Techno-Economic Analysis and Design Optimization of Concentrated Solar Power Plants for Sustainable Energy Development in Bangladesh

By

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Declaration

I hereby declare that the work contained in this thesis has not been previously submitted to meet the requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is cited.

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(For Postgraduate Students only)

Dedication

I want to dedicate this thesis to the Almighty Allah, who is the source of life and strength of knowledge and wisdom, for his guidance, power of the mind, and protection, and for giving me a healthy life to carry out this study.

This research, which is proudly and sincerely devoted to the individuals who inspire us, is the result of innumerable and costly sacrifices. I sincerely dedicate this work to my beloved father Md. Nurul Islam Bhuiyan and my mother Shahanaz Begum, who have been my sources of strength and inspiration during this research. I completed this thesis because of their continuous financial, emotional, spiritual, and moral support. This thesis is also dedicated to my teachers, who direct me on the right life path. From parents, relatives and guardians to classmates and circle of friends, who extended their help with problems while doing this work. Thanks for making me see this adventure through to the end.

List of Publications

Conference

- Publication 1: M.S. Miah, S. Sarker, **A. B. M. N. Bhuiyan**, N. Mohammad, R. Akter and M.I. Hossain**,** " Feasibility and Optimization of Hybrid Renewable Energy Systems for Off-Grid Electrification in Durgapur Village, Barishal, Bangladesh," *2025 International Conference on Electrical, Computer and Communication Engineering (ECCE),* 13-15 February 2025, CUET, Chattogram-4349, Bangladesh. [Accepted & Presented]
- Publication 2: M. Ray, **N. Mohammad**, M.F. Kabir, **A. B. M. N. Bhuiyan**, R. Akter, R. Uddin and M. Raihan**,** " Assessing the Viability and Economic Impact of Grid-Connected Photovoltaic Systems Across Diverse Locations in Bangladesh," *2025 International Conference on Electrical, Computer and Communication Engineering (ECCE),* 13-15 February 2025, CUET, Chattogram-4349, Bangladesh. [Accepted & Presented]
- Publication 3: R. Rafi**, A. B. M. N. Bhuiyan,** N. Mohammad**,** R. Akter, M. M. Gani and S. Ghosh, "Analyzing the Efficacy of Differential Relay Systems for Transformer Protection Under Different Internal Faults," *2023 10th IEEE International Conference on Power Systems (ICPS),* Cox's Bazar, Bangladesh, 2023, pp. 1-5, DOI: 10.1109/ICPS60393.2023.10428690.
- Publication 4: T. Akand, **A. B. M. N. Bhuiyan**, R. Akter, M.I. Hossain, N. Mohammad and M.A. Hossain**,** "Renewable Energy Generation for Cold Country Using TEG in Fire-Place," *2024 3rd International Conference on Advancement in Electrical and Electronic Engineering*

(ICAEEE), Gazipur, Bangladesh, 2024, pp. 1-6, DOI: 10.1109/ICAEEE62219.2024.10561723.

- Publication 5: T. Akand, **A. B. M. N. Bhuiyan**, N. Mohammad, R. Akter and M.I. Hossain**,** " Angle Optimization For Energy Harvest From Raindrop Kinetic Energy Using PVDF Thin Film Piezoelectric Transducer," *2025 International Conference on Electrical, Computer and Communication Engineering (ECCE),* 13-15 February 2025, CUET, Chattogram-4349, Bangladesh. [Accepted & Presented]
- Publication 6: R. Hossain, **N. Mohammad**, M.I. Hossain, **A. B. M. N. Bhuiyan** and S.F. Suchi**,** "Development of Integrated Sensors and IoT Solutions for Modern Agriculture Practices," *2025 International Conference on Electrical, Computer and Communication Engineering (ECCE),* 13-15 February 2025, CUET, Chattogram-4349, Bangladesh. [Accepted & Presented]

Approval by The Supervisor

This is to certify that ***A. B. M. Noushad Bhuiyan*** has carried out this work under my supervision, and he has fulfilled the relevant Academic Ordinance of the Chittagong University of Engineering and Technology, so that he is qualified to submit the following thesis in an application for the degree of MASTER of SCIENCE in Electrical & Electronic Engineering.

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Alhamdulillah! In the beginning, Almighty Allah gave me the patience to complete the thesis successfully. It truly gives me great pleasure to convey my sincere appreciation and gratitude to my mentor, philosopher, and supervisor, *Dr. Nur Mohammad*, Professor of the Department of Electrical and Electronic Engineering, Chittagong University of Engineering and Technology (CUET). Above all, his dedication and keen interest in his overwhelming attitude towards helping his students had been solely and mainly responsible for completing my work. His timely advice, meticulous scrutiny, scholarly advice and scientific approach have helped me to a very great extent to accomplish this thesis.

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Abstract

This study assesses the feasibility of Concentrated Solar Power (CSP) in Bangladesh, evaluating four CSP technologies—Solar Tower (ST), Solar Dish (SD), Parabolic Trough Collector (PTC), and Linear Fresnel Reflector (LFR)—across the three highest Direct Normal Irradiance (DNI) regions: Cox's Bazar, Bandarban, and Chapai Nawabganj. Key performance indicators, including capacity factor, annual energy generation, Levelized Cost of Electricity (LCOE), and Net Present Value (NPV), were analyzed. Among the technologies, PTC showed the best performance, with a 67.5% capacity factor, 889.26 GWh energy generation, and the lowest LCOE (8.98 ¢/kWh) in Chapai Nawabganj. ST had the highest energy yield (472.09 GWh) in Cox's Bazar with a competitive LCOE (7.49 ¢/kWh). LFR demonstrated strong economic feasibility, achieving an NPV of $382.24 million and a 51.9% capacity factor. SD, while less efficient, was suitable for decentralized applications. A comparative study was conducted against existing CSP projects, including Noor II and Noor III (Morocco) and Dhursar (India), revealing that the designed plants offer higher capacity factors and lower LCOE relative to global benchmarks. The study utilized System Advisor Model (SAM) for performance optimization, considering solar field design and thermal storage integration. Key challenges include high capital costs and land constraints. Recommendations include hybrid CSP-PV systems and optimized heliostat layouts to enhance feasibility. The findings provide valuable insights for policymakers and investors, laying the groundwork for future CSP development in Bangladesh's transition toward sustainable energy.

বিমূর্ত

এই গবেষণায় বাংলাদেশের জন্য কেন্দ্রীভূত সৌরশক্তি (CSP) প্রযুক্তির সম্ভাব্যতা মূল্যায়ন করা হয়েছে, যেখানে চারটি CSP প্রযুক্তি—সোলার টাওয়ার (ST), সোলার ডিশ (SD), প্যারাবোলিক ট্রাফ কালেক্টর (PTC), এবং লিনিয়ার ফ্রেনেল রিফ্লেক্টর (LFR)—পরীক্ষা করা হয়েছে দেশের তিনটি সর্বোচ্চ সরাসরি স্বাভাবিক বিকিরণ (DNI) সম্পন্ন অঞ্চল: কক্সবাজার, বান্দরবান এবং চাঁপাইনবাবগঞ্জ। কর্মক্ষমতা পরিমাপের মূল সূচক যেমন ক্ষমতা ফ্যাক্টর, বার্ষিক বিদ্যুৎ উৎপাদন, লেভেলাইজড কস্ট অফ ইলেকট্রিসিটি (LCOE), এবং নেট প্রেজেন্ট ভ্যালু (NPV) বিশ্লেষণ করা হয়েছে। পরীক্ষিত প্রযুক্তিগুলোর মধ্যে, PTC সর্বোচ্চ কর্মক্ষমতা প্রদর্শন করেছে, চাঁপাইনবাবগঞ্জে ৮৯৯.২৬ GWh বিদ্যুৎ উৎপাদন, ৬৭.৫% ক্ষমতা ফ্যাক্টর, এবং সর্বনিম্ন LCOE (৮.৯৮ ¢/kWh) অর্জন করেছে। ST কক্সবাজারে সর্বাধিক বিদ্যুৎ উৎপাদন (৪৭২.০৯ GWh) এবং প্রতিযোগিতামূলক LCOE (৭.৪৯ ¢/kWh) অর্জন করেছে। LFR অর্থনৈতিকভাবে লাভজনক, ৫১.৯% ক্ষমতা ফ্যাক্টর এবং সর্বোচ্চ NPV ($৩৮২.২৪ মিলিয়ন) অর্জন করেছে। SD তুলনামূলকভাবে কম কার্যকর হলেও বিকেন্দ্রীভূত বিদ্যুৎ উৎপাদনের জন্য উপযুক্ত। একটি তুলনামূলক বিশ্লেষণে দেখা গেছে যে Morocco-এর Noor II ও Noor III এবং ভারতের Dhursar CSP প্রকল্পের তুলনায় প্রস্তাবিত CSP ডিজাইনগুলোর কর্মক্ষমতা ভালো। গবেষণায় System Advisor Model (SAM) ব্যবহার করে সৌর ক্ষেত্রের নকশা ও তাপীয় সংরক্ষণ অপ্টিমাইজ করা হয়েছে। তবে, উচ্চ মূলধনী ব্যয় এবং ভূমির প্রাপ্যতা এই প্রযুক্তির প্রসারের প্রধান চ্যালেঞ্জ। ভবিষ্যৎ CSP উন্নয়নের জন্য হাইব্রিড CSP-PV সিস্টেম এবং অপ্টিমাইজড হেলিওস্ট্যাট বিন্যাসের সুপারিশ করা হয়েছে। গবেষণার ফলাফল বাংলাদেশের টেকসই জ্বালানি রূপান্তরের জন্য নীতি-নির্ধারক ও বিনিয়োগকারীদের জন্য গুরুত্বপূর্ণ দিকনির্দেশনা প্রদান করে।

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Nomenclature

Acronyms and Abbreviations	
NREL	National Renewable Energy Laboratory
PEPCO	Professional Electric Products Company
TEA	Techno Economic Assessment
IPPs	Independent Power Plants
HTF	Heat Transfer Fluid
CPPA	Central Power Purchasing Agency
DISCOs	Distribution Companies
GENCOs	Generation Companies
NSRDB	National Solar Radiation Database Battery
SCA	Solar Collector Assembly
HFO	Heavy Fuel Oil
HSD	High-Speed Diesel
PDF	Probability Density Function
CDF	Cumulative Distribution Function
SAM	System Advisor Model
SES	Stirling Energy Systems
WGA	Wilkinson, Goldberg and Associates
SAIC	Science Applications International Corporation
SBP	Schlaich Bergermann and Partner
TES	Thermal Energy Storage
SM	Solar Multiples
DNI	Direct Normal Irradiance
LCOE	Levelized Cost of Electricity
NPV	Net Present Value
IRR	Internal Rate Of Return
HSAT	Horizontal Single Axis Trackers
HTSAT	Horizontal Single Axis Trackers With Tilted Modules
VSAT	Vertical Single Axis Trackers
TSAT	Tilted Single Axis Trackers
TTDAT	Tip-Tilt Dual-Axis Trackers
AADAT	Azimuth-Altitude Dual-Axis Trackers
PSMP	Power System Master Plan
GIS	Geographic Information System
LFR	Linear Fresnel Reflector
SPT	Solar Power Tower
PTC	Parabolic Trough Collector
SD	Solar Dish
CF	Capacity Factor

Symbols

$E_{PV(AC)}$	Energy generated and injected into grid (kWh)
G	Irradiance
H_T	Total horizontal irradiance on PV array plane (Wh/m²)
I_{DC}	DC current (A)
$N_{Batt(max)}$	Maximum battery banks required
$N_{Batt(min)}$	Minimum battery banks required
$P_{PV(total)}$	Rated/installed capacity of the integrated solar PV system/plant
P_{in}	Input power
P_{load}	Load or output power (W)
P_{max}	Output maximum Power
$P_{nominal}$	Nominal power at STC
$P_{total\ def}$	Total deferrable load
T	Temperature
V_{DC}	DC or Battery voltage (nominal) (V)

Chapter 1: Introduction

This chapter provides a background study on Concentrated Solar Power (CSP) technologies, their techno-economic potential, and optimization strategies in Section 1.1. Section 1.2 describes the problem statement, highlighting the challenges in CSP deployment in Bangladesh. Section 1.3 presents the research objectives, detailing the specific aims of this study. Then, an overview of the scope of the study, including key focus areas and limitations, is provided in Section 1.4. Section 1.5 discusses the methodology overview, outlining the research approach, data sources, and analytical techniques employed. Finally, Section 1.6 explains the structure of the report, summarizing the contents of each chapter.

1.1 Background

Modern world is facing a serious crisis of energy, and therefore the need for sustainable and secure sources of energy has never been more crucial. Energy sources are generally categorized into two categories: conventional and non-conventional. The conventional energy sources of coal, natural gas, and oil have deep negative effects on the environment as well as human health. Fossil fuel burning emits toxic pollutants, including nitrogen oxides responsible for smog and sulfur dioxide responsible for acid rain. These fuels also emit greenhouse gases that cause global warming. In addition, their resources are being used up at an alarming rate. To overcome this, the attention has to be diverted to "green energy" for electricity. Green energy is comprised of clean and renewable energy resources like solar, wind, biomass, and tidal power that are sustainable and eco-friendly.

Among the renewable energy sources, wind power is suitable for producing plenty of power but requires coastal or hilly areas with high velocity winds. Biomass and tidal power are useful for small usage, but they are limited by large-scale application. Biomass power depends upon the availability of vegetation and organic waste, which might not be available everywhere. Among all the options at hand, solar power has the greatest potential to bring an end to the current power crisis without harming the environment. Solar power comes in two types: solar photovoltaic (PV) and solar thermal, or concentrated solar power (CSP) [1]. Presently, CSP technology is used to concentrate the sun's rays and generate electricity with maximum efficiency. The greatest advantage of CSP is that it can store thermal energy in such a way that electricity can be produced even during cloudy conditions or after dark. CSP plants can be coupled with combined-cycle power plants to develop hybrid systems so that there is uninterrupted and constant supply of power.

These features make concentrated solar power (CSP) one of the most attractive alternative energy options, especially in Sunbelt states. Even though a solar PV system occupies up to ten square meters of roof space, CSP occupies just three to four square meters. CSP is more efficient as well, producing around 90% of solar radiation into heat and solar PV produces 15%-20%. CSP is gaining popularity worldwide currently. A study conducted by Greenpeace International, the European Solar Thermal Electricity Association, and the Solar PACES group of the International Energy Agency estimated the CSP potential. The study concluded that CSP could supply up to 25% of the world's energy needs by 2050, with investments in the world increasing from 2 billion to 92.5 billion Euros. Countries like the USA and Spain are placing emphasis on the development of CSP. In California, efforts were planned to produce 33% of the total energy from solar by 2020 and 88% of it would come from CSP and the remaining from solar PV [3].

1.2 Problem Statement

Human reliance on energy has intensified to the point where its environmental consequences are often overlooked, leading to significant harm to the world's ecosystem. Fossil fuels have been depleted because of overuse, as well as causing global warming and a global energy crisis. That has made them understand that there is a need for alternative sources of energy for meeting the world's growing need for power. Energy sources can be divided into two major categories: conventional and renewable. Conventional energy sources, i.e., natural gas, coal, and oil, are non-renewable and have been utilized for centuries to generate power and fuel industrial development. Renewable energy sources, on the other hand, are limitless, clean, and green. They include hydro, wind, geothermal, solar, and tidal energy. Now, only a fraction of our energy comes from renewable resources, whereas most of our energy needs still depend on conventional sources [4]. Around 90-92% of our total energy needs are derived from conventional energy sources, with coal contributing the highest share at 38.4%, followed by natural gas at 33.9%, oil at 16.4%, nuclear at 9.9%, and other sources making up 0.9%. In contrast, renewable energy sources account for only about 14.7% of the total energy production. Among them, hydro power leads with 14.7%, followed by wind at 10.3%, bio & waste at 6.2%, solar at 2.5%, and geothermal at 0.2%. This distribution highlights the heavy reliance on fossil fuels while emphasizing the need for greater investment in renewable energy alternatives, as depicted in Fig. 1.1. The overuse of these resources has led to their rapid depletion. Petroleum reserves in India can last for not more than a few decades, whereas coal reserves can last for approximately a century. Resolving this energy crisis needs an international endeavor, with the government from all over the world playing a leading role. Rising energy prices are forcing world leaders to recognize the significance of research in discovering alternative sources of energy. Hopefully, this will make nations act and prevent any further harm to our world [5].

