 30%.

4.10.4 Scenario 4 (For the year of 2035)

I would now go on to the next goal, which was line alteration. Empirical studied indicate that it was feasible to enhance transmission losses and optimize line limitations. Instead of discussing how to expand line capacity, focus on identifying how much extra capacity was required to obtain the best cost for the network's overall production. Due to a 25% rise in demand and a 45% increase in solar supply, the Kaptai station's light-generating capability would expand from 399.91 MW (minimum) to 579.86 MW (maximum) in 2035. Similarly, the solar production in cox's bazar would change from 479 MW (minimum) to 695 MW (maximum).

4.10.5 Scenario 5 (For the year of 2041)

Ultimately, in 2041, the station's solar-generating dispatch for Kaptai had been 579. 86 MW (minimum) to 927. 78 MW (highest), while its solar generating dispatch for cox's bazar had been 695 MW (Minimum) to 1113.34 MW (maximum), with an extra 30% of load and a 60% more solar energy.

However, boosting production capacity to satisfy the growing consumption in Bangladesh's energy sector would not alleviate the supply-demand imbalance until transmission connections are expanded.

4.11 GENERATION MIXING

Table 4.8: Generation Mixing of Modified 7 Bus System

Case Status	Generation Capacity (MW)
2023	K_{SG} =267.5, K_{HG}= 213.9, S_G= 209.25, H_G= 93, D_G= 93, C_G = 321, R_G =530.1
2025	K_{SG} =307.63, K_{HG}=179.12, S_G=177.86, H_G= 79.05, D_G= 79.05, C_G = 369.15 R_G =450.59
2030	K_{SG} =399.91, K_{HG}=125.38, S_G=124.50, H_G= 55.34, D_G=55.34, C_G = 479.89, R_G =315.41
2035	K_{SG} =579.87, K_{HG}= 68.96, S_G= 68.48, H_G= 30.43, D_G= 30.43, C_G = 695.84, R_G =173.47
2041	K_{SG}=927.78, K_{HG}=27.58, S_G= 27.39, H_G=12.17, D_G= 12.17, C_G = 1113.34, R_G = 69.39.

The generational mixing of several different situations is seen in Table 4.8. In 2023, solar supply grew by 7%, but existing supplies were reduced by the same percentage to reduce maintenance costs. Additional resources are depleted by the comparable volume to reduced costs when utilized in the form of solar energy generated yearly increases by 15% in 2025, 30% in 2030, 45% in 2035, and 60% in 2041. Figure 4.6 illustrates generations mixing with years.

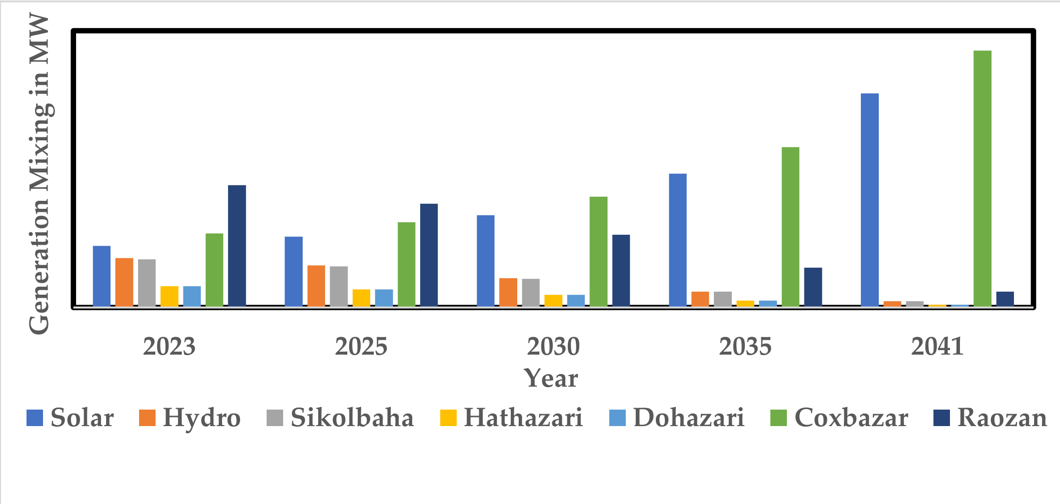

Figure 4.6: Solar power generation in different locations (modified)

4.12 LINE FLOW

Figure 4.7 provided a graphic representation of the line flowing with the year. The power flow was acquired for various case statuses. A negative symbol for power flow meant that it would flow in the opposite direction of the lines that were specified. But no line flow goes beyond its maximum amount.

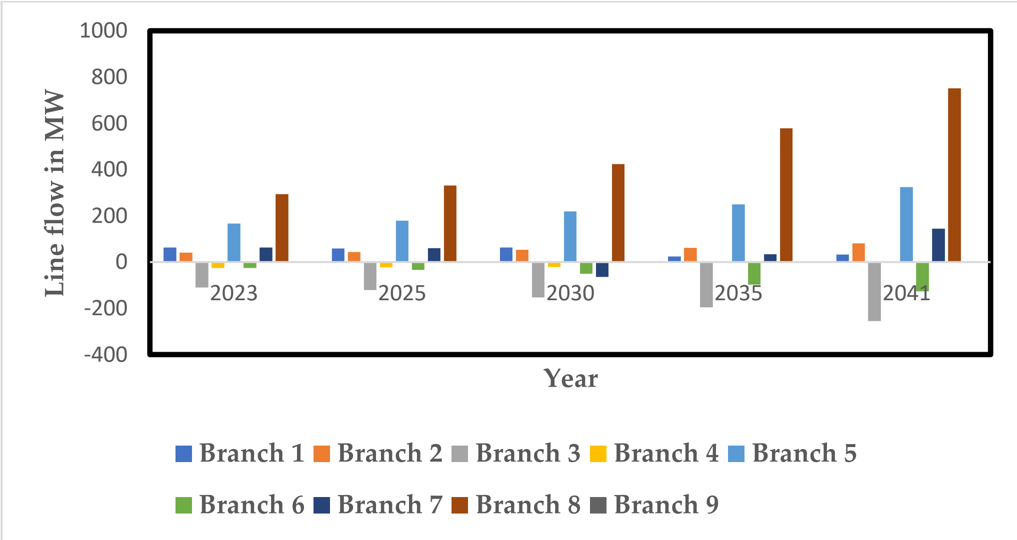

Figure 4.7: Line flow at several places using a modified 7-bus system with solar

4.13 SOLAR PENETRATION IN GRID

Based on the prior explication, it was determined that the supply profile for conventional power running costs was greater than that of solar power. Initially, in 2023, the operational cost difference was 68.45%; however, in instance 2, it had increased to 70.18% by 2025. The difference in operating expenses in scenarios 3, 4, and 5 shows a clear rising tendency. Figure 4.8 graphically depicts the operational expenses of solar and conventional electricity supplies on the grid. When compared to solar supply, a considerable increase in operational expenses for conventional electricity were observed.

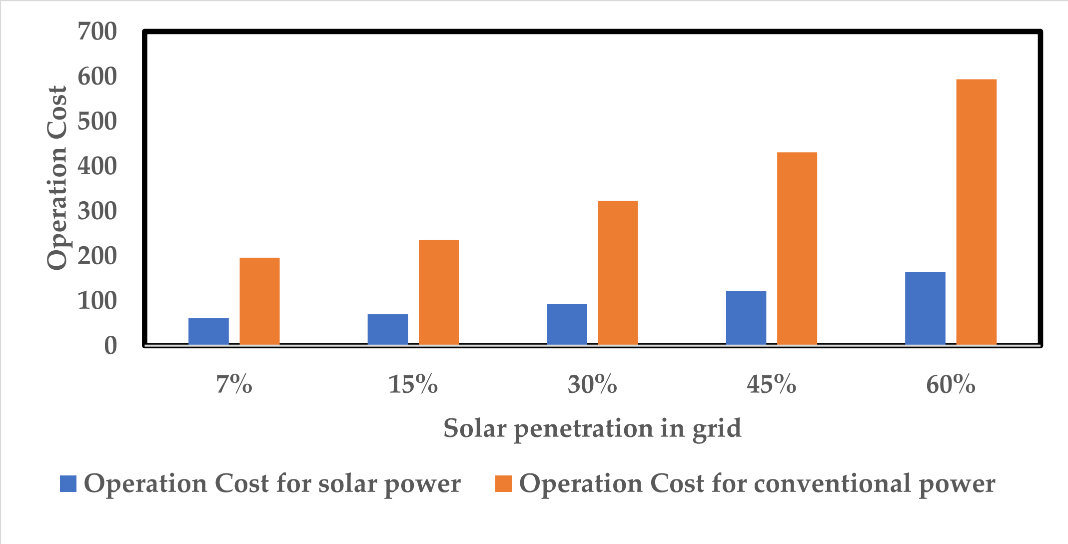

Figure 4.8: Operation cost of varying solar penetration in the grid (modified).