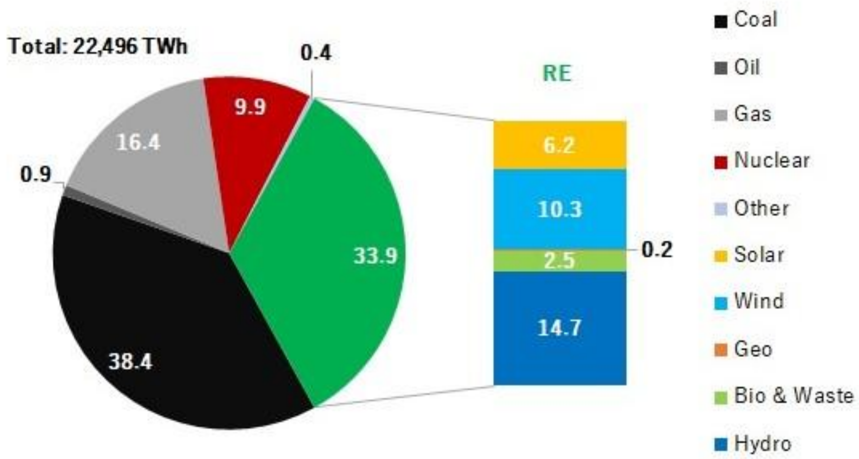

Fig. 1.1 Global Energy Source in Percentage. Reproduced with Permission from [6].

Owing to uncontrolled dependence on fossil fuels even for the next two decades, fossil fuels are subjected to depletion. It is projected that if energy consumption continued in current rate all the conventional energy sources reserve will finished within next 40-50 years [7].

In the recent decade, the generation of power has shifted quite significantly from conventional to alternative resources due to their various merits. China, the European Union, and America are major catalysts for the transformation. The energy crisis largely owes its cause to the excessive exploitation of fossil fuels and slow adaptation to alternate power sources, thereby producing an unbalanced energy composition. China, which is the world's biggest carbon dioxide polluter according to the United Nations, must take the lead in fighting global warming by coming up with effective measures to reduce emissions and comply with environmental regulations.

Currently, about 41% of all electricity comes from coal-burning power plants. Despite the enormous environmental hazards, including global warming from greenhouse gases, coal remains a prevalent source of energy, especially in developed countries like China, Australia, and certain European countries. The global leaders gathered at the 23rd International Climate Change Conference in Paris to exchange their policies and programs to achieve climate change. If we can use solar energy effectively, it itself could provide the entire world's energy requirement.

The mechanical industry uses the largest share of distributed power. Despite worldwide policies aimed at reducing the consumption of traditional energy, carbon dioxide emissions have continued to rise—from 31 billion metric tons in 2010 to 36 billion metric tons in 2020 and a forecasted 45 billion metric tons by 2040, a 46% increase.

Fig. 1.2 illustrates global carbon dioxide emissions from fossil fuels by region. The International Energy Outlook foresees that global energy consumption will increase by 56% between 2010 and 2040. Total energy consumption is expected to grow from 524 quadrillion British Thermal Units (BTUs) in 2010 to 630 quadrillion BTUs in 2020 and 820 quadrillion BTUs in 2040 [8].

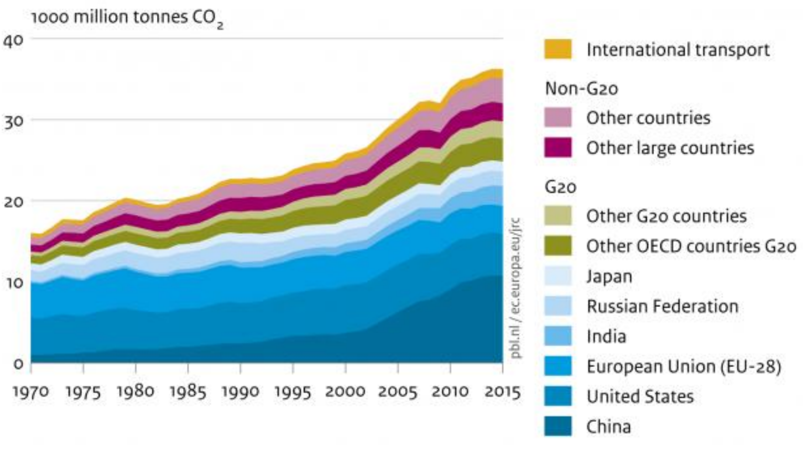

Fig. 1.2 Global Carbon Dioxide Emission Per Region from Fossil Fuel. Reproduced with Permission from [8].

The world has not yet emerged from the international energy recession of 2008-2009. Since this crisis has had long-term consequences, financial instability continues to grow. In Europe and the United States, unresolved financial issues are a major barrier to economic growth.

The United States' economic recovery has been slow, and growth has been uneven. Japan also has not recovered from a series of recessions, most recently the 2011 earthquake catastrophe. Political upheavals in Africa and Gulf states have also led to economic issues. Political upheavals as a result of the Arab Spring in Egypt, Syria, and Yemen have also impacted negatively on stability. As a result, oil prices fluctuated between $90 and $130 per barrel well into 2013.

Today, the world is progressing towards renewable power for generating electricity. This drive is due to clean, eco-friendly, and reusable forms of energy. Denmark has already achieved 140% of its electricity needs from wind power. Scotland set a ambitious goal of reaching 50% of its electricity from renewable means by 2015 and 100% by 2020 [9].

The United States Energy Information Administration (EIA) report, "International Energy Outlook 2013" indicates that renewable energy sources provide approximately 11% of global energy demand and will increase to 15% by the year 2040. Alternative sources provided 21% of the world's electricity, and this will increase to 25% by the year 2040. Nuclear power and clean energy are among the fastest-increasing sources of energy, increasing by 2.5% annually.

However, energy production is not necessarily coordinated with usage. The United States has below 3% of the world's oil reserves and only 3.5% of gas reserves. Similarly, China and Japan also heavily rely on the importation of energy. The largest gas and oil reserves exist in Gulf states and Russia but are not consumers on a large scale [10].

Such unbalanced resource allocation creates a supply-and-demand imbalance and therefore the energy crisis. To end the world's shared malady, the countries need to reconstruct their diplomatic efforts, most importantly leading players like the United States, China, and Russia that have been entangled in years of oil-driven war.

One of the major sources of environmental pollution is fossil fuels, as they lead to global warming and ozone layer depletion. Hence, there is a need to shift to renewable energy and energy-efficient systems. Table 1.1 the total reserve at the end of 2024.

Table 1.1 Total Proved Reserve of Fossil Fuels [10].

Fuel type	**Total Reserve at the End of 2024**
Oil	1726.6 thousand million barrels
Natural Gas	205.23 trillion cubic meters
Coal	15260 million tons

Renewable energy is not just ever more the best solution to the climate crisis, it is also becoming less expensive. According to the International Renewable Energy Agency (IRENA), cost can no longer be used as an excuse to take action.

There is growing evidence that among the most significant challenges of our era is global climate change. However, in the years since the world's first global binding climate agreement was signed in Kyoto in 1997, clean energy technologies have advanced a long way, states the Solar Energy Industries Association of the United States [11].

Rider University has developed a list of five criteria for evaluating any energy source, including non-renewable sources [2]:

i. Availability – For how long will the energy source last? A short-term source lasts up to 15 years, a medium-term source lasts between 15 and 50 years, and a long-term source lasts longer than 50 years.

ii. Energy Yield – How much energy is gained compared to the energy used to produce it? Rider University measures this using a net energy ratio: Energy produced ÷ Energy used during production. A higher ratio means a better energy yield.

iii. Cost – How expensive is it to develop and produce the energy? For example, nuclear energy requires advanced technology, which can make it less feasible.

iv. Environmental Effect – What effect does the energy source have on the environment? Does the damage caused by extracting, transporting, and using it outweigh the benefits it provides? Coal, for instance, poses environmental concerns.

v. Renewability – Is the energy source renewable? Is it sustainable? Rider University experts note that extracting a non-renewable resource, like oil, may not be a long-term solution.

Bangladesh is also experiencing an energy crisis like the rest of the world and can adopt common measures to reduce it. The world electricity production by fuel type till 2040 is forecast in Fig. 1.3.

Circular debt is one of the major causes of the energy crisis in Bangladesh. It happens when different government departments are responsible for paying for electricity but do not pay their bills in full. For example, the Bangladesh Power Development Board supplies electricity to other government agencies, but they do not pay in full, and the consequence is that there is an incomplete cost recovery.

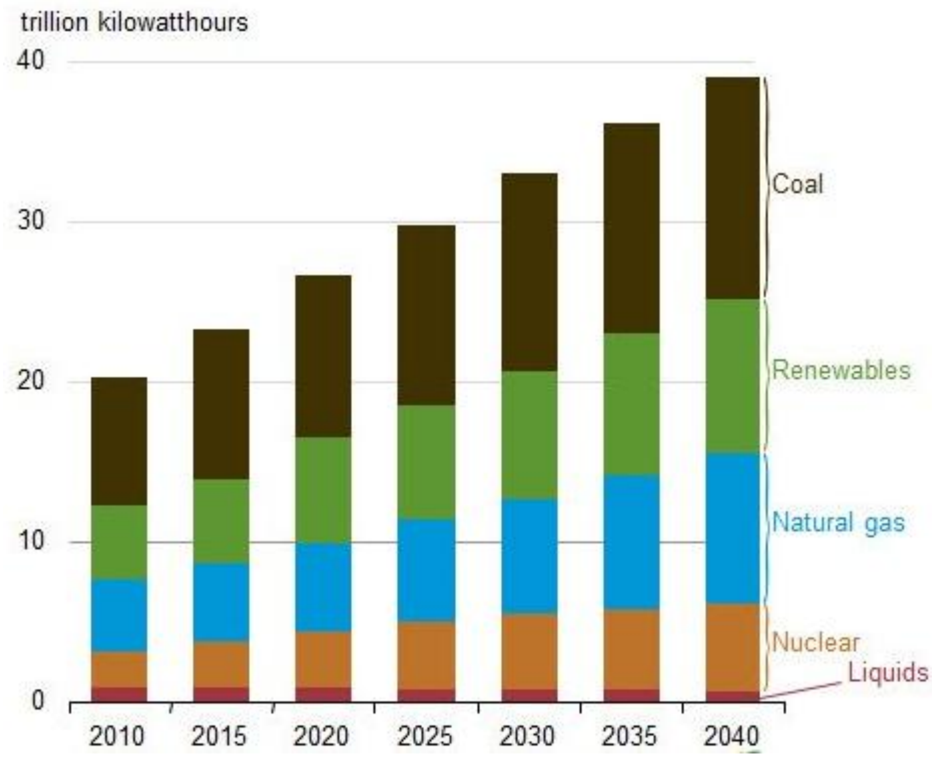

Fig. 1.3 World Net Electricity Generation by Fuel. Reproduced with Permission from [12].

As a result, the Professional Electric Products Company (PEPCO) cannot pay independent power plants (IPPs) under the Central Power Purchasing Agency (CPPA). IPPs cannot pay fuel companies for the procurement of fuel, halting power production altogether.

Circular debt is mainly due to underpayment by Distribution Companies (DISCOs), transmission and distribution losses, and an inefficient fuel mix by Generation Companies (GENCOs). The power losses are also increased by electricity theft and unpaid bills that further squeeze the supply system.

In summary, although renewable energy is costly to install compared to fossil fuels, its long-term benefits make it a necessary and eco-friendly option. With increasingly growing conservation of the environment becoming an increasingly common global issue, not only does renewable energy deter pollution but also ensures balance in the supply of energy. With the world energy demand likely to continue increasing during the span of the next three decades, limited resources could be able to cause economic instability and inter-regional war. Therefore, now is the time to divert our attention towards renewable and creatable sources of energy to secure the world's energy future.

To get a sense of the potential of solar power, have a look at the following quick facts. On a typical day, around 100 watts of solar power strikes each square foot of the Earth's surface. Using 12 hours of sunlight to a day, that amounts to 438,000 watt-hours per square foot per year. Because a square mile is roughly equivalent to 27.9 million square feet, this is the sun producing roughly 12.2 trillion watt-hours per year per square mile.

By scaling this calculation up to the entire Earth, we can figure that the Earth receives a total of about 274 million gigawatt-years of solar energy annually. That's about 8.2 million quadrillion British Thermal Units (quad BTUs) of energy. For context, human beings consume about 400 quad BTUs of energy annually. So the solar energy that strikes the Earth is more than 20,000 times bigger than the entire quantity consumed by humans [12].

Clearly, there is enough solar power to supply all the energy requirements of the whole human population at the moment, and for all intents and purposes, for eternity. The problem is to identify technologies that transfer solar power into usable energy efficiently at a reasonable cost.

1.3 Energy Trends and Conventional Resources in Bangladesh

Bangladesh has experienced significant economic growth in recent years, which has led to a substantial increase in energy demand across residential, industrial, commercial, and agricultural sectors. As of 2023, the total installed electricity generation capacity of Bangladesh is approximately 25,700 MW, with peak demand approaching 16,000 MW during summer seasons [8]. Current Energy mix of Bangladesh shown in Fig. 1.4.

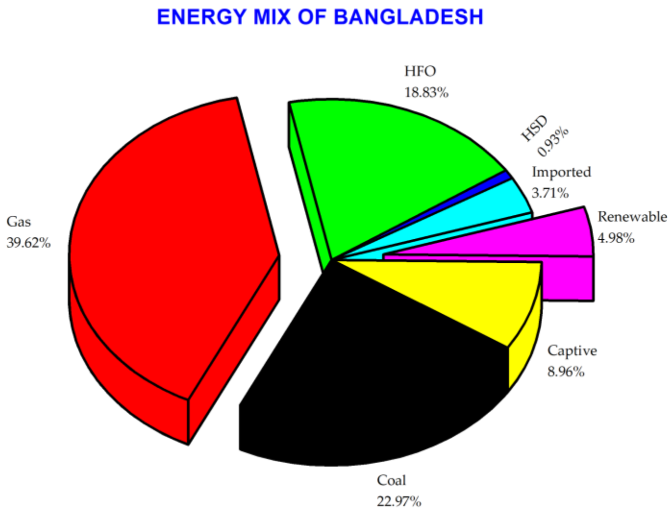

Fig. 1.4 Energy Generation Mix of Bangladesh. Reproduced with Permission from [8].

The country's energy supply is still heavily dependent on conventional fossil fuel resources:

- **Natural Gas:** The primary energy source, accounting for nearly 40% of total electricity generation. However, domestic gas reserves are depleting, and increasing reliance on liquefied natural gas (LNG) imports raises concerns about long-term affordability and security.
- **Coal:** Contributes around 23% of total electricity production. Bangladesh has modest coal reserves, mostly located in Barapukuria and Phulbari, but mining is constrained by environmental and social challenges.
- **Oil (HFO and HSD):** Accounts for nearly 20% of generation through costly high-speed diesel (HSD) and heavy fuel oil (HFO) plants. These are primarily used for quick-rental and emergency peaking power.

- **Imported Electricity:** Around 1,160 MW is imported from neighbouring India.

Despite these efforts, renewable energy contributes less than **5%** of the national energy mix shown in Fig. 1.5.

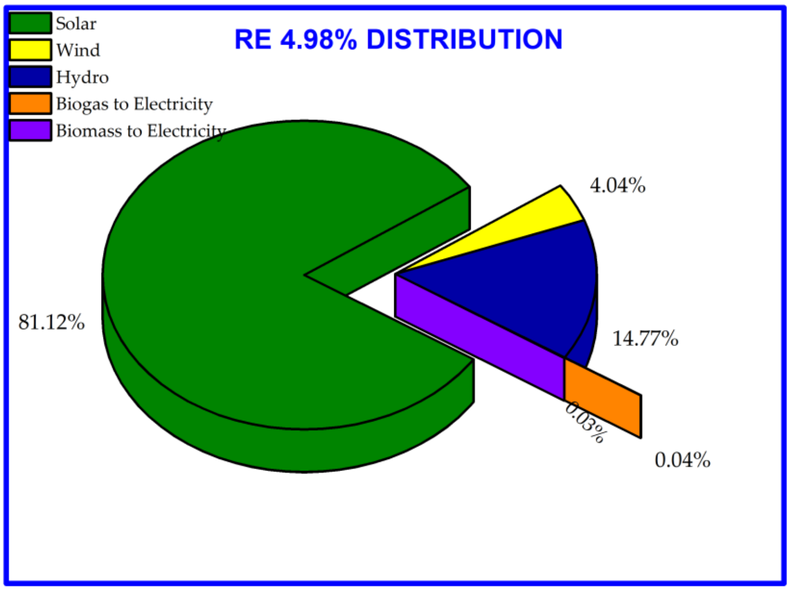

Fig. 1.5 Renewable Energy Sources of Bangladesh. Reproduced with Permission from [8].

This reflects an urgent need to diversify the energy portfolio and enhance energy security by adopting scalable and sustainable alternatives, such as Concentrated Solar Power (CSP).

1.4 Comparative Analysis of Renewable Energy Sources in Bangladesh

A comparative evaluation of renewable energy sources has been conducted to determine the most suitable options for large-scale deployment in Bangladesh. As summarized in Table 1.2, solar PV remains the most cost-effective and widely adopted technology due to its low LCOE and minimal maintenance requirements. However, its low-capacity factor and intermittency issues make it less suitable for base-load power generation. In contrast, Concentrated Solar

Power (CSP) offers dispatchable energy with thermal storage, making it suitable for stable grid integration, albeit with a higher land and cost requirement. Biomass and hydropower provide high-capacity factors and dispatchability, but their geographic and environmental limitations restrict scalability. Wind energy potential remains largely untapped in Bangladesh due to low average wind speeds. Considering land availability, cost, and output stability, CSP emerges as a promising option for long-term energy planning in high-DNI zones of Bangladesh.