4.13.1 Modified PGCB network scenario at 7 bus system

A modified PGCB network scenario for a 7-bus system is shown in Table 4.9. Five scenarios, including those for the years 2023, 2025, 2030, 2035, and 2041, were assessed using MATLAB simulation to determine the running costs and prices of conventional and solar-power-plants. It has been noted that the operational expenditures of solar-power-plant are growing at a faster rate than those of typical sources of electricity. The cost of solar-power-plant is almost constant, whereas the cost of traditional power plants is continually growing due to the differential in running expenses. The exit flag has been analysed according to this simulation result to verify that its solution is optimal.

Table 4.9: Modified PGCB network scenario at 7 bus system

Year	Operating cost(fuel) for conventional power FVAL($/hr)	Operating cost(fuel) for solar power FVAL($/hr)	Difference in operating cost	Price for conventional power λ($/MW-hr)	Price for solar power λ($/MW-hr)
2023	195.89	61.79	68.45%	53.3	14.1005
2025	235.24	70.14	70.18%	53.3	14.1005
2030	322.07	93.09	71.09%	53.3	14.1005

2035	430.59	121.78	71.71%	53.3	14.1001
2041	593.31	164.79	72.22%	53.3	14.1001

4.14 COMPRISING OPERATING COST FOR CONVENTIONAL AND SOLAR POWER PLANT

Based on the prior discussion, it was discovered for both networks that the supply profile for conventional power running expenses was greater than the supply profile for solar power. Figure 4. 9 shows the network operating expenses for solar and conventional power on the grid. Deep blue and orange represent the running cost for solar and conventional power in network one, while yellow and light blue represent the similar method in network two. Initially, in 2023, the operational cost differences between the two networks were \$11. 23/hr and \$68.45/hr. The difference in operational expenses in cases 3, 4, and 5 indicates a definite upward trend. When compared to running expenses with solar supply, a considerable increase in operating cost in typical power plant were identified.

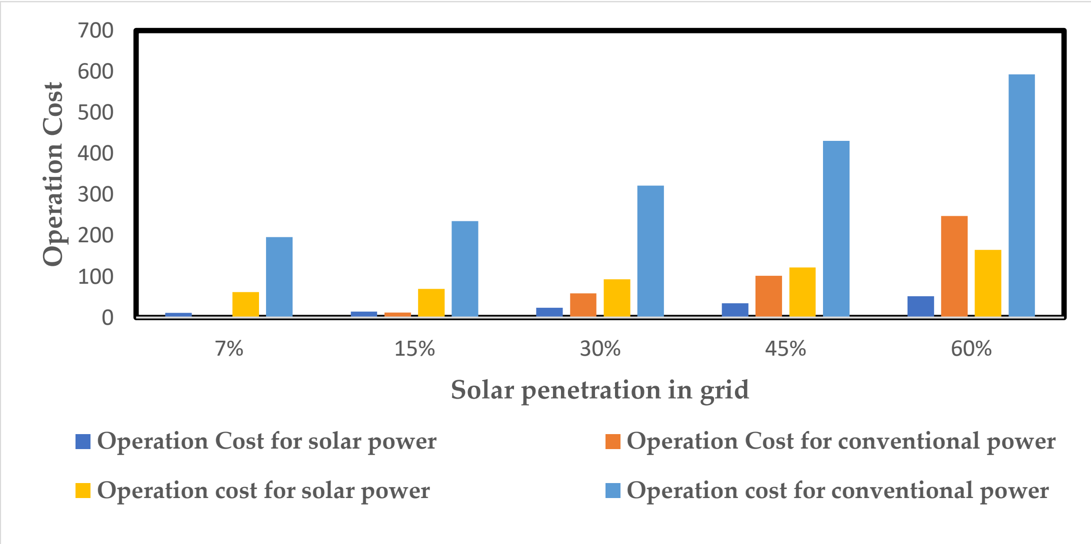

Figure 4.9: Comparative graph of operational costs of varying solar penetration in grid

4.15 OVERALL PRICE COMPARISON FOR TWO NETWORK SYSTEM

Table 4.10 shows the overall prices comparison for two networks with identical solar PV penetration. In a four-bus system, the price for solar power for the entire penetration is \$14.1/MW-hr. however the price for conventional power is frequently growing. In a modified seven-bus system, the price of solar power is frequently changing, while the price of conventional power is almost \$53.3/MW-hr.

Table 4.10: Price comparison for two network system

Different level of penetration	Price for 4 Bus System, λ ($/MW-hr)		Price for 7 Bus System, λ ($/MW-hr)	
	Solar power	Conventional power	Solar power	Conventional power
7%	14.1	0	14.1005	53.3
15%	14.1	4.7	14.1005	53.3
30%	14.1	53.3	14.1005	53.3
45%	14.1	53.3	14.1001	53.3
60%	14.1	178.6	14.1001	53.3

4.16 COMPRISING BETWEEN PROPOSED LMP & PPA SELLING PRICE

LMP and Power Purchase Agreement (PPA) are both significant strategies for pricing and controlling power, although they serve distinct purposes. PPAs can offer a long-term cash stream for the project, increasing its appeal to investors. LMP has a significant impact on electricity pricing in energy markets, influencing the profitability of power plants as well as the conditions of PPAs. The table below compares the planned LMP (λ) for solar power plants based on my study with the selling price from BPDB.

Table 4.11: Comprising proposed LMP & selling price

Bus No.	Name of Project	Proposed LMP, λ ($/MW-hr)	Selling Price from PDB ($/MW-hr)	% Difference Price
1	20MW (AC) Solar Park by Joules Power Limited (JPL).	(1.5×0.0094) = 14.1	106.9	9.28%
	50 MW Solar Power Plant in Mirsharai.	14.1	109.4	9.33%
	Cox's Bazar 200 MW (SunEdison) Solar Power Plant	14.1	13.6×0.0094= 127.84	11.37%

4.17 DISCUSSIONS

The obtained results provide input from producing units that feed multiple busses. Additionally, it displays each generating unit's price (λ) in MW/hr. For each network, 10 scenarios in total were examined. The ideal circumstance was taken into consideration for scenario one. It was assumed that all transmission lines had infinite capacity, that there was no transmission line cost, and that the load was distributed equally across all buses. Based on Tables 4.2 and 4.3, scenarios were executed to investigate the solar and conventional energy profiles for each case. These simulations provide me the pricing ($/MW-hr) and the operation cost ($/hr). In scenario 1 (for the year 2023) for network one, the operational cost is $11.23 per hour, and the pricing is also determined as 14.1$/MW-hr. Under scenario 2, at the same pricing as in example 1, the operational cost increases to 14.52/hour in 2025. Similar to scenario 3, 4, and 5, the prices are 14.1$/MW-hr, 14.1$/MW-hr, and 14.1$/MW-hr respectively, even though the operating expenses for the years 2030, 2035, and 2041 are 23.55 $/hr, 34.84 $/hr, and 51.76 $/hr. Table 4.2 indicates that an operating cost calculation for traditional electrical power is included in the supply profile. In these circumstances, solar electricity costs less than Kaptai-hydro power, Sikolbaha , Hathazari and Dohazari power generation, which are $12.05/hr, $58.98/hr, $101.66/hr, and $247.63/hr, respectively. The costs are also $4.7/MW-hr, $53.3/MW-hr, and $178.6/MW-hr.