Table 1.2 Comparison of Renewable Energy Sources [1], [13-15].

Parameter	**Solar PV**	**Wind**	**Biomass**	**Hydropower**	**CSP (Solar Thermal)**
LCOE (¢/kWh)	4–6	5–9	6–12	4–7	7–15
Capacity Factor (%)	15–22	25–35	70–85	35–60	30–60
Land Requirement	High	Moderate	Low	Very High (Reservoirs)	High
Maintenance	Low	Moderate	High	Moderate	Moderate to High
Dispatchability	No	Limited	Yes	Yes	Yes (with TES)
Initial Cost	Low	Moderate	Moderate to High	Very High	High
Suitability in BD	High	Low (Wind Potential is Low)	Moderate	Limited (few sites)	High in high-DNI regions

1.5 Research Objectives

This research aims to optimize the design and techno-economic analysis of Concentrated Solar Power (CSP) plants in Bangladesh by evaluating suitable locations, selecting appropriate technologies, and improving performance through optimization strategies. A comparative analysis is conducted to assess the economic viability of CSP implementation. The key research objectives are as follows:

1. To identify suitable locations for CSP plants based on geographic and climatic conditions in Bangladesh.
2. To evaluate and select appropriate CSP technologies for efficient and sustainable energy generation.
3. To optimize the performance of chosen CSP plants through technological enhancements and operational strategies.
4. To conduct a comprehensive techno-economic analysis to assess the feasibility and viability of implementing CSP plants in Bangladesh.

1.6 Scope of Study

Solar energy can be used to generate electricity in two main ways. One method uses sunlight directly and the other method focuses sunlight using special mirrors which are called solar concentrators. The basic idea is to capture energy from the sun's rays and convert it into electricity.

In Concentrated Solar Power (CSP) technology, mirrors focus direct sunlight onto a special liquid which is known as Heat Transfer Fluid (HTF). This heated fluid moves through a system of heat exchangers, where it turns water into steam. The steam then powers a turbine to produce electricity. Some of the heat is also stored in special materials like molten salts so that electricity can still be generated even at night or on cloudy days. General classification of solar energy shown in Fig. 1.6.

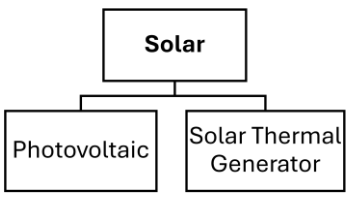

Fig. 1.6 General Classification of Solar Energy.

Solar concentrators, like those used in CSP, can focus sunlight for two different purposes:

i. **Photovoltaic (PV) Systems-** These are used to convert sunlight directly into electricity using semiconductor materials.

ii. **Solar Thermal Systems-** These are used to focus the sunlight to heat a liquid, which then produces steam to drive a turbine.

Although both methods use sunlight, they work differently. Photovoltaic systems use visible and ultraviolet light to create electricity, while solar thermal systems use infrared energy to heat a fluid. Generation from CSP is called solar thermoelectricity, where mirrors and tracking systems concentrate sunlight onto a small area. This concentrated light heats oil, salt or water, which is then used in a power plant to generate electricity. In addition to electricity generation, CSP can also provide heat for industrial processes like solar-powered air-conditioning.

CSP systems are divided into two types:

i. **Line-Focusing Systems-** These systems focus sunlight onto long tubes that absorb heat. Mirrors in these systems track the sun along a single axis to ensure sunlight remains concentrated on the tubes. This is also known as single-axis tracking technology.

ii. **Point-Focusing Systems-** These systems concentrate sunlight onto a single point, also known as the focal point. Examples include solar towers and parabolic dishes.

In point-focusing systems, all the mirrors focus sunlight onto a central receiver, where the heat is collected and used to generate electricity. A diagram (Fig. 1.7) illustrates the classification of CSP systems.

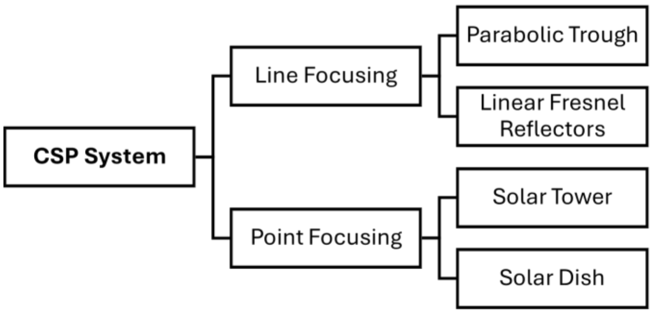

Fig 1.7 Block Diagram of Classification of CSP System.

A brief overview of the various solar energy harnessing technologies currently in use is essential to understand how CSP systems enable energy storage. CSP is considered a well-rounded technology because it can also make use of waste heat from electricity production.

Although various types of CSP technologies exist, they all operate on the same fundamental principle to produce electricity. The CSP systems are divided into four types:

- **i.** Parabolic Trough Collector (PTC)
- **ii.** Solar Tower (ST)
- **iii.** Solar Dish (SD)
- **iv.** Liner Fresnel Reflector (LFR)

1.7 Methodology Overview

There are several CSP configurations found in the literature, which depend on various criteria such as solar field area, heat transfer fluid (HTF), power block cycle, and auxiliary components like thermal energy storage (TES) and fuel backup. Selecting an efficient and reliable configuration is necessary for conducting techno-economic and design optimization of CSP systems.

The System Advisor Model (SAM), developed by NREL, provides access to geographic and meteorological data along with key technical and economic parameters. SAM is an essential tool for predicting performance and estimating energy costs. The methodology adopted in this study is illustrated in Fig. 1.8.

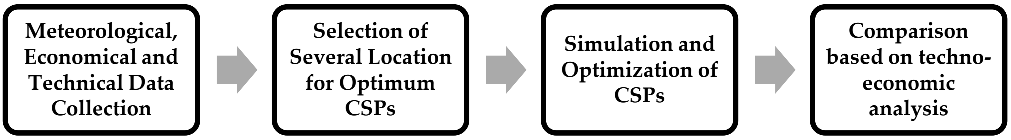

Fig. 1.8 The Block Diagram of The Methodology Steps in This Study.

The methodology consists of the following steps:

- Obtaining meteorological, economic, and technical data from SAM.
- Simulating and optimizing plants with varied solar multiples (SM) and TES full-load hours.
- Comparing the optimized plants based on tecno-economic criteria to select the most efficient and cost-effective CSP.
- Conducting a feasibility study with the selected CSP to determine the most favourable locations in different regions of Bangladesh.

1.8 Significance and Scope

Concentrated Solar Power (CSP) is a promising solution for mitigating the future energy crisis. It is a clean, reliable, and environmentally friendly technology. This research contributes to the potential deployment of CSP in Bangladesh, focusing on the optimal placement of CSP technology based on efficiency, land requirements, and Direct Normal Irradiance (DNI) levels. Additionally, this study aims to optimize key parameters of the solar tower system, including collectors, receivers, efficiency, lifetime, power cycle, and thermal storage, to maximize its performance and feasibility for future implementation in Bangladesh.

1.9 Thesis Organisation

Including the first stated introduction chapter, this thesis is divided into the following four chapters (Chapters 2 through 5). The thesis is organized into the following chapters, with a short description of each chapter.

Outline of Chapter 2

Chapter 2 provides a comprehensive review of existing research and technologies related to Concentrated Solar Power (CSP). It discusses various CSP technologies, focusing on their efficiency, feasibility, and implementation challenges. It also highlights previous studies on CSP deployment in Bangladesh and other similar regions.

Outline of Chapter 3

Chapter 3 is organized based on details of the methodology used in this research. It describes the selection of suitable CSP configurations, data sources, simulation tools, and optimization techniques. The modelling of solar tower CSP using SAM is explained, including the assumptions and boundary conditions considered.

Outline of Chapter 4

Chapter 4's organization is based on the performance and simulation result analysis. This chapter presents the findings of the research, including the performance analysis of different CSP configurations. It includes discussions on energy yield, efficiency, cost analysis, and environmental impact. A comparative study of optimized CSP plants is also provided.

Outline of Chapter 5

Finally, the conclusions and outlook are presented in Chapter 5. This chapter summarizes the key findings of the research and provides recommendations for future studies. It discusses the feasibility of implementing

CSP in Bangladesh and suggests potential improvements for enhancing its performance and economic viability.

Chapter 2: Literature Review

This chapter provides a comprehensive overview of Concentrated Solar Power (CSP) technologies and their relevance to sustainable energy solutions. Section 2.1 traces the history and evolution of CSP systems, providing a foundation for understanding their development and significance. In Section 2.2, we delve into the various CSP technologies, with detailed discussions on the four primary types: Parabolic Trough (Section 2.2.1), Solar Tower (Section 2.2.2), Linear Fresnel Reflector (LFR) (Section 2.2.3), and Dish-Stirling System (Section 2.2.4). Each of these technologies is explored for its unique attributes, advantages, and challenges in the context of power generation. Section 2.3 focuses on solar tracking systems, essential for enhancing CSP efficiency, with discussions on Single-Axis Trackers (Section 2.3.1) and Dual-Axis Trackers (Section 2.3.2). Section 2.4 provides a comprehensive review of existing research on CSP, identifying key gaps that this study aims to address. Finally, Section 2.5 highlights the novelty of the present study, emphasizing its unique contributions to the field of CSP technology and its applicability in sustainable energy development.

2.1 History of CSP

As global interest in clean energy grows, investment in renewable energy is increasing. In the past 30 years, wind energy has experienced rapid growth, with an average yearly increase of approximately 30%. By the close of 2011, the total global installed wind power capacity had reached 239 gigawatts, contributing close to 3% of the world's electricity production [16]. Wind energy is now being installed at a faster rate than nuclear power. Meanwhile, the solar photovoltaic (PV) industry has experienced similar or even higher growth rates but from a lower base and in 2011 had a worldwide installed capacity of approximately 69 GW [17].

Concentrated Solar Power (CSP) began its first phase of commercial application between 1984 and 1995. While development slowed afterward, research and pilot projects continued during the interim. A significant revival occurred around 2005, marking the start of a new wave of CSP deployment. Since then, commercial installations have increased notably, though the overall global capacity of CSP remains much lower than that of photovoltaic (PV) systems, partly because CSP technologies reached market maturity later than PV counterparts [16-22].

i. One of the earliest conceptual uses of concentrated sunlight dates back to ancient times. A popular legend credits Archimedes with using polished bronze shields—later termed "burning glasses"—to reflect and focus sunlight onto Roman ships attacking Syracuse, allegedly causing them to ignite. In 1973, Dr. Ioannis Sakkas from Greece tested this theory experimentally. He enlisted around 60 sailors, each holding a mirror angled to reflect sunlight onto a tar-coated plywood mock-up situated approximately 160 feet away. After several minutes of concentrated reflection, the target ignited, as illustrated in Fig. 2.1. Despite this modern experiment, many historians remain skeptical about the historical accuracy of Archimedes' supposed solar weapon [25].

ii. In 1866, Auguste Mouchout built the first parabolic trough system to generate steam from sunlight.

iii. The evolution of solar thermal technology began in 1886 when Alessandro Battaglia, an Italian inventor from Genoa, filed the earliest known patent for a solar collector. Following this innovation, notable inventors including John Ericsson and Frank Shuman advanced the development of solar concentrating systems aimed at practical applications like irrigation, refrigeration, and propulsion.

Fig. 2.1 Archimedes destroyed the Roman fleet using concentrated sunlight. Reproduced with Permission from [25].

iv. In the late 1920s, Dr. Robert H. Goddard—renowned for pioneering liquid-fueled rocketry—constructed one of the earliest parabolic dish systems for solar power. He published a significant article in 1929 asserting that earlier technical barriers to solar energy utilization had been overcome.

Later, Professor Giovanni Francia, a prominent Italian researcher, designed and deployed the first modern-style concentrated solar power (CSP) plant in 1968 in Sant'Ilario, near Genoa. This installation featured a central receiver surrounded by a field of mirrors, closely resembling today's CSP plant configurations. It was capable of producing 1 MW of power using superheated steam at 100 bar and 500°C.

In the United States, CSP technology advanced further in the 1980s. The 10 MW Solar One power tower was commissioned in Southern California in 1981.

However, the development of the Solar Energy Generating Systems (SEGS) beginning in 1984 marked a more practical turning point. With an installed capacity of 354 MW, SEGS remains the world's largest operational solar thermal power plant [18], [24-25].

2.2 Concentrated Solar Power (CSP) Technologies

Concentrated Solar Power (CSP) generation systems collect sunlight, heat it, and utilize the heat to generate electricity with the assistance of other technologies like steam turbines, gas turbines, Stirling engines, or pressure-staged turbines. Parabolic Trough, Solar Tower, Linear Fresnel, and Dish-Engine Systems are four commercially operating solar thermal power plants. Solar thermal systems concentrate sunlight to reach higher temperatures in an effort to optimize efficiency. The efficiency of Concentrated Solar Power (CSP) technology is based on Direct Normal Irradiance (DNI), i.e., the amount of direct sunlight incident on a surface held stationary on the sun. CSP power stations are optimal in the "sun belt" region, between latitudes 20° to 40° north and south. Solar Updraft Towers differ from CSP systems in that they don't concentrate the energy of the sun.

They employ both diffuse and concentrated sunlight, with lower efficiency and lower operating temperatures. Electricity generation systems vary depending on the system. Central receivers and parabolic troughs primarily employ steam turbines to produce electricity by utilizing heat, with heat transfer fluids such as molten salt, oil, air, or water employed to facilitate the process. Central receivers can be heated up to over 1,000°C and can be used for power generation in gas turbines along with steam turbines for enhanced efficiency [26-27] . Dish-Stirling systems can place an engine over the focus of a single dish or heat from multiple dishes is funnelled into a central power unit. Solar Updraft

Towers employ a central pipe to generate an updraft air stream that drives pressure-staged turbines to generate electricity.

In Concentrated Solar Power (CSP) technology, the Direct Normal Irradiance (DNI) of the sun is focused onto a Heat Transfer Fluid (HTF). The fluid flows through a series of heat exchangers in order to produce superheated steam, which drives a steam turbine to produce electricity. Some of the heat is also retained in liquid or solid substances, for example, molten salt, so that electricity can still be generated at night or when sunlight is not available, thereby providing round-the-clock turbine operation [28-29]. General working flow diagram of CSP is shown in Fig. 2.2.

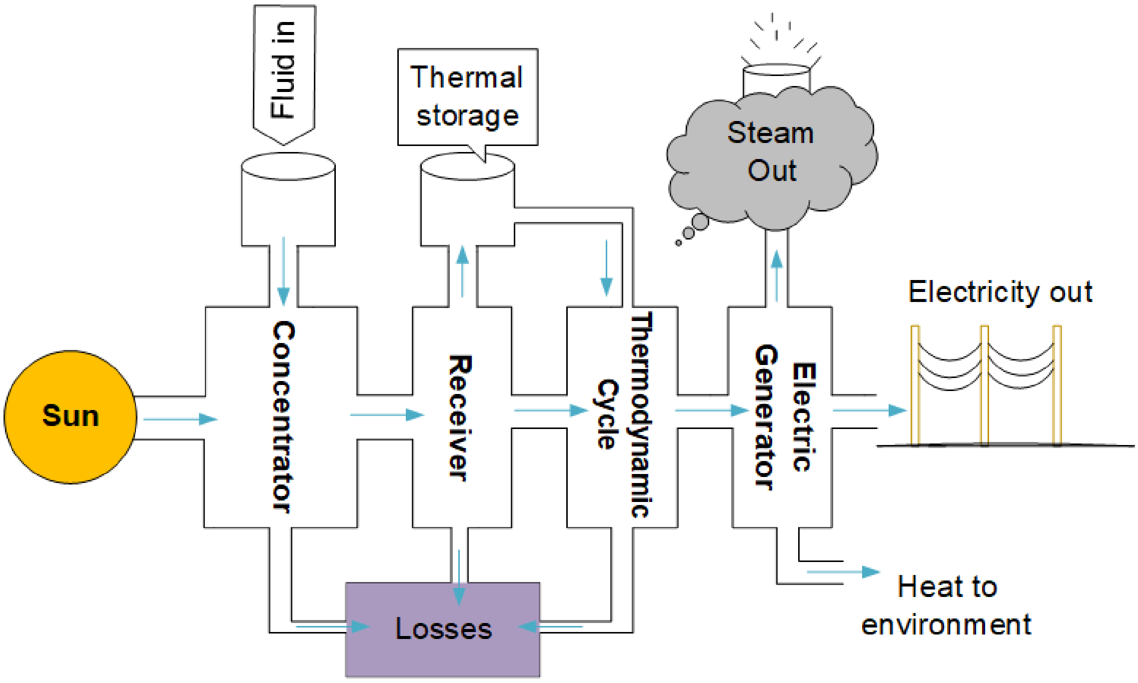

Fig. 2.2 General working diagram of CSP. Reproduced with Permission from [1].