Similar figures apply to network two: in example 1 (for the year 2023), the hourly operational cost is $61.79/hr, and the pricing is also 14.1005/MW-hr. Under scenario 2, at the same pricing as in scenario 1, the operational cost increases to 70.14$/hr in 2025. Similar to conditions 3, 4, and 5, the prices are 14.1005$/MW-hr, 14.1001$/MW-hr, and 14.1001$/MW-hr, respectively, even though the operating expenses regarding 2030, 2035, and 2041 are 93.09$/hr, 121.78$/hr, and 164.79$/hr. Table 4.6 shows that the supply profile includes an analysis of the operational cost for conventional electrical power. In these instances, the operating costs of the power generation plants—Kapai Hydro, Sikolbaha, Hathazari, Dohazari, Cox's Bazar, and Raozan—are higher than those of the supply scenario using solar power, at \$195.89/hr, \$235.24/hr, \$322.07/hr, \$430.59/hr, and \$593.31/hr, respectively. The price is overall 53.3 \$/MW-hr for all scenario.

Based on the above explanation, a notable reduction in operation costs was seen. The average operating cost and selling price of electricity for network one over time were 27.18 (\$/hr) and 14.1 (\$/MW-hr), but for conventional power they were 84.06 (\$/hr) and 57.98 (\$/MW-hr). For network two, these values are 102.32 (\$/hr) and 14.1 (\$/MW-hr) for solar whereas they are 355.42 (\$/hr) and 53.3(\$/MW-hr) for conventional power.

Chapter 5

5 Conclusions & Recommendations

In this chapter, I have given a final overview of my thesis (section 5.1), my contribution, and my expectations (section 5.2). Also, I have provided the limitation of this study and future scope for further improvisation (section 5.3). Section 5.4 presents the recommendation for further study of my research.

5.1 GENERAL

For those who create and operate power systems, OPF is a significant concern. For the purpose of enhancing a certain goal function such as system loss, total generation cost or bus voltage deviation, OPF's main objective is to find new methods for optimizing a given power system network while abiding by system protection, equipment operating limits and load flow equations. By altering system of power management parameters, the OPF problem aims to satisfy limitations on the units' operations and the system while fulfilling the necessary demand at the lowest feasible production cost. A nonlinear programming problem known as "optimal power flow" is often utilized to locate the bus voltage, best generator and transformer tap settings for the power system with the preset goal of lowering the overall cost of production. To guarantee the safety of any electrical system, the entire network has to be able to sustain the absence of one or more transformers, transmission lines or generators; these outage or loss occurrences are sometimes referred to as likely or credible contingencies. Optimal load flow analysis may be used to manage these eventualities rather well. The OPF issue is a large-scale, static, fluctuating, and nonconvex problem in optimization involving control variables that are both continuous and discontinuous in its most generic formulation.

5.2 KEY FINDINGS

- The KKT optimality conditions were followed in the development and resolution of the OPF problem. The optimal energy mixing, line flow, operating cost, and pricing have been developed throughout numerous time periods. It was investigated how rising solar PV energy will affect operational costs.
- Five possible situations were examined. The modelling results were compared, and it was revealed that installing solar PV significantly reduced operating expenses. However, the price did not change significantly.
- Even with a 60% increase in demand, operation costs were predicted to shift drastically by 2041, at 79.09% for network one and 80.12% for network two. Solar PV alone will produce 927.776 MW and 1113.34 MW by 2041 to meet the growing demand.

5.3 LIMITATION OF THE STUDY

- Determining operating costs is crucial for power system management and design. It assists in figuring out the best way for power network systems to function when subject to limitations like active and reactive power restrictions, transmission network temperature limits and load loss limits. This is especially important when combining sources of energy that are renewable, like the sun and the wind.
- In order to get network information regarding generation and line capacity, it is also crucial and refined to conduct OPF in a currently operational system of transmission or a newly established communication network. It is important to identify the precise network nodes at which the network's capacity may be expanded to accommodate future increases in demand while maintaining the lowest possible cost of energy generation.

- Several socioeconomic variables, including industry, population expansion, technological advancement, urbanization, and other social activities, all have a significant contribution to rising energy use. A comprehensive grasp of how energy demand impacts the power grid is necessary for the efficient layout and functionality of a power system network with regard to accessible energy production and distribution line capacity.
- The investigation's main weakness is the absence of systematic plant data and feasibility studies.

5.4 RECOMMENDATION FOR FURTHER STUDY

This research could be taken to a new level in future, as discussed below:

- To transition to cleaner and more ecologically friendly energy conditions, future planning and execution are required.
- In addition to traditional solar and hydropower, the nation has enormous potential for renewable energy. When adding energy, these sectors must be taken into account.
- As a result, it is possible to guarantee both the affordability of electricity and a better environment for sustainable growth.