Most Concentrated Solar Power (CSP) systems generate electricity using principles similar to those in conventional thermal power stations. Common CSP configurations—such as parabolic trough collectors, central receiver systems, and linear Fresnel reflectors—rely on solar radiation to heat a fluid that ultimately produces steam. This steam drives a turbine coupled with a generator to produce electricity. Unlike fossil-fuel plants where combustion provides the necessary heat, CSP systems harness solar energy by concentrating sunlight onto a working fluid using reflective surfaces [32].

To extend power generation beyond daylight hours or align energy output with demand peaks, CSP facilities often incorporate thermal energy storage (TES). These storage systems typically use media such as molten salts or pressurized steam. However, the choice of heat transfer fluid (HTF) influences operational limits. Synthetic oils—commonly used in many CSP setups—can degrade at temperatures above approximately 400°C, thereby restricting the maximum steam temperature available to drive turbines. In contrast, molten salts and pressurized water offer higher thermal stability, enabling operation at around 550°C and 500°C respectively. A trade-off exists, as molten salts tend to solidify below 220°C (e.g., the eutectic mixture of 60% sodium nitrate and 40% potassium nitrate), defining the lower limit for heat extraction from the solar field [33].

The extent of a CSP solar field can be described not only by its physical footprint but also through the concept of solar multiple—which expresses the field's aperture area as a multiple of what's required to operate the power block at full capacity. The aperture area, usually reported in square meters, represents the effective solar collection area. For curved collectors such as parabolic troughs, the aperture is less than the actual reflective surface due to geometry [33-34].

CSP plants predominantly operate on the Rankine cycle, which necessitates a cooling system to condense steam after it exits the low-pressure turbine. The most effective cooling technologies use water, although water availability is often limited in regions with high Direct Normal Irradiance (DNI). As a result, CSP installations typically adopt one of two cooling approaches: wet cooling (water-based) and dry cooling (air-based), depending on site conditions and resource availability.

Today, four major CSP technologies are in use: parabolic trough systems, central tower receivers, linear Fresnel systems, and parabolic dish engines, as illustrated in Fig. 2.3. Each of these technologies varies in its level of maturity, efficiency, and practical deployment.

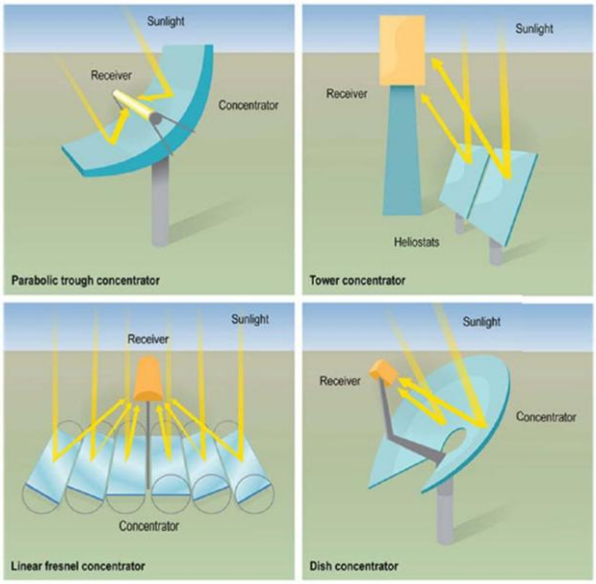

Fig. 2.3 Images representing the four main types of CSP technologies. Reproduced with Permission from [2].

Since Concentrated Solar Power (CSP) plants share operational similarities with conventional thermal power stations, they offer the flexibility to integrate fossil fuel support alongside solar thermal input. This hybrid approach can enhance the reliability of electricity generation, especially during periods of low solar radiation or peak demand. Traditionally, this has involved the use of auxiliary boilers for backup heat supply. In some configurations, CSP systems have even functioned as supplemental sources within larger thermal power frameworks, assisting in steam production. Additionally, the concept extends to the potential application of CSP heat in driving gas turbines, such as those employed in combined cycle power plants [4], [35-36].

2.2.1 Parabolic Trough

Parabolic trough technology is the most advanced CSP design for utility-scale power plants. Parabolic trough collector (PTC) is a concave mirror-like surface solar collector that is utilized to concentrate sunlight onto a receiver tube, as illustrated in Fig. 2.4.

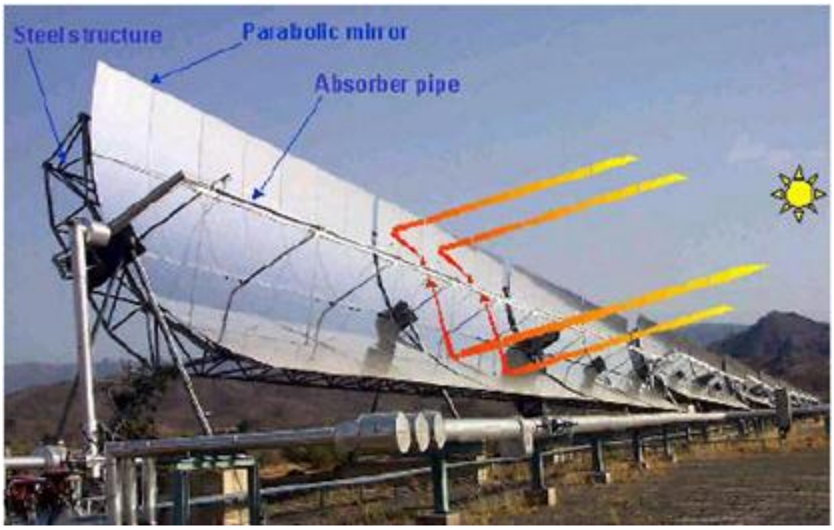

Fig. 2.4 Parabolic-trough collector (PTC). Reproduced with Permission from [38].

The tube has a heat transfer fluid inside it, which absorbs and transfer heat. The system traces the movement of the sun from east to west during the day by rotating around its axis. The bent mirrors are tilted to trap sunlight and concentrate it along a single line of focus. This concentrated heat is utilized to produce steam, which drives a turbine to produce electricity. PTC systems are effective and popular because they have a proven track record. They are most suitable for high direct solar radiation sunny sites. Heat transfer fluid facilitates energy storage for electricity production during times of sunlight unavailability. Parabolic trough technology is therefore a reliable option for large-scale solar power production.

A large collector aperture captures and redirects direct solar radiation onto the narrower surface of the external receiver tube, where it heats the working fluid inside. This concentrated solar energy is then converted into thermal energy, either as sensible heat or latent heat, depending on the fluid's properties [39]. This thermal energy can be utilized either directly in industrial processes that require heat—such as in the petrochemical or food processing sectors—or indirectly to generate electricity through steam turbines using Rankine cycle systems, typically within solar thermal power plants. Among the current technologies, parabolic trough collectors are capable of delivering thermal outputs reaching up to 398°C. This temperature threshold is primarily constrained by the properties of the thermal oil commonly used as the heat transfer fluid, which begins to degrade beyond this limit. However, ongoing advancements in heat transfer fluids aim to extend operational temperatures to around 500°C in the near future [40].

Through plants are established most commercial plants commissioned today [38], [41]. A parabolic trough collector (PTC) system typically comprises long rows of curved mirrors—often about 100 meters in length and 6 meters in width—shaped parabolically along one axis. These mirrors are designed to focus incoming sunlight onto a central focal line where a receiver tube, or absorber, is positioned. As shown in Fig. 2.5, the absorber tube is enclosed within a vacuum-sealed glass envelope and coated with a selective material that enhances solar energy absorption while minimizing thermal losses. This coating permits high solar irradiance to heat the working fluid inside the tube but prevents significant infrared radiation from escaping into the environment, thereby improving thermal efficiency.

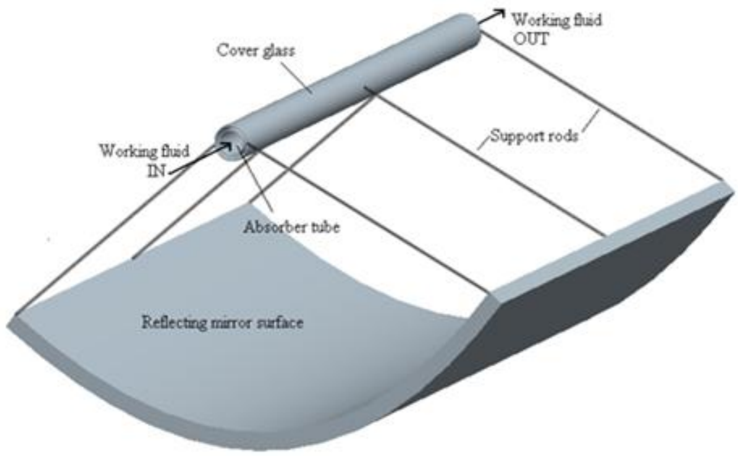

Fig. 2.5 Component of parabolic-trough collector (PTC). Reproduced with Permission from [1].

The troughs are generally designed to track the sun in a single direction, mainly north-south [42]. This is accustomed achieve optimal performance of the solar field throughout the morning and afternoon, attempting to coincide with the demand profile. With this one axis tracking orientation, the cosine effect is responsible for some loss of energy at noon. Cosine losses occur when mirrors are not aligned perpendicular to the incoming sunlight, resulting in a reduction of the effective reflecting area. This apparent decrease is proportional to the cosine of the angle between the mirror surface and the direction of solar radiation [33], [43].

Parabolic trough power plants use different working fluids such as steam, synthetic oil, or molten salts. While most of them use synthetic oil since no adequate investment has been provided to run them on molten salts, the operating temperature of the oil-based ones is a maximum of 400°C. The concentration factor for parabolic trough plants is currently in the range of 60-80 times with highest efficiency of 14-20% and annual efficiency of 11-16%[43-44].

Thermal oil parabolic trough systems are the most advanced Concentrated Solar Power (CSP) technology, largely because of experience in California. Commercial success in the technology was rekindled in 2006 when a 1 MW facility began operations in Arizona after almost 20 years. Nevada Solar One, the third-largest CSP power plant in the world, generating 64 MW, in June 2007. These advances have been made possible by the new U.S. policies supporting CSP deployment. Several larger CSP plants, varying in capacity from 177-553 MW, have been planned but will go ahead only if a 30% investment tax credit is given [45-46].

Spain is still the most promising market for CSP, with 22 cents per kWh as an incentive under the Renewable Energy Act (RD 436/2004). The country has a capacity limit of 500 MW for CSP facilities, but already over 1,000 MW are projected. The Andasol 1 and Andasol 2 power facilities, each of 50 MW, are under construction at Granada with 7.5 hours of thermal storage and designed 3,820 hours of full-load operation per year. A third unit, the Andasol 3 to be finished by 2010, will have steam instead of thermal oil as its working medium. Future development of CSP technology is proposed to replace synthetic oil with either direct steam or molten salts to achieve higher efficiency [15], [41].

Direct Steam Generation (DSG) technology enhances overall plant efficiency by enabling higher operational temperatures and eliminating an intermediate heat exchange stage. This method also removes the necessity of replacing conventional heat transfer fluids like thermal oil, which are often costly, energy-intensive to produce, and environmentally hazardous. Consequently, DSG offers both economic and environmental benefits. One of the earliest commercial implementations of this technology is the 50 MW Andasol 3 project in Spain. Similarly, using molten salts as a primary heat transfer medium offers advantages such as elevated operating temperatures for the solar field—leading to improved efficiency—and the potential to bypass additional heat exchangers when integrated with molten salt thermal storage. However, a key technical challenge lies in maintaining consistent heating of the system to prevent the salt from solidifying. Despite its promise, research and commercial deployment of these innovations remain limited at present [40].

Technology Constraints:

• The current maximum operating temperature is limited to 400°C due to the use of thermal oil.

• Using thermal oil increases investment, operation, and maintenance costs. In some countries, oil spills from the system could cause environmental issues.

• Strong winds can damage mirror reflectors, especially at the edges of the field.

• Affordable and efficient energy storage systems have not yet been fully developed.

• Heat loss occurs when transferring energy from the receivers to the central power unit.

• Heat losses between the receivers and the central conversion unit are high

• The system requires complex flexible connections between the moving receivers and fixed pipes, making it less reliable.

2.2.2 Solar Tower

A central receiver system operates by using a field of heliostats—mirrors that track the sun—which are strategically positioned to prevent shading or overlap. These mirrors redirect direct solar radiation toward a high-mounted receiver or secondary reflector [28]. The sun's energy is trapped and focused by the receiver, usually converting it into heat at a very high temperature. The heat is transferred to a special fluid, which can store the energy, generate electricity, or supply heat for process applications. There are many challenges in designing, building, and operating a complete solar thermal power plant, which are outlined in a recent Sandia report [29]. Instead of using a thermal receiver, photovoltaic panels are used to convert sunlight directly into electricity. Sunlight (photons) can also be used in chemical reactions or even to power lasers. Solar power towers are hard to design and optimize because many factors are involved. Every heliostat (mirror) continuously adjusts to follow the sun and synchronize with others. Solar power towers are worthwhile despite this because they efficiently absorb sunlight, concentrate it intensely, and generate high temperatures, and are thus used for many applications. One of the primary benefits of central receivers is that energy conversion takes place in one stationary location—the receiver. This reduces the need for advanced energy transport systems and allows for cost-effective performance and efficiency enhancements.

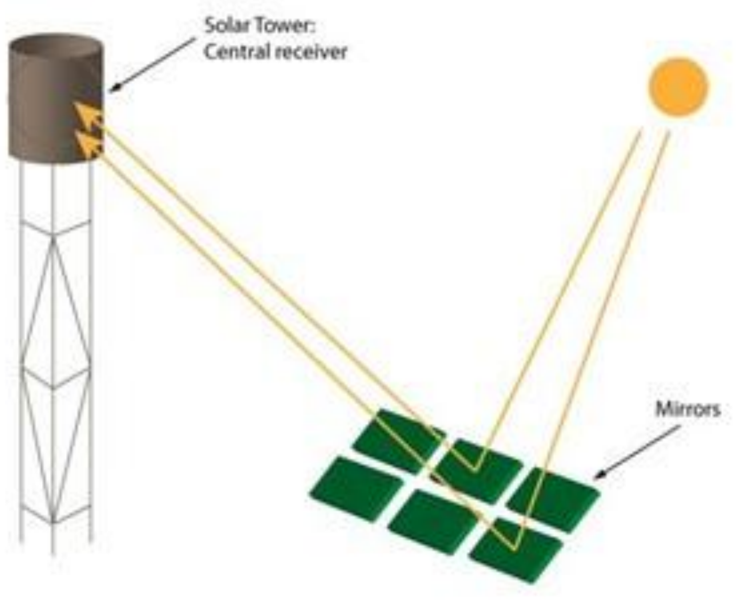

Fig. 2.6 Solar Tower System. Reproduced with Permission from [48].

A solar tower system, as seen in Fig. 2.6, will usually be designed as a single large unit for generating electricity with a steam cycle. Modular multi-tower units or smaller versions are feasible but will be of use in certain applications. Disadvantage of solar towers is that the receiver is fixed, and hence the heliostats (mirrors) don't necessarily face directly towards the sun. This results in less sunlight each mirror receives, an effect known as the cosine effect. All the other forms of solar collectors, like parabolic troughs or parabolic dishes, also employ sloping reflectors, but their light is lost to a very minor extent. Compared to that, Fresnel-type systems like linear Fresnel systems and solar towers both employ flat sections of mirrors, which focus sunlight onto the receiver. However, some sunlight spills on the ground diminish efficiency compared to the parabolic-type systems [31], [49]. As a result, mirror spacing must be adjusted to prevent significant shading of neighbouring mirrors during solar movement or obstruction of reflected sunlight route to the receiver, even if it means losing some incoming energy.

A central receiver system must be designed to compromise among several factors to collect sunlight in the most cost-effective way. This chapter discusses the design and construction of solar power towers and the most significant factors affecting their performance. In this system, a central receiver is placed atop a tower, where it collects concentrated sunlight reflected by heliostats (mirrors that track the sun). At the top of the tower, a work fluid is utilized to take in the concentrated sun's rays and transfer it to steam. The system can operate at very high temperature, between 800°C to over 1000°C, which implies that it would also be suitable for use with a gas turbine. This improves the efficiency of conversion from heat to electricity and helps lower thermal storage costs[49-51]. In CSP plants, water/steam, molten salt, and air are used as the heat transfer fluid. The power plants generally generate electricity in megawatt capacity. Solar power plants can concentrate sunlight 600 to 1000 times to generate high temperature. The maximum efficiency of conversion of sunlight into electricity is 23-35% and the average efficiency annually is 7-20% [51].

2.2.3 Linear Fresnel Reflector (LFR)

A single-axis linear Fresnel reflector (LFR) system consists of a number of long rows of reflectors focusing images of sunlight overlapping on a tall linear tower receiver parallel to the rotational tracking axis of the reflectors. The Linear Fresnel System is shown in Fig. 2.6. This design allows for the construction of a larger array at lower cost using identical or very similar long focal length glass mirror elements, which are almost flat. This chapter covers the historical and recent technological development of LFR technology. It also discusses thermal performance trade-offs and future directions. Linear Fresnel plants are almost as close to parabolic troughs as possible, the main difference being the way in which the reflecting mirrors are mounted.

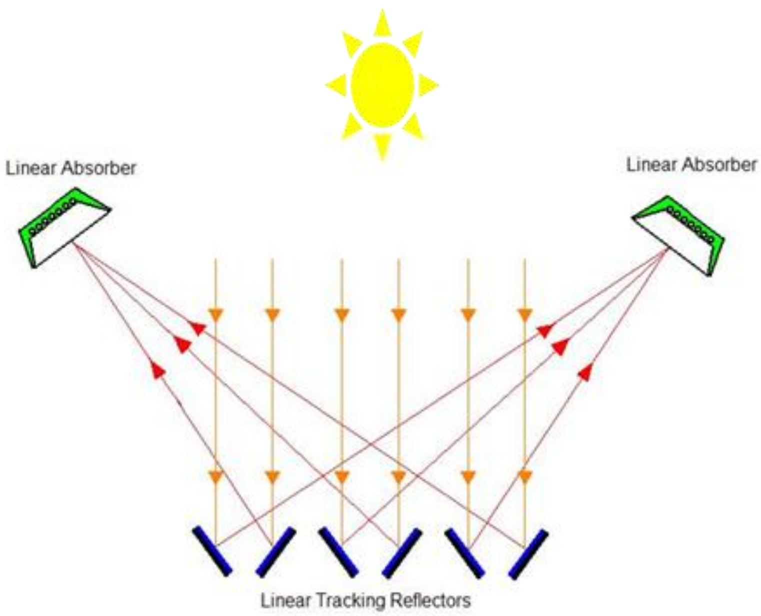

Fig. 2.7 Linear Fresnel System. Reproduced with Permission from [52].

They employ long flat, slightly curved mirrors in close proximity to each other to concentrate the sun's rays onto a downward-facing stationary receiver, as compared to employing parabolic mirrors, like in the trough system. Linear systems are cheaper because the mirrors are less complex to produce and occupy less space. The concentration factor in these systems is less than in troughs, and therefore the fluid temperatures across the receivers are lower, at 250-300ºC. This lower temperature makes the Rankine cycle less efficient but with cheaper materials. Since the temperature is lower, these plants can use water as the working fluid for direct steam generation, incurring cost savings by not using extra heat transfer fluids and heat exchangers. Linear Fresnel plants concentrate 60-80 times. The highest efficiency of the solar energy conversion into electricity is about 18%, while the average annual efficiency is close to 13% [53]. There have been recent advancements in the technology, in spite of challenges, leading to new optical designs of the solar field and even at the commercial level Improvements are being made to allow operations above 500ºC using molten salts, which help lower the levelized cost of energy (LCOE) [54]. Enhancements in optical design allow Fresnel collectors to reach elevated flux levels and operating temperatures, although their overall efficiency remains comparatively lower. These advancements suggest that in southern Europe, systems utilizing molten salts heated to approximately 550°C could potentially attain energy production costs as low as 11 Euro/kWh. A schematic overview illustrating the configurations of Parabolic Trough, Solar Tower, and Linear Fresnel Reflector systems is presented in Fig. 2.8.

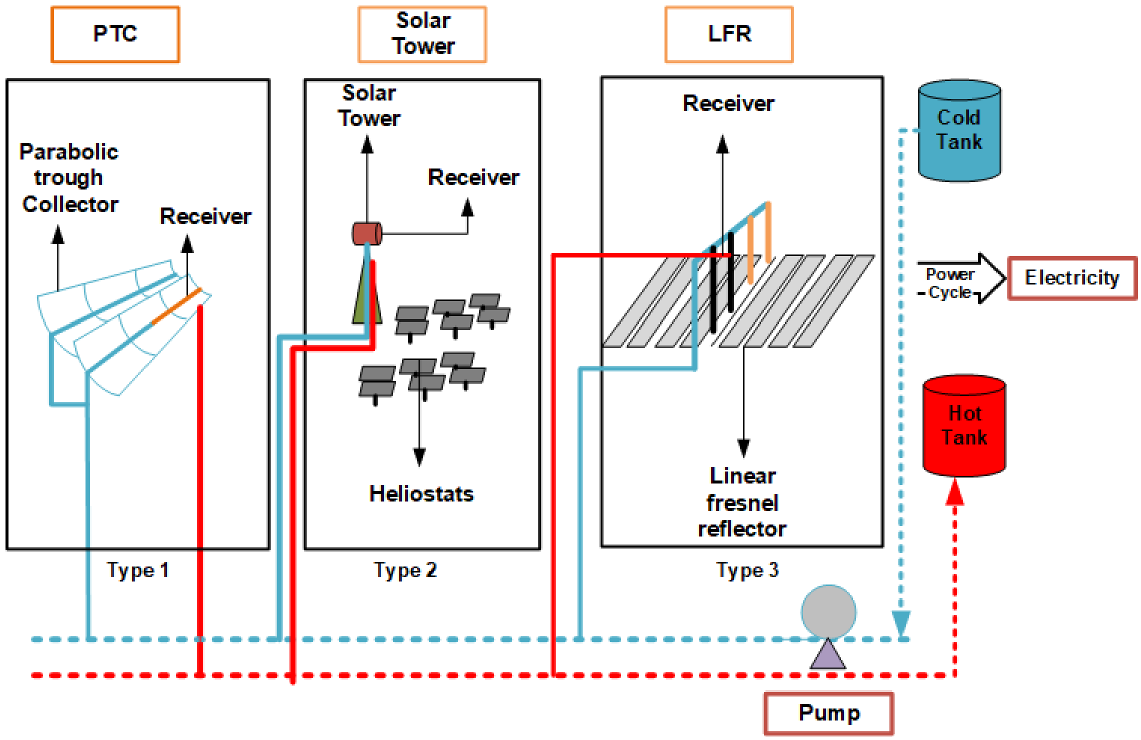

Fig 2.8 Generic Working Diagram of Parabolic Trough, Solar Tower and Linear Fresnel Reflector System.

A lesser cost would even be probable for locations like north of Chile, parts of Africa, Australia and North America. A lot of projects using Fresnel systems are being promoted worldwide amounting for a total capacity of 513 MW. In New South Wales, Australia, a Compact Linear Fresnel Reflector (CLFR) system has been successfully tested as a 1 MWth thermal addition to support steam generation in a coal-fired power plant. Plans are underway to scale this integration up to 38 MW in capacity [55].

The "Jordan/Aqaba Solar Water Project" is set to feature the largest direct use of Fresnel collectors, incorporating a hybrid design that combines solar power with natural gas for co-firing. This system is intended for tri-generation, with the final configuration capable of generating 8.5 MW of electrical power, 40 MWth of thermal energy, and 140 GWh of cooling annually, operating for 8,470 full-load hours [53].

Technology Constraints:

- Energy storage solutions like molten salt and volumetric air receiver technologies are currently restricted by their demonstrated generation capacities.
- There is still a lack of industrial-scale demonstration for mass production of heliostat components.
- Each individual mirror requires a separate dual-axis control, unlike the parabolic trough design where a single axis can serve a large array of mirrors.

2.2.4 Dish-Stirling System

Dish-type Concentrated Solar Power (CSP) systems utilize paraboloidal mirrors that continuously track the sun, concentrating solar radiation onto a receiver. This receiver either channels the energy into a heat transfer fluid—delivered to a ground-level power plant—or directly powers a heat engine or generator. Among all CSP technologies, dish concentrators offer the highest optical efficiency, concentration ratios, and overall energy conversion performance. Commercially, these systems are primarily paired with Stirling engines integrated into the receiver to generate electricity directly. Nevertheless, dish concentrators are versatile and can support various energy conversion methods employed in CSP systems.

Potential applications range from supporting both small- and large-scale grid-connected systems to powering independent setups such as water pumps or desalination units. When multiple dish Stirling systems are grouped together, they can collectively deliver capacities of up to 10 MW [56].

Fresnel collectors have seen advancements in optical design, allowing them to generate high thermal flux and reach elevated temperatures, albeit with somewhat lower overall efficiency. These improvements suggest that molten salt systems operating at temperatures up to 550ºC could potentially achieve a cost of around 11 Euro/kWh in southern Europe. In regions like northern Chile, Africa, Australia, and North America, the costs could be even lower. Currently, Fresnel-based systems are being implemented globally, with a total installed capacity reaching 513 MW. One example is in New South Wales, Australia, where a 1 MWth Compact Linear Fresnel Reflector system has been successfully integrated for steam production in a coal-fired power plant, with plans underway to scale it up to 38 MW [57]. A Solar Parabolic Dish System shown in Fig. 2.9.

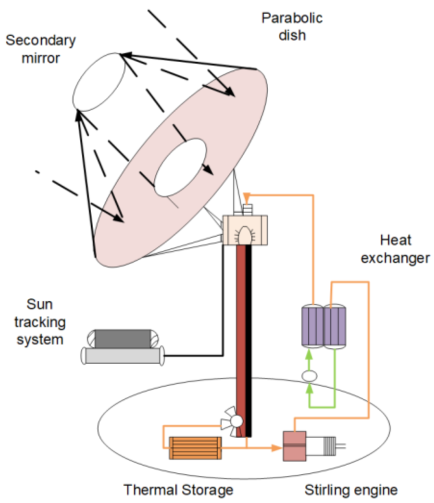

Fig. 2.9 Parabolic Dish System. Reproduced with Permission from [56].

This technology focuses the sunlight onto a middle receiver in the dish, heating a gas or fluid to approximately 750 ºC. The whole system follows the movement of the sun. Most systems use a micro-turbine or a small piston Stirling engine to generate electricity, without the need for a cooling water system and a heat transfer fluid [58-59]. Fig. 2.10 represented the Generic working diagram of Parabolic Dish system.

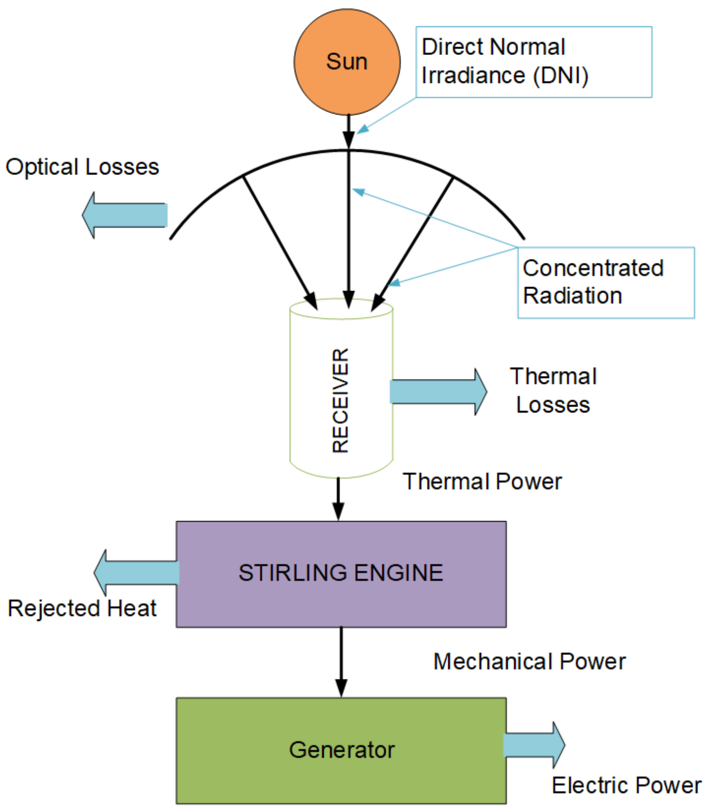

Fig. 2.10 Generic working diagram of Parabolic Dish system.

Dishes are more effective than other technologies at turning solar energy into electricity but are expensive to install and have not been funded to the same extent as troughs and towers. But CSP dish technology could compete with PV designs because dishes are more modular and compact. Dishes typically produce a few kilowatts each. Parabolic dishes focus solar energy 600-1000 times [60]. Peak solar energy-to-electricity efficiency is approximately 30%, and average annual efficiency is 12-25%. It is currently less efficient than three other leading CSP technologies [57].

Dish-Stirling units of 25 kW have attained an efficiency of nearly 30%, the highest among non-laboratory solar energy conversion systems. The high efficiency of Dish-Stirling systems means that the systems produce more electricity from the sun compared to other solar systems. The compactness and modularity of Dish-Stirling units make them simple to incorporate into applications and thus an attractive option for renewable energy generation. Parabolic dish systems are not included in this study since they generate low power (5 to 50 kW). They are better for decentralized or stand-alone uses. Parabolic dish systems are efficient, but low power generation makes them best for specific markets, for instance, for remote locations or personal consumption. Their compact size allows them to be used in areas where larger power generation schemes would be unfeasible to install. Thus, they find less application for large power generation schemes [57].

As the capital cost has fallen to approximately USD 3,000 per kW, new market opportunities are emerging in green power and distributed generation markets in regions/countries like the southwestern United States, India, the Mediterranean, southern Europe, and Africa. As utility markets around the globe are restructured, green power markets emerge, and the demand for distributed generation grows, the prospects for small power systems ranging from a few kW to several MW are rapidly increasing. Despite these difficulties, the high conversion efficiencies achieved motivate ongoing efforts in this field. What this means is that as the cost decreases, there's growing potential for green energy in these markets. The changing energy market and increasing demand for distributed generation are increasing the potential for small power systems, which are becoming more popular and widespread. The high efficiency of these systems continues to fuel innovation and development.

Technology Constraints:

• A dish/Stirling unit's electricity output is limited due to its physical characteristics and geometry, which cause low power ratings.

• Large-scale deployment is yet to take place due to issues of production, transportation, and installation. All these have discouraged mass use up to now.

• Long-term cost estimates, system performance, and plant availability are not available or are unproven.

• There is no suitable or current energy storage system to utilize.

• The process of electricity generation from heat involves moving components, and that brings with it the need for constant maintenance.

• A centralized design is generally better suited to such conversion rather than a decentralized dish arrangement.

2.3 Tracking System

A solar tracker is a device employed to maintain solar panels and other equipment in the direction of the Sun. It is typically applied to solar panels, mirrors, and lenses to capture more sunlight. For flat-panel solar systems, trackers adjust the angle to maximize sunlight absorption and enhance energy production. Between 2008 and 2009, trackers were expected to be used on at least 85% of commercial solar power plants bigger than a megawatt between 2009 and 2012. By April 2014, however, no information supported this estimate [61].

In CSP systems, trackers are employed to position the optical components appropriately to get maximum sunlight. The trackers adjust the system's orientation throughout the day to increase efficiency.

In concentrated solar applications, the optics collect direct sunlight and need to be aligned in the correct direction to harvest energy. All installations of concentrators use tracking systems because they can only generate energy when they are facing the Sun. The systems automatically adjust to follow the path of the Sun throughout the day in order to harvest maximum energy[62].

2.3.1 Single Axis Trackers

Single-axis solar trackers possess a single rotational component, typically enabling movement along an axis aligned parallel to true North. However, modern tracking systems have enhanced capabilities, allowing these trackers to tilt at various angles beyond the conventional axis. There are several variations of single-axis trackers, such as Horizontal Single Axis Trackers (HSAT), Horizontal Single Axis Trackers with Tilted Modules (HTSAT), Vertical Single Axis Trackers (VSAT), Tilted Single Axis Trackers (TSAT), and Polar Aligned Single Axis Trackers (PSAT). When modeling their performance, it is important to consider the orientation of the solar modules relative to the tracker's axis of rotation, as this significantly influences the system's ability to capture sunlight throughout the day [63], [64].

2.3.2 Dual Axis Trackers

Dual-axis tracking systems operate with two perpendicular axes of rotation. The main axis, which remains stationary and is anchored to the ground, serves as the base, while the secondary axis moves in relation to it. The configuration of the primary axis in relation to the ground distinguishes different types of dual-axis trackers. Among the most common configurations are tip-tilt dual-axis trackers (TTDAT) and azimuth-altitude dual-axis trackers (AADAT). In performance modeling of these systems, it is crucial to consider the alignment of the solar panels relative to the rotational axes. To ensure optimal energy capture, solar modules are typically aligned parallel to the secondary axis [66-67]. Dual axis trackers enable the realization of maximum amounts of solar energy since they are able to track the Sun vertically and horizontally. No matter where the Sun is, dual axis trackers are able to position themselves in direct contact with the Sun.

2.4 Review of Existing Research and Identified Gaps

There are four prominent alternatives of Concentrated Solar Power (CSP) technology: parabolic trough, solar tower, linear Fresnel, and parabolic dish. The most developed and demonstrated for electricity production on a utility scale, especially in the desert and semi-arid areas, is the parabolic trough technology [67]. It uses curved mirrors to focus sunlight onto a receiver tube filled with HTF to generate electricity from the sun [61]. The technology is made up of a solar field, TES, and a power cycle, molten salt being the favored HTF due to its greater temperature capacity [28]. Levelized Cost of Electricity (LCOE) is important to CSP viability and relies on operating fluid, power plant design, and operating expense [68]. Optimization of system performance was investigated and molten salt was effective and low-cost HTF alternative [69]. CSP efficiency was also studied for higher efficiency, lower LCOE, and higher energy output [45].