A summary of the work's efficiency has been provided in this chapter. A summary of the thesis's major objectives is provided in section 5.2. Increasing solar PV for operational cost measurement was less expensive than any other case studied during analysis. The thesis has several limits, which are addressed in section 5.3. Several subjects for further research have been proposed in the latter section of this chapter. Lastly, this thesis will help researchers and governments in Bangladesh in promoting renewable energy sources and developing a smart grid.

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Appendices

Appendix A: MATLAB coding for supply profile with solar

```
%Load is system load plus losses
Load=2.33;
%Build objective function vector.
c=[4.7 14.1 53.3 178.6 178.6 0 0 0 0 0 0 0 0 0]';
%Build Aeq matrix for equality constraints.
Aeq=[0 0 0 0 0 -1 0 0 0 0 1.275 0 0 -1.275;
0 0 0 0 0 0 -1 0 0 0 2.617 -2.617 0 0;
0 0 0 0 0 0 0 -1 0 0 0 83.33 -83.33 0;
0 0 0 0 0 0 0 0 -1 0 0 0 -0.712 0.712;
0 0 0 0 0 0 0 0 0 -1 11.76 0 -11.76 0;
-1 -1 0 0 0 0 0 0 0 0 15.656 -2.617 -11.764 -1.275
0 0 -1 0 0 0 0 0 0 0 -2.617 85.947 -83.33 0;
0 0 0 -1 0 0 0 0 0 0 -11.764 -83.33 95.806 -0.712;
0 0 0 0 -1 0 0 0 0 0 -1.275 0 -0.712 1.987;];
A=[];b=[];
%Build right-hand side of equality constraint.
beq=zeros(9,1);
beq(7)=-3.35;
beq(8)=-0.715;
beq(9)=-1.1395;
%Build upper and lower bounds on decision variables.
%LB=[0 .035 .525 .25 .49 -500 -500 -500 -500 -500 -pi -pi -pi -pi]';
LB=[0 0 0 0 0 -500 -500 -500 -500 -500 -pi -pi -pi -pi]';
UB=[2.3 9.37 2.25 1 1 500 500 500 500 500 pi pi pi pi]';
[X,FVAL,EXITFLAG,OUTPUT,LAMBDA]=linprog(c,A,b,Aeq,beq,LB,UB)
LAMBDA.eqlin
```

Appendix B: MATLAB coding for supply profile without solar

```
%Load is system load plus losses
Load=2.33;
%Build objective function vector.
c=[4.7 0 53.3 178.6 178.6 0 0 0 0 0 0 0 0 0]';
%Build Aeq matrix for equality constraints.
Aeq=[0 0 0 0 0 -1 0 0 0 0 1.275 0 0 -1.275;
0 0 0 0 0 0 -1 0 0 0 2.617 -2.617 0 0;
0 0 0 0 0 0 0 -1 0 0 0 83.33 -83.33 0;
0 0 0 0 0 0 0 0 -1 0 0 0 -0.712 0.712;
0 0 0 0 0 0 0 0 0 -1 11.76 0 -11.76 0;
-1 -1 0 0 0 0 0 0 0 0 15.656 -2.617 -11.764 -1.275
0 0 -1 0 0 0 0 0 0 0 -2.617 85.947 -83.33 0;
0 0 0 -1 0 0 0 0 0 0 -11.764 -83.33 95.806 -0.712;
0 0 0 0 -1 0 0 0 0 0 -1.275 0 -0.712 1.987;];
A=[];b=[];
%Build right-hand side of equality constraint.
beq=zeros(9,1);
beq(7)=-3.35;
beq(8)=-0.715;
beq(9)=-1.1395;
%Build upper and lower bounds on decision variables.
%LB=[0 .035 .525 .25 .49 -500 -500 -500 -500 -500 -pi -pi -pi -pi]';
LB=[0 0 0 0 0 -500 -500 -500 -500 -500 -pi -pi -pi -pi]';
UB=[2.3 0 2.25 1 1.6 500 500 500 500 500 pi pi pi pi]';
[X,FVAL,EXITFLAG,OUTPUT,LAMBDA]=linprog(c,A,b,Aeq,beq,LB,UB)
LAMBDA.eqlin
```