In the context of Bangladesh, the majority of solar energy efforts and installations have been photovoltaic (PV)-based. In 2023 alone, the Bangladesh government approved 2.19 GW capacity of utility-scale PV projects, including a 300 MW Saudi-based ACWA Power solar power plant and a 240 MW Energon Renewables and PWR Energy Trading LLC power plant in Mymensingh. Additionally, plans for a 200 MW ground-mounted and floating solar power plant at Barapukuria coal mine in Dinajpur district are reflective of the scale of solar projects in Bangladesh [70]. Rays Power Infra's 275 MW PV plant at Sundarganj, Gaibandha, is the largest commissioned solar plant that was commissioned early this year 2023. The project is established on a parcel of land covering an area of 600 acres and greatly helps in mitigating carbon emissions. In spite of all these efforts, renewable energy makes a negligible contribution to the nation's total energy mix, though the government plans to achieve solar capacity of 2,277 MW by 2030 [71]. But a priority was not given for diversified sources of renewables, and progress was never visible on the side of CSP initiatives. No exhaustive techno-economic feasibility evaluation of CSP on Bangladesh's climate is ever visible as the strongest hurdle.

A number of studies and plans have been conducted on solar energy utilization in Bangladesh, the majority of which focused on photovoltaic (PV) technology. Nevertheless, large-scale renewable power stations are required to support continued development and long-term sustainable energy aspirations. Concentrated Solar Power (CSP) with Thermal Energy Storage (TES) offers higher capacity factors and grid stability by mitigating intermittency issues [72]. Despite these advantages, there have been limited studies examining the feasibility of large-scale CSP projects in Bangladesh. Hossain et al. [56] optimally designed a solar tower power plant in a high DNI region of Bangladesh, demonstrating its technical feasibility. Abbas et al. [73] examined the feasibility of CSP in Bangladesh considering Spain's GemaSolar plant as a reference without analyzing the economy. Bhuiyan et al. [15] investigated a 50 MW parabolic trough CSP plant and its economic and exergy viability at eight locations, among which Cox's Bazar was the most favorable location. The paper lacked the explanation of the selection process of the design parameters. Hossain et al. [49] simulated a 150 MW solar tower power plant in Cox's Bazar, evaluating the effect of some of the major heliostat field design parameters, without economic viability. Shabbir et al. [74] conducted a techno-economic evaluation of a 150 MW parabolic trough CSP plant in Chattogram and it was found feasible with low efficiency because of a lack of optimization. Hossain et al. [75] suggested a renewables-based system for round-the-clock electricity generation on Saint Martin's Island predicated on a central receiver system with TES and illustrated that power could be supplied at a cheaper rate than the prevailing tariffs. Hossain et al. [56] conducted techno-economic analysis for a 100 MW Dish Stirling CSP power plant with more efficiency (24.91%) and similar LCOE (0.191 USD/kWh) but low-capacity factor and power output due to the incompatibility of the system with TES. Overseas, the System Advisor Model (SAM) has been used by researchers for CSP modeling. Bishoyi and Sudhakara [76] validated a design of a 100 MW parabolic trough CSP plant in Udaipur, India, which can be used as a reference for similar studies. Bishoyi & Sudhakar [77] also investigated a 100 MW linear Fresnel reflector (LFR) plant for Rajasthan, but power generation was not as anticipated due to the absence of optimization methodology. Ahmad et al. [78]compared CSP power plants under varying climates, and it was found that solar towers are 5–6% less expensive and 3–7% more efficient compared to parabolic troughs but not through optimizing TES load hours and solar multiple (SM). Morin et al. [79] compared LFR and PTC technology and calculated their performance differences. Elfeky et al. [9] evaluated a 100 MW solar tower power plant in Egypt with an LCOE of 11.3 cents/kWh at an SM of 2.8 and TES load of 8 hours without comparing other CSP technologies.

These efforts are geographically limited—mostly confined to Cox's Bazar or select divisional zones, and do not explore comparative performance among different CSP technologies using robust simulation tools like System Advisor Model (SAM). Furthermore, multi-objective optimization techniques for minimizing LCOE and maximizing energy yield (via key parameters like SM, TES hours, HTF choice, and receiver efficiency) are largely absent.

To clarify these gaps, Tables 2.1 and 2.2 provide a comparative summary of both global and Bangladesh-specific CSP research. These highlight a lack of district-wide assessments, insufficient techno-economic modeling, and the absence of technology comparisons tailored to Bangladesh's climatic and economic conditions.

Table 2.1 Comparative Summary of Global CSP Research.

Authors	Year	Focus	Research Gaps	Locations (L)	Technology & Capacity	LCOE (¢/kWh)	TES (hr)
Elfeky & Wang [9]	2023	Techno-economic assessment (TEA) & Optimization	One Technology & No Comparison With Existing CSP	Egypt (6 L)	ST (100 MW)	10.57	8
Bayoumi et al. [80]	2023	Multi-criteria performance	Optimization & TEA	Egypt (28 L)	ST+PTC (2*115 MW)	5.5-7 for ST 6-9 for PTC	10
Seepana et al. [36]	2022	TEA & Environmental Impacts	Optimization, One Technology & limited Comparison	India (6 L)	ST (100 MW)	12-17	6
Alfailakawi et al. [48]	2022	Aerosol impact on economics	Optimization & One Technology	Kuwait	ST (50 MW)	12.06-12.87	16
Tahir et al. [81]	2021	TEA	Optimization & One Technology	Pakistan (6 L)	PTC (100 MW)	14.7-15.3	15
Agyekum et al. [82]	2020	TEA of two CSP types	Two Technology & No Comparison	Ghana (2 L)	ST+PTC (2*100 MW)	13.6 for ST 25.8 for PTC	12
Abdelhady [57]	2020	SD performance & cost evaluation	Optimization & No Comparison	Egypt	SD (50 MW)	13.38	Not Performed
Tasbirul et al. [5]	2019	Energy mix & land optimization	Optimization of land & Small scale	Malaysia (16 L)	ST+PTC +SD (3*10 MW)	17 for PTC 18.6 for ST 43.8 for SD	Not Performed

Table 2.2 Comparative Summary of Bangladesh-specific CSP Research.

Authors	**Year**	**Focus**	**Research Gaps**	**Locations (L)**	**Technology & Capacity**	**LCOE (¢/kWh)**	**TES (hr)**
Rabbir et al. [83]	2025	Large-scale CSP potential & challenges	Lacked detailed TEA & Optimization	5 locations	ST+PTC+LFR (3×50 MW)	12.51	6
Yeamin et al. [84]	2024	Simulation & feasibility survey	One technology & No TEA	Rajshahi, Kishoreganj	ST (100 MW)	19.4	5
Hossain et al. [56]	2023	SD CSP performance	One technology & lacks TEA compatibility	Cox's Bazar	SD (100 MW)	10.18	Not Performed
Abbas et al. [73]	2021	Technical feasibility study	No economic analysis	6 locations	Unspecified	Not Performed	Not Performed
Bhuiyan et al. [15]	2020	4E (Energy-Exergy-Economic-Environmental) analysis & Optimization	One technology & Limited TEA	8 locations	PTC (50 MW)	9.86-10.13	8
R. Islam et al. [1]	2017	CSP review & Opportunity study in Bangladesh	Optimization & TEA missing	8 locations	General feasibility	Not Performed	Not Performed

Thus, this study fills these gaps by:

- Evaluating four CSP technologies (PTC, ST, LFR, and SD) under Bangladesh-specific conditions.
- Conducting district-wide DNI analysis for all 64 districts.
- Performing multi-objective optimization using SAM to determine the most viable configurations.
- Recommending deployment strategies, including a potential 600 MW CSP roadmap for policy consideration.

2.5 Novelty of The Present Study

Concentrated Solar Power (CSP) is a well-established renewable energy technology with significant potential for large-scale electricity generation. However, despite its prospects, a comprehensive techno-economic feasibility analysis of large-scale CSP plants in Bangladesh or similar climatic regions remains largely unexplored in the literature. This study seeks to fill this critical research gap by conducting a detailed investigation into the feasibility, optimization, and comparative performance of various CSP technologies, including solar tower, parabolic trough (PTC), linear Fresnel reflector (LFR), and solar dish systems.

The Power System Master Plan (PSMP)- 2016 charts an ambitious trajectory for Bangladesh's energy sector, forecasting a total energy demand of 60,000 MW by 2041 [8]. In alignment with global sustainability goals, the plan aims to generate 10% of this demand from renewable sources, with 600 MW specifically allocated for CSP plants positioned in strategic locations across the country. Despite this national commitment, limited research has been conducted to assess the feasibility, viability, and optimal configurations of CSP plants tailored to Bangladesh's unique climatic and geographic conditions.

This research involves the design, modeling, and optimization of three 150 MW concentrated solar power (CSP) plants—namely solar tower, parabolic trough collector (PTC), and linear Fresnel reflector (LFR)—to evaluate their potential for integration into the national grid. In addition, a 150 MW solar dish system has been studied as a standalone, off-grid power solution. The System Advisor Model (SAM) has been utilized to simulate yearly energy output, fine-tune critical design parameters, and perform a comparative assessment of the CSP technologies in terms of power output, operational efficiency, and cost-effectiveness [85].

An important outcome of this research is the creation of an optimized design framework for Concentrated Solar Power (CSP) plants using advanced multi-objective optimization methods. The study systematically adjusts key design variables—such as solar multiple (SM), design-point direct normal irradiance (DNI), and receiver temperature—to achieve the lowest possible levelized cost of electricity (LCOE) while simultaneously enhancing energy output and system efficiency. This tailored optimization strategy is not only well-suited to Bangladesh's conditions but also holds potential for adaptation in other regions with comparable solar and climatic profiles.

In addition, the research offers strategic guidance for renewable energy planning in Bangladesh, supporting evidence-based policymaking, infrastructure development, and the integration of utility-scale solar energy. By illustrating the technical feasibility, cost-effectiveness, and environmental advantages of CSP technologies, the study aids in advancing national goals related to energy access, sustainability, and climate resilience. The approaches and models proposed here may also serve as valuable tools for engineers, researchers, and decision-makers involved in CSP implementation across diverse global settings.

Chapter 3: Research Methodology

This chapter describes the design adopted by this research to achieve the aims and objectives stated in Section 1.5 of Chapter 1. It provides a detailed explanation of the assessment methods used for climate conditions, site selection, and feasibility analysis for CSP implementation in Bangladesh. The chapter further discusses key economic and material considerations essential for CSP development. Additionally, it presents the research tools and simulation methodologies applied in this study, including the System Advisor Model (SAM) for performance analysis and an iterative multi-objective optimization approach for refining design parameters. Section 3.8 details the optimization of CSP plant configurations, focusing on energy concentration, solar multiple, and thermal energy storage (TES) to maximize power output and minimize LCOE. Finally, Section 3.9 summarizes the key findings and methodological approach presented in this chapter.

3.1 Introduction

Concentrated Solar Power (CSP) systems harness direct solar radiation to produce electricity, making their performance highly dependent on the availability of high-intensity sunlight. As a result, the most favorable locations for CSP deployment are typically found within the "Sunbelt" — a geographic belt around the globe characterized by high levels of direct solar irradiance. Based on satellite-derived data for Direct Normal Irradiance (DNI), shown in Figure 3.1, Bangladesh lies within a moderately suitable region, indicating potential for CSP applications, though with some limitations compared to high-DNI zones.

CSP power plants generate electricity using direct solar radiation and convert it to energy and therefore are ideally placed for installation in the Sunbelt nations of the world. In accordance with satellite observations of Direct Normal Radiation (DNI), Bangladesh is found to fall into a moderate category for installing CSP plants. Generally, a region needs a minimum of 1800 - 2000 kWh/m^2 per year for CSP plants to be economically viable, with the best locations having more than 2800 kWh/m^2 per year [5], [82-84].

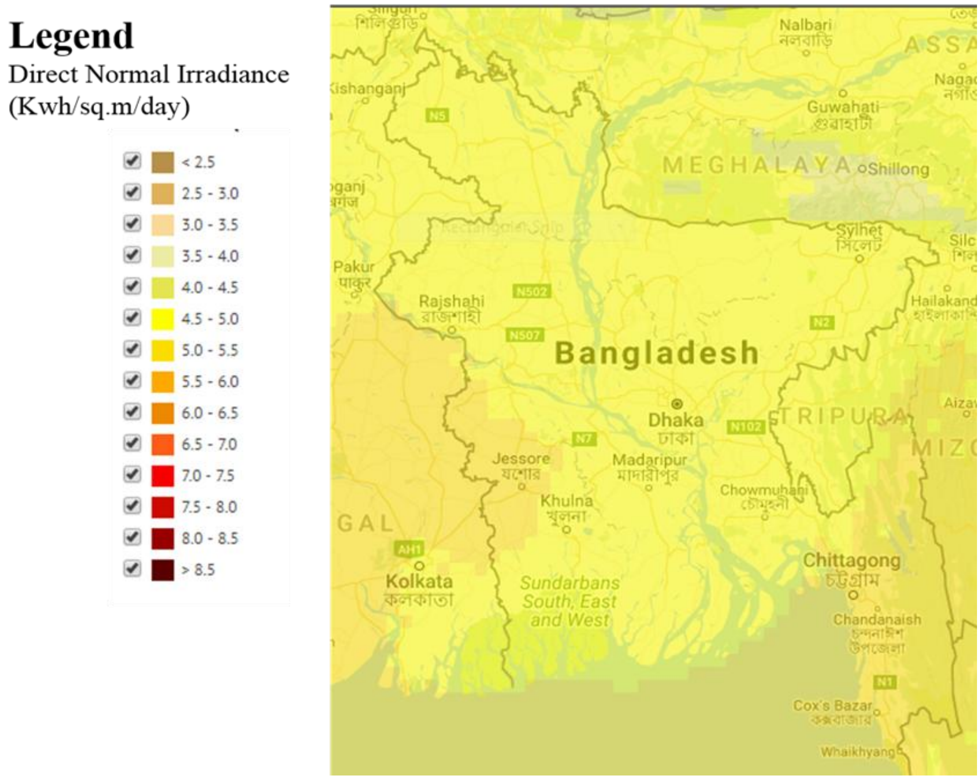

Fig 3.1 Direct Normal Irradiance of Bangladesh. Reproduced with Permission from [89].

Although these DNI values constitute the benchmarks, feasibility in reality depends on site-specific conditions. The most suitable areas for CSP deployment globally are North and South Africa, the Middle East, Northeast India, Australia, and North and South America, which collectively overlap extensively with arid areas. In the case of Bangladesh, solar power is a viable solution to meet rising energy demands. As a developing country, Bangladesh can reap the maximum advantage from solar energy due to its high exposure to sunlight and low cost compared to other forms of energy, which are expensive and environmentally unfriendly. With the advancement in solar technology, electricity can be made cheaper and more efficient. Effective utilization of solar energy can reduce dependence on the national grid and improve the standard of living of the people. By prioritizing solar power above all other forms, Bangladesh can be a paradigm for the use of renewable energy.

3.2 Climate And Solar Resource Assessment

3.2.1 Climate Conditions of Bangladesh

The climate of any region is influenced by long-term atmospheric patterns near the Earth's surface, which include variables such as temperature, rainfall, humidity, wind patterns, cloud formation, and air pressure. The geographical setting and physical features of a country significantly influence its climatic characteristics. Bangladesh lies between latitudes 20°34'N and 26°38'N and longitudes 88°01'E and 92°41'E. The majority of its landscape is comprised of flat, low-lying plains, with the exception of the south-eastern part, which features hilly topography.

To the east, Bangladesh is flanked by the Assam Hills; to the north lies the Meghalaya Plateau, with the towering Himalayan range situated even further north. The Bay of Bengal borders the country to the south, while the western boundary connects with the plains of West Bengal and the extensive Gangetic Plain. Climatically, Bangladesh falls within the tropical monsoon zone and is characterized by high temperatures, substantial rainfall, persistent humidity, and distinct seasonal transitions [90].

Bangladesh's climate is distinguished by a seasonal shift in wind patterns between summer and winter, which plays a crucial role in the overall climatic system of the South Asian subcontinent. The country experiences three primary seasons based on climate trends: a cool and dry period from November to February, a hot pre-monsoon season from March to May, and a rainy monsoon phase from June to October. Additionally, March is often associated with spring, and the time between mid-October and mid-November is occasionally referred to as autumn.

The dry season typically begins in mid-December in the west-central region, lasting for around four months. It gradually moves eastward and southward, reaching the eastern and southern parts of the country by mid-March, where it persists for about a month.

The pre-monsoon hot season is noticeable by high temperatures and frequent thunderstorms. April is typically the hottest month, with average temperatures ranging from 27°C in the east and south to 31°C in the west-central region. In some areas of western Bangladesh, summer temperatures can rise to 40°C [90]. However, after April, temperature reduces due to increased cloud cover. This pre-monsoon period acts as a transition phase, during which the cold northerly and north-westerly winds of winter gradually shift to the warm southerly and south-westerly winds of the summer monsoon, which lasts from June to September. At the start of this season, winds are weak and inconsistent. But as it progresses, wind speed increases and wind direction stabilize.

In the early pre-monsoon phase, a narrow band of air mass discontinuity stretches across the country from the southwest to the northeast. This zone serves as the boundary between the hot, dry air from the upper Gangetic Plain and the warm, moist air from the Bay of Bengal. As the season progresses, this discontinuity weakens, gradually shifts to the northwest, and eventually dissipates by the end of the season, clearing the way for the onset of the summer monsoon. The rainy season, which coincides with the summer monsoon, is characterized by southerly and south-westerly winds, high humidity, and intense rainfall. This period is marked by prolonged spells of continuous rain, occasionally interrupted by brief dry periods. Tropical depressions moving from the Bay of Bengal are the primary cause of the rainfall during this time.

Bangladesh experiences seasonal variations in atmospheric pressure and wind patterns between summer and winter. In winter, a high-pressure system develops over north-western India, causing cold air to flow eastward and enter Bangladesh through the northeast after a nearly right-angled clockwise turn. This wind movement is part of the larger winter monsoon circulation of the South Asian subcontinent. During this time, the prevailing winds in Bangladesh are generally from the north or northwest.

In contrast, during the summer, intense surface heating creates a low-pressure center over west-central India. This causes warm, moisture-rich air from the Bay of Bengal to move toward the low-pressure area, passing through Bangladesh. A similar air flow is seen from the Arabian Sea to India during this season. The wind in summer generally flows toward the low-pressure zone, part of the South Asian monsoon system, bringing southerly winds—either from the south, southwest, or southeast. In transitional seasons like spring and autumn, wind directions become more unpredictable. Wind speeds are typically higher in summer, ranging from 8 to 16 km/hr, compared to the slower speeds of 3 to 6 km/hr in winter. Atmospheric pressure varies as well, with an average of 1,020 millibars in January and 1,005 millibars from March to September.

January is the coldest month in Bangladesh, but the cold air from north-western India weakens significantly by the time it reaches the northwest of Bangladesh. During January, average temperatures range from around 17°C in the northern and northeastern regions to 20°C–21°C along the coastal areas. In late December and early January, the minimum temperatures in the northernmost and northeastern regions may dip to 4 to 7 degrees Celsius above freezing. As winter transitions into the pre-monsoon season, temperatures begin to rise, peaking in April, which is the hottest month before the monsoon.

In April, average temperatures range from 27°C in the northeast to 30°C in the west-central regions of the country. In areas like Rajshahi and Kushtia, summer temperatures can exceed 40°C. Following April, temperatures slightly decrease as the rainy season begins. The increased cloud cover towards the end of the pre-monsoon season helps cool the air. By July, average temperatures vary from 27°C in the southeast to 29°C in the northwest.

March and April are the driest months in the western parts of Bangladesh. The lowest average relative humidity recorded in March is 57% in Dinajpur. In the eastern regions, the least humid months are January to March, with Brahmanbaria recording a low of 58.5% in March. From June to September, the relative humidity remains above 80% across the country. The annual average relative humidity ranges from 78.1% in Cox's Bazar to 70.5% in Pabna [91].

In Bangladesh, cloud cover exhibits two distinct seasonal patterns corresponding to the winter and summer monsoons. During the winter, cold and dry winds from northwestern India limit cloud formation, resulting in an average cloud cover of about 10% nationwide. As the season progresses, cloud cover gradually increases, reaching approximately 50-60% by the end of the pre-monsoon hot period. The summer monsoon, which coincides with the rainy season, leads to significant cloud coverage. During the peak months of July and August, cloud cover ranges from 75% in the northwest to 90% in the southern and eastern regions. After the monsoon season ends, cloud cover decreases swiftly, falling to about 25% in the northern and western parts, and 40-50% in the southern and eastern regions [90].

Rainfall is the most important climatic element in Bangladesh, largely due to its position within the tropical monsoon zone, which leads to substantial rainfall. The annual pattern of rainfall follows a clear seasonal trend, which is more noticeable than temperature changes. The winter months are especially dry, accounting for just 2-4% of the total yearly rainfall. In this season, rainfall varies from under 2 cm in the western and southern regions to slightly more than 4 cm in the northeast, where the Meghalaya Plateau causes the uplift of moist air, enhancing precipitation [92].

During the pre-monsoon hot season, rainfall varies across regions, with the west-central part receiving around 20 cm, while the northeast experiences over 80 cm due to similar uplifting effects. The bulk of rainfall occurs during the monsoon season, which is influenced by tropical depressions originating from the Bay of Bengal. This season contributes about 70% of the annual rainfall in eastern Bangladesh, 80% in the southwest, and over 85% in the northwest. Rainfall during the monsoon season ranges from 100 cm in the west-central region to more than 200 cm in the south and northeast. The number of rainy days varies, from 60 in the west-central region to 95 in the southeastern area, and over 100 days in the northeastern parts. Annual rainfall also varies across the country, from approximately 150 cm in the west-central area to more than 400 cm in the northeast and southeast. The highest rainfall is recorded in the northern Sylhet region, along with the districts of Cox's Bazar and Bandarban.

Key climatic stations with long-term data include Barisal, Bhola, Bogra, Chittagong, Comilla, Cox's Bazar, Dhaka, Dinajpur, Faridpur, Feni, Hatiya, Ishwardi, Jessore, Khepupara, Khulna, Kutubdia, Madaripur, Maijdi Court, Mymensingh, Patuakhali, Rajshahi, Rangamati, Rangpur, Saidpur, Sandwip, Sitakunda, Sreemangal, Sylhet, and Teknaf.

The Bangladesh Meteorological Department (BMD) is tasked with producing and distributing weather reports nationwide. This includes the observation, recording, operation, and maintenance of weather stations and instruments. The BMD provides daily and weekly weather updates to the public. Weather stations across Bangladesh send their recorded data electronically to the BMD headquarters in Dhaka every day. This data is then analyzed, interpreted, and mapped. The results, along with upper-air observations, satellite images, and radar data collected in Dhaka, are utilized for weather forecasting [90].

To predict the weather, the BMD combines upper-air data, satellite images, and radar information gathered in Dhaka. Satellite and radar imagery are particularly important for forecasting severe weather events, such as cyclones. The department issues weather bulletins and forecasts for 6-hour, 12-hour, and 24-hour intervals, which are broadcast on radio and television. When a cyclone is approaching, continuous observations, updates, and warnings are provided through these media. Additionally, newspapers publish daily weather reports based on the data supplied by the BMD.

Climate change in Bangladesh is a part of the broader global climatic shifts. Scientists claim that Earth's temperature has been rising since the early 20th century. This phenomenon is known as global warming. This warming is primarily attributed to the increased concentration of carbon dioxide (CO_2) in the atmosphere, caused by the burning of fossil fuels. However, not all scientists fully agree with this theory.

It has been estimated by some scientists that before industrialization, atmospheric CO_2 levels ranged from 285 to 290 parts per million by volume (ppmV). Observations from the Mauna Loa Observatory in Hawaii indicate that CO_2 levels have risen from 315 ppmV in 1958 to 352 ppmV in 1988. If this trend continues, it is predicted that CO_2 levels could reach 450 ppmV by 2050. Since the early 20th century, Earth's temperature has risen by approximately 0.3 to 1°C due to increased CO_2 levels. Computer models suggest that if CO_2 concentration doubles from its current level, global temperatures may increase between 1.3°C and 4°C. The temperature rise is expected to be minimal in tropical regions (only 0.05°-0.25°C) but significantly higher in mid-to-high latitude areas (5°-9°C). Furthermore, winter temperatures are expected to rise more than summer temperatures.

Some analysts believe that global temperature increases will have both positive and negative consequences by benefiting some regions and harming others. One significant impact of global warming is the gradual melting of polar and Himalayan ice caps, which is expected to increase sea levels to rise by 2-3 meters by 2050. If this prediction becomes true, many low-lying coastal and delta regions worldwide will be submerged which will lead to the loss of fertile agricultural land. This could result in reduced food production, worsening food shortages, increasing poverty and widespread human suffering. If sea levels rise as projected, a large portion of southern Bangladesh may be engulfed by the Bay of Bengal [92].

3.2.2 Annual Direct Normal Irradiance (DNI) Analysis

For the efficient operation of a Concentrated Solar Power (CSP) plant, a sufficient and consistent amount of Direct Normal Irradiance (DNI) is essential. DNI refers to the intensity of solar radiation that directly reaches the Earth's surface without being scattered by the atmosphere. It is the key parameter determining the feasibility of CSP technology, as CSP plants rely on direct sunlight to generate thermal energy efficiently. The annual DNI in Bangladesh ranges from 4 to 6.5 $kWh/m^2/day$, with the highest values observed in regions such as Chapai Nawabganj, Bandarban, and Cox's Bazar. These areas receive higher solar radiation due to lower cloud cover and drier climatic conditions compared to other parts of the country.

Fig. 3.2 illustrates the average annual DNI distribution in Bangladesh, highlighting the regions with the highest solar potential. DNI refers to the intensity of solar radiation that reaches the Earth's surface directly from the sun without being scattered by the atmosphere. Bangladesh is situated in an advantageous geographical position, lying between 20.30° to 26.38° north latitude and 88.04° to 92.44° east longitude. Due to its proximity to the equatorial plane, sunlight strikes almost perpendicularly in this region. Bangladesh is located very close to the equator at approximately 23.50° north latitude which makes it suitable for harnessing solar energy.

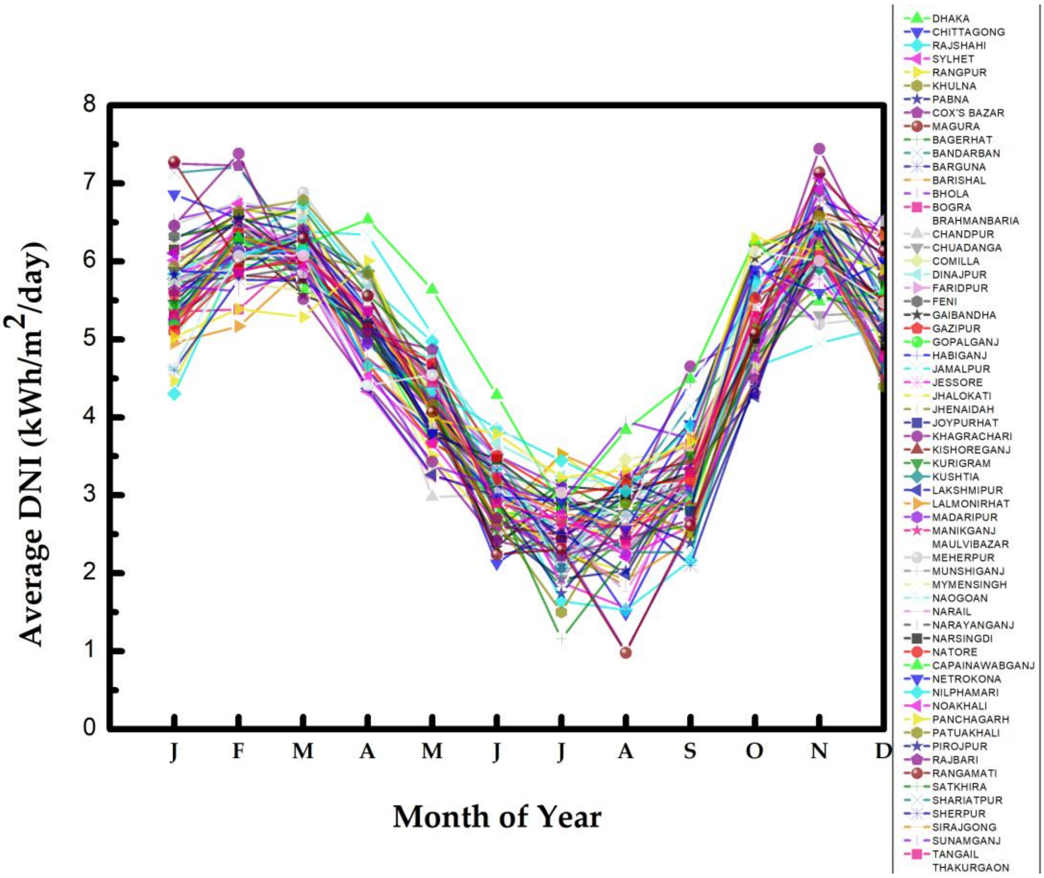

Fig. 3.2 Average DNI in Bangladesh.

DNI varies across the country, ranging from 4 to 6.5 kWh/m²/day. For CSP technology the required annual average Direct Normal irradiations (DNI) is 2 kWh/m²/day. In Bangladesh, there is abundant of solar radiation annually which is nearly 1.9 kWh/m²/day [1-2].

3.3 Site Selection and Feasibility Analysis Approach

Selecting a proper location for a concentrating solar power (CSP) or solar thermal energy system should be carried out with the greatest care. It's best to have a clear checklist and a straightforward plan that fits into the overall project strategy and timeline. Site selection and feasibility study for a CSP plant are more complex than they would seem at first. As opposed to photovoltaics or wind power, where it is possible to install several identical units in parallel and connect them quite easily, solar thermal systems are distinctive and individually designed. They consist of combining a solar field with power generation and, in some installations, combined heat and power, useful for industrial processes or desalination.

Additionally, incorporating thermal energy storage and hybrid fuel sources, including regenerative or fossil fuels, can increase the availability and dispatch of solar thermal power plants. This can make them capable of providing energy at a consistent, base-load level. It's also common for solar thermal projects to import components from abroad to reduce costs.

The project development and implementation schedule of a typical CSP project is typically longer. Development right from the beginning may take 2 to 3 years before it even begins the construction phase. The construction itself takes another 2 to 3 years after that. The plant life is actually over 30 years, while financing loan tenure typically takes 15 to 20 years [93].

3.3.1 Market Analysis for CSP in Bangladesh

While choosing a specific market, first take into account the general facts and future outlook of Concentrated Solar Power (CSP). The purpose of this market analysis is to make sure that current market conditions and future outlooks are suitable for profitable CSP projects. This has to be done by analyzing systematically such determinants as the energy market, the likely buyers or off-take agreements, energy price spread, and government support level, such as political and legal stability. Where they are in equilibrium, one is able to ascertain if there is sufficient room in the market for sustainable CSP investments.

3.3.2 National and Regional Study for Site Identification

When choosing a location for a solar thermal power plant in a given country or region, it is advisable to get to know the entire region. Instead of driving around the region for long hours trying to find locations, it is possible to employ the use of a Geographic Information System (GIS). A GIS is an application program running on data with geographic coordinates. It combines a database system with other capabilities for handling spatial information and provides capabilities for data analysis [94]. GIS allows you to combine various types of remotely sensed data and information collected from ground surveys. This entails having reliable data sets, i.e., direct normal irradiance (DNI), topography, roads, electric grids, surface water, and hydrological maps. According to pre-defined selection criteria and algorithms, GIS allows identification of the most suitable locations for a CSP plant. These locations can then be analyzed in more detail. For example, a GIS-based selection process with respect to different factors is demonstrated for North Africa in Broesamle's study [95].

3.3.3 Pre-Feasibility Analysis of Potential Sites

The objective of a pre-feasibility study is to determine the overall viability of a proposed project location at an early phase, based on preliminary but extensive information. It is not necessarily simple to commence the pre-feasibility analysis because all the components of the project are connected and can influence each other. This analysis typically includes a "fatal flaw" assessment to identify whether there are any major issues at the project location, an initial site condition survey to determine possible technology configurations, and a summary of the financial projection for the project. The financial analysis considers the project location, available infrastructure, and solar resources. Fig. 3.3 shows Potential Site visit for Pre-Feasibility Analysis at Sonadia Island, Cox's Bazar with available area 2900 acres.

In the initial stages of project development, conceptual designs are translated into early technical models and prototypes to estimate energy output and assess potential economic returns. These preliminary evaluations are typically grounded in engineering assumptions, best-available industry benchmarks, and publicly accessible datasets rather than comprehensive, site-specific measurements.