Appendix C: MATLAB coding for supply profile with solar

```
%Load is system load plus losses
Load=2.1787;
%Build objective function vector.
c= [4.7 14.1 53.3 178.6 178.6 14.1 53.3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]';
%Build Aeq matrix for equality constraints.
Aeq= [0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 1.275 0 0 -1.275 0 0 0;
0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 2.617 -2.617 0 0 0 0 0;
0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 83.33 -83.33 0 0 0 0;
0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 -0.712 0.712 0 0 0;
0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 11.764 0 -11.764 0 0 0 0;
0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 5.045 -5.045 0 0;
0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 9.4304 0 -9.4304 0;
0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 25.188 -25.188 0;
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 25.673 0 0 0 -25.673;
-1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 15.656 -2.617 -11.764 -1.275 0 0 0;
0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 -2.617 85.947 -83.33 0 0 0 0;
0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 -11.764 -83.33 121.479 -0.712 0 0 -25.673;
0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 -1.275 0 -0.712 16.46 -5.045 -9.430 0;
0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 -5.045 30.233 -25.188 0;
0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 -9.43 -25.188 34.6184 0;
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -25.673 0 0 0 25.673;];
A= []; b= [];
%Build right-hand side of equality constraint.
beq=zeros (16,1);
beq(11)= -3.35;
beq(12)= -0.715;
beq(13)= -1.1395;
beq(14)= -0.06703;
beq(15)= -7.9543;
%Build upper and lower bounds on decision variables.
%LB= [0 .035 .525 .25 .49 -500 -500 -500 -500 -500 -pi -pi -pi -pi]';
LB= [0 0 0 0 0 0 0 -500 -500 -500 -500 -500 -500 -500 -500 -500 -pi -pi -pi -pi -
pi -pi -pi]';
UB= [2.3 9.277 2.25 1 1 11.13 5.7 500 500 500 500 500 500 500 500 500 pi pi pi
pi pi pi pi]';
[X, FVAL, EXITFLAG, OUTPUT,LAMBDA]=linprog(c,A,b,Aeq,beq,LB,UB)
LAMBDA.eqlin
```

Appendix D: MATLAB coding for supply profile without solar

```
%Load is system load plus losses
Load=2.1787;
%Build objective function vector.
c= [4.7 0 53.3 178.6 178.6 0 53.3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]';
%Build Aeq matrix for equality constraints.
Aeq= [0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 1.275 0 0 -1.275 0 0 0;
0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 2.617 -2.617 0 0 0 0 0;
0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 83.33 -83.33 0 0 0 0;
0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 -0.712 0.712 0 0 0;
0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 11.764 0 -11.764 0 0 0 0;
0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 5.045 -5.045 0 0;
0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 9.4304 0 -9.4304 0;
0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 25.188 -25.188 0;
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 25.673 0 0 0 -25.673;
-1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 15.656 -2.617 -11.764 -1.275 0 0 0;
0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 -2.617 85.947 -83.33 0 0 0 0;
0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 -11.764 -83.33 121.479 -0.712 0 0 -25.673;
0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 -1.275 0 -0.712 16.46 -5.045 -9.430 0;
0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 -5.045 30.233 -25.188 0;
0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 -9.43 -25.188 34.6184 0;
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -25.673 0 0 0 25.673;];
A= []; b= [];
%Build right-hand side of equality constraint.
beq=zeros (16,1);
beq(11)=-3.35;
beq(12)=-0.715;
beq(13)=-1.1395;
beq(14)= -0.06703;
beq(15)= -7.9543;
%Build upper and lower bounds on decision variables.
%LB= [0 .035 .525 .25 .49 -500 -500 -500 -500 -500 -pi -pi -pi -pi]';
LB= [0 0 0 0 0 0 0 -500 -500 -500 -500 -500 -500 -500 -500 -500 -pi -pi -pi -pi -
pi -pi -pi]';
UB= [2.3 0 2.25 1 1 0 9.12 500 500 500 500 500 500 500 500 500 pi pi pi pi pi
pi pi]';
[X,FVAL,EXITFLAG,OUTPUT,LAMBDA]=linprog(c,A,b,Aeq,beq,LB,UB)
LAMBDA.eqlin
```

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Operation Cost Minimization Planning in South Eastern PGCB Grid with Increasing Solar PV Energy

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***Abstract*— Cost-effective electric power system operation is pivotal for cheaper energy delivery. The purpose of this paper is to investigate the technoeconomic impact of renewable energy penetration in the south-eastern PGCB network. An optimal power flow model is implemented in a four-bus test power system grid. A Lambda-iteration method is utilized to assess the optimum power flow model for the southern zone of the PGCB (Power Grid Company of Bangladesh) system. The bus one of the test systems is considered for renewable energy injection. Conventional power plants supply the load with five different kinds of fuel sources. These plants are connected by five transmission lines. Several credible case studies have been simulated to investigate the operation cost and selling price over time being. The optimal power delivery, operation cost, and selling price were recorded without and with solar energy. A significant amount of operation cost was reduced in 2041, which is accounted to be 17.74% even though considering a 60% increase in load.**

Keywords*— *Power system, Operation cost, Optimal power flow, Transmission line, Lagrange Multiplier.

I. Introduction

The global demand for electricity is rising due to rapid economic development. One of the most crucial elements for development is the steady flow of electricity. The availability of an affordable, reliable, and sustainable supply of electricity will be crucial for future economic growth. The leadership of Bangladesh has formulated many energy-system strategic plans with the aim of enhancing power generation capacity to satisfy projected future demand [1] [2] [3]. The most recent report states that even though the installed capacity currently in place exceeds the current demand, load shedding has been occurring regularly. Currently, there are more than 22,031 MW of total generation capacity, which is primarily made up of hydro, gas, furnace oil, diesel, coal, and HFO [2]. The system is adding a sizable amount of renewable solar energy each year. Additionally, the neighbouring nation supplies electricity [4]. Significant study has been done on the grid-wise operation of power systems to discover the most cost-effective way to transfer electricity from a variety of producing plants [5] [6]. A cost-minimizing power system model having wind energy along with centralized solar PV generation is proposed by the authors in [7]. In addition, writers examined market clearing as a solution for renewable-integrated power networks with the goal of minimizing operating costs while maintaining a balance between supply and load demand. Furthermore, a bi-level optimization strategy utilizing the optimal power flow technique was provided by the authors in [8] and [9], who took into account several entities that are present in the current market framework. Additionally, by locating the exact nodes in the network, the authors in [10] have enhanced the capacity of electrical transmission.

Based on data from five electrical zones in Bangladesh, the reference in [11] has designed a generating system with the lowest possible generation costs. The Lagrangian approach is used to tackle the problem of using the OPF to create the power system. However, they didn't consider solar energy integration in the grid.

The goal of this study is to create a simulation model of the South Eastern (PGCB) grid with varying degrees of solar photovoltaic (PV) generation and to find the most economical way to distribute electricity from various power plants. Optimal power flow is crucial to the development of the next-generation grid and to understanding the ideal state of the existing power grid. The energy price is calculated at full efficiency. This study does not include reactive power flow related to the variation of AC optimal power flow. Taking into account these aforementioned factors, an extensive representation of the power grid that sustains the southern part of Bangladesh is developed. This model encompasses four buses, five generating units, and five transmission lines [12].

II. Methodology

Researchers, engineers, and the electrical industry often use the Optimal Power Flow (OPF) approach to cut down on expenses associated with running generating units. Operating costs of generators are shown using fuel cost, heat rate, input-output, and incremental cost curves [3].

The optimum power flow approach is used as a framework for economic dispatch. The OPF approach eliminates the problems related to traditional load dispatch that were addressed in the introduction. The generator constraints are already taken into account as inequality constraints, so the line flow constraints are brought into mind as inequality constraints likewise. The next step is making the OPF linear. For the sake of simplicity, it is presumed that each generator delivers just one pricing offer. Each unit's unique price offer multiplied by its MW of generation is used to construct the objective function [13] also known as the cost function. Let the individual price proposals be S_1, S_2, and S_3, and the resulting amounts be Pg_1, Pg_2, and Pg_3, respectively. Fig. 1 is a diagrammatic representation of the whole theory. The objective function

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