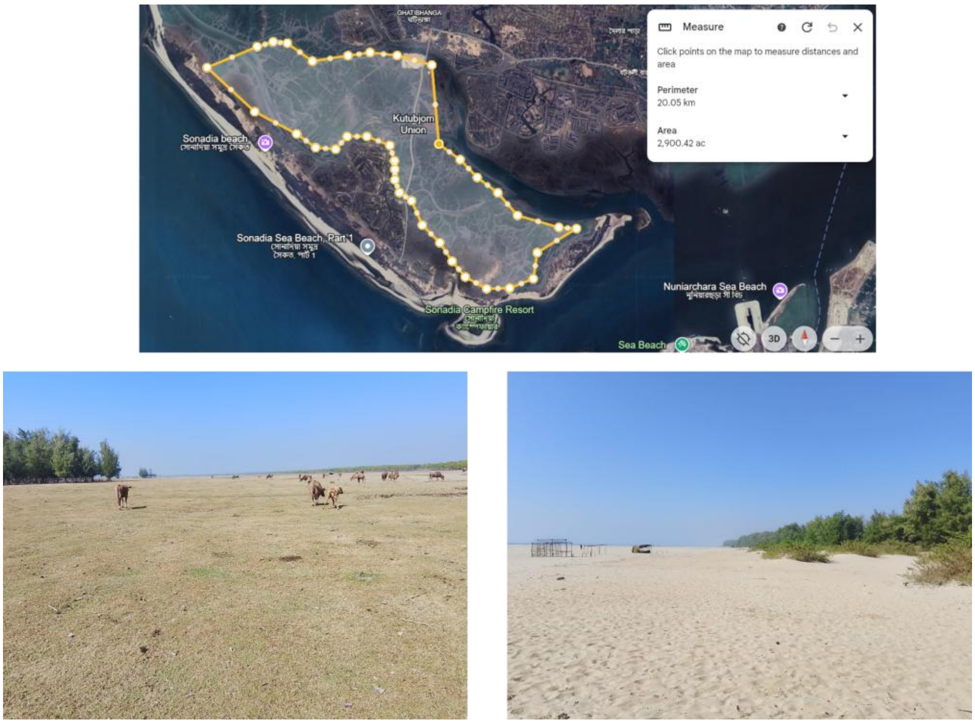

Fig. 3.3 Potential Site visit for Pre-Feasibility Analysis at Sonadia Island, Cox's Bazar.

Fig. 3.4 illustrates a potential site visit conducted as part of the pre-feasibility analysis in Lama, Bandarban—an area identified to have approximately 2,900 acres of land that may be suitable for solar infrastructure deployment.

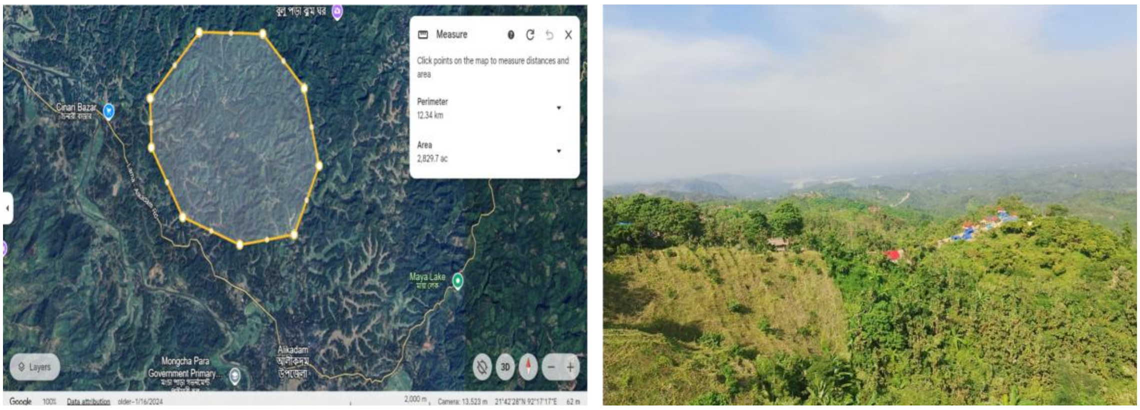

Fig. 3.4 Potential Site visit for Pre-Feasibility Analysis at lama, Bandarban.

To complement the initial assessments, sensitivity analysis is employed to systematically examine how variations in critical parameters can impact project performance and viability. These parameters typically include direct normal irradiance (DNI), the capital cost of solar field equipment, and the expected price of electricity in future markets. By evaluating a range of best-case and worst-case scenarios, this analysis provides a clearer understanding of financial risk, operational performance margins, and return on investment. Ultimately, it assists decision-makers in refining system configurations and prioritizing locations that balance technical viability with economic benefit before advancing to the detailed feasibility and engineering design phases.

In the event of multiple sites being considered, a combined pre-feasibility study can be conducted to identify synergies and rank the sites in order of preference [96] as an example; in deciding between two locations in Bangladesh, this kind of method may be applied. However, since most projects are conducted by private companies and are not publicly known, published examples of such analysis are limited.

3.3.4 Feasibility Analysis Framework

The feasibility analysis builds upon the findings from the pre-feasibility study, moving into a more detailed exploration of the project. Its goal is to refine the project's potential, finalizing many of its specifics and addressing key concerns. Some data that was initially based on assumptions or estimations will now be verified and elaborated upon during this stage.

Specialized studies essential for the feasibility analysis include: a DNI measurement campaign and solar resource assessment, using long-term satellite data in combination with these measurements, geotechnical and topographical site evaluations, technical concept development, energy yield modelling, permit engineering, environmental and socio-economic studies, financial modelling, and legal consultation on administrative processes. The figure below (Fig. 3.5) illustrates the feasible site for the CSP plant installation in Capainawabganj.

Fig. 3.5 Feasible Site for Installation of CSP plant at Capainawabganj.

As with the pre-feasibility process, here again it's not linear. Conclusions of one field do have some degree of impact upon the conclusions resulting from the conclusions in another field. The entire approach remains in circles. Private entities undertake all such projects as have been previously stated, and feasibility reports get infrequently posted to the open area, so hence, for that reason also there is less of published instances here.

3.4 Raw Materials and Economic Considerations

The second stage of the CSP value chain involves sourcing and collecting both raw materials and processed materials. Some of these materials are available on the global market, while others are sourced locally based on factors like cost and logistics. In terms of quantity, concrete, steel, and glass are the primary materials required for a CSP plant. For instance, a 600 MW reference plant would need around 120,000 tons of concrete, between 12,000 and 135,000 tons of steel, and 72,000 tons of glass. These materials are essential for the plant's construction: glass for the mirrors, steel for the mounting framework, chemicals for the heat-transfer fluid (HTF), and insulating materials, along with various metals for the piping system [93-94].

The supporting framework for the system is typically constructed from either steel or aluminum, sourced from conventional metal manufacturers. This structure must be engineered to withstand wind forces and maintain accurate mirror alignment along the entire collector row, which can extend up to 150 meters. In the CSP sector, mirrors may be flat—commonly used in tower and linear Fresnel systems—or curved, as seen in parabolic troughs and dishes. The processes of bending and applying reflective coatings to the mirrors are well-established within the glass industry and can be carried out using standard machinery. High precision in mirror fabrication is crucial, as even slight losses in reflected direct solar radiation can significantly reduce electrical output, negatively impacting the project's economic performance. To be commercially sustainable, mirror production facilities for CSP systems generally need a minimum annual output of over 200 to 400 MW equivalents. Companies that manufacture glass and mirrors often serve various sectors, including the automotive industry [99].

The solar field primarily consists of mirrors, receivers, and their supporting structures. Alongside these, the heat transfer fluid (HTF) system plays a crucial role. This system comprises the HTF itself, associated piping, insulation materials, and pumps. In most modern concentrated solar power (CSP) plants, thermal oil—typically supplied by major chemical manufacturers—is the preferred HTF. Approximately 13 metric tons of thermal oil are required per megawatt (MW) of installed capacity. Insulation materials, used at a rate of about 20 tons per MW, are critical for minimizing thermal losses and enhancing system efficiency, which in turn affects overall power output. Numerous suppliers exist for these materials due to their widespread use.

While thermal oil is common, some CSP systems are exploring the use of molten salt, which offers higher thermal storage capacity. However, it also presents challenges such as the risk of salt solidification at lower temperatures. The operation of CSP plants involves complex and costly equipment like hydraulic pumps to move HTFs through extensive piping networks—ranging from 20 km to 200 km—and heat exchangers that convert thermal energy into steam. These components are typically provided by specialized international firms with significant expertise.

In literature, HTF systems are sometimes classified within the solar field, though this study will consider them as a separate subsystem. Additionally, high-quality electrical, electronic, and hydraulic components—used for controlling mirror alignment and various operations in both the solar field and the power block—are essential to ensure the facility's long-term performance, ideally up to 40 years [100].

3.4.1 Land Cost and Availability

Although the land requirement for a solar thermal power plant is significantly higher than that of a conventional fossil fuel-based power plant, this 600 MW thermal power project incorporates a unique land utilization approach. Unlike other solar thermal plants, this project will allocate 20% of the total land area for infrastructure, including buildings for the turbine, generator, control room, administration office, solar tower access, internal roads and other necessary machinery. The remaining 80% of the land will be dedicated to heliostat or collector installation as well as agricultural activities such as crop cultivation and fisheries. Government allocated plenty of land for mega projects which will boost economic growth of the country.

The heliostats will be positioned at a safe height above ground level which allows the cultivation of crops like Aman or Boro rice beneath them. Since heliostats continuously move throughout the day to track the sun, some portions of the land will receive direct sunlight at different times which supports the agricultural growth. This innovative land-use strategy enables the project to generate multiple streams of income not only from electricity production but also from crop and fish or shrimp farming. As a result, the project's overall revenue potential surpasses that of conventional power plants [1].

3.4.2 Availability of Steel for CSP Infrastructure

While the world steel market is decelerating, Bangladesh's steel sector is increasing at an accelerating rate. It increased by 15% in the past year due to mega infrastructural projects. Industry experts predict consistent growth as government spending on bridges and big-size construction projects increases which drives the steel demand. Bangladesh is becoming one of Asia's leading steel markets because of rising raw material demand and technological improvement in steel production. In 2015, according to estimates by industry organizers, crude steel output was set to rise from below a million tonnes to over three million tonnes [101].

The country's first steel mill, Bangladesh Steel Re-Rolling Mills (BSRM), was established in 1952 by H Akberali Group of Industries in Nasirabad, Chittagong. It initially produced reinforcing bars and structural sections. The organization slowly expanded and added a European cross-nation mill in 1987, which had a wire-rod producing unit as well. In 1996, BSRM set up its factories to produce billets to ensure a steady supply. Later in 2006, it commissioned a trial cold rolling mill for the production of ribbed high-strength wires [102]. Table 3.1 represents Major Players in Steel Market of Bangladesh.

KSRM Steel Plant Ltd has become notable by recently setting up a billet plant in Chittagong. Its plant is set up at Ghoramara, Sitakunda. KSRM is owned by the Kabir Group of Industries and is among the biggest rolling mills in Bangladesh.

Table 3.1 Major Players in Steel Market of Bangladesh [97-103].

Major Players in Steel Market	**Per Annum Production Capacity in MT**
Abul Khair Steel (AKS)	6,40,000
BSRM Group	7,00,000
Mohsteel Limited	500,000
Kabir Steel Rolling Mills Ltd. (KSRM)	800,000
Anwar Ispat Limited	360,000
Ratanpur Steels Re-Rolling Mills Ltd.	187,200
Baizid Steel Industries Ltd.	180,000
Bashundhara Steel Complex Limited	160,000
GPH Ispat Limited	120,000
Bandar Steel Limited	120,000
Sheema Automatic Re-Rolling Mill	45,000

Moreover, a few other steel companies have also become renowned. A few of them are GPH Ispat, Kabir Steel Re-Rolling Mills (AKS), Anwar Ispat, HKG Steel Mills Ltd., Rahim Steel Mills Ltd., Seema Steel Re-Rolling Mills Ltd.and Bashundhara Steels. Bangladesh's steel sector is a major industry today. It is comprised of small and large factories that re-roll and melt steel. They manufacture deformed bar rods of different grades (40, 60, 500), angles, channelsand coils, which are utilized in construction work. The sector is not old but has a bright future. There were no steel mills in Bangladesh before 1971and even after independence, there were only some factories.

The sector started growing in the 1990s when real estate developers and construction companies started developing modern infrastructure. As the demand increased, new investors came into the business of steel and rod manufacturing. In 2012, there were around 400 steel mills in Bangladesh, mainly in Dhaka and Chittagong. Though the majority of the mills run manually, about 30 mills have started using machinery. The majority of the steel companies have become brand names, such as MSW, GPH Ispat, BSRM, RSRM, KSRM, Anwar Steel, HKG Steel, AK Steel, Rahim Steel and Abul Khair Group. BSRM is the country's largest manufacturer of steel. It has been in production for more than 60 years and can produce approximately 750,000 tonnes of steel yearly, which is 26% of the country's needs [97-102].

The industry is also witnessing a shift from grade 60 rods to g500 rods, which allows real estate developers to reduce steel consumption by at least 15%, enhancing cost-effectiveness [107].

3.4.3 Glass Manufacturing Facilities for Reflectors

Glass is a non-crystalline solid. It can undergo change in a process known as the glass transition. This takes place when amorphous materials, or the non-crystal part of semi-crystalline materials, change from being brittle and hard to soft or molten. Glass is usually brittle and often allows light to pass through it. Soda-lime glass is the most common glass. It has around 75% silicon dioxide (SiO_2). It also has sodium oxide (Na_2O) from sodium carbonate (Na_2CO_3), lime (CaO) and a few other trace additives [108].

Prior to examining the Bangladesh glass container market, let's examine the world glass industry first. A study reveals that China, the world's most densely populated nation, has 50% of the market. Europe and other regions come after China. South East Asia has only 7% of the overall market share, while Bangladesh lags much behind in this sector.

One of the most significant reasons why Bangladesh is backward in the glass container sector is that most consumers are not even aware of the benefits of glass bottle usage compared to other forms of packaging materials. Most people have no idea about glass containers. A worrying trend is the growing use of cheap plastic or PET instead of glass packaging. These materials are dirty and unsafe and are not suitable for some products according to industry standards. Moreover, there is little government control in this matter, which aggravates the situation [109]. Table 3.2 shows the Top Contributors in Glass Market of Bangladesh.

Table 3.2 Top Contributors in Glass Market of Bangladesh [104-108].

Contributors in Glass Market	Per Annum Production Capacity in Million sq feet
Usmania Glass Sheet Factory Limited	20
The Bengal Glass Works Limited	35
P H P Glass Factory	40
Nasir Glassware & Tube Industries Limited	40

3.4.4 Labour Availability and Cost

A recent study reveals that Bangladesh has the most affordable labour costs in the automotive and auto parts sector when compared to India, Indonesia, China, and Singapore. According to the findings, Bangladesh allocates only 1.87% of its total production value to wages and labour-related benefits. In contrast, India allocates 8.29%, China about 7%, Indonesia 4.46%, and Singapore the highest at 13.13%. The report, titled "Assessing India's Manufacturing Cost Competitiveness," was prepared in partnership with the Associated Chambers of

Commerce and Industry of India (Assocham) and the Thought Arbitrage Research Institute.

The study states that India is less cost-competitive than China, Singapore, Indonesia and even Bangladesh in the auto and auto components industry. It took into account major parameters such as labour, fuel costs and raw material costs.

Bangladesh spends only 0.18% of what it produces on fuel. China spends 1.22%, while India spends a lot more at 1.99%. Only Indonesia, among the three nations discussed, spends a larger amount on fuel at 2.03% of the output value. Assocham Secretary General DS Rawat pointed out that if India is to achieve its Make in India program and receive more foreign direct investment (FDI), it has to move towards decreasing costs of production across all sectors, especially with the current low global demand. Director of Thought Arbitrage Research Institute, Kaushik Dutta, also pointed out that to be competitive in both domestic and international markets, cost effectiveness is the most important factor since the production cost has a direct impact on price competitiveness. Compared to China, Indonesia and Singapore, India spends far more on raw materials in auto and auto component production [113].

3.5 Key Factors Considered In Pre-Feasibility Study

3.5.1 Land, Topography, and Soil Suitability

Orientation and slope

It is best ideally if the land is oriented north-south. Solar technologies can all adapt to some incline, though the equator-facing orientation is ideal. The parabolic trough systems operate at their best on slopes of up to 2%, while linear Fresnel reflector systems sustain up to 5% slope. Solar tower systems are less forgiving and could be installed on steeper slopes provided proper space for construction, maintenance, and placement of the heliostat in the best possible position. The slope limit is also subject to the tower design since varied designs have varying requirements. Distributed arrays of dish systems are possible, but the systems must be located so as not to shade one another with adequate maintenance access [2].

In parabolic trough plants, the solar field may be divided into small segments, perhaps at different heights with a terracing system. This will enable slopes over 2%. Terraces, however, are expensive to construct, and their extra costs should be included in the overall economic analysis of the project.

Topography and soil

The slope of the land needs to be carefully considered in order to satisfy the requirements. It's important to evaluate the earthworks, area, and requirements for leveling. This includes examination of the conditions of the soil, which play a key role in planning foundations and civil engineering works. In the event of soft soil, it might be necessary to implement robust subsoil structures, whereas sandy ground might be removed or replaced. If the soil is hard, then a lot of effort will be required in leveling. Since the nature of the soil could be varying in a vast area of a project, which could be in several square kilometers, detailed study of the soil of the whole area is crucial for effective planning and estimation.

Free horizon

There should be no objects around that can throw shadows on the mirrors, and the angle above the horizon should be a minimum of 3° to prevent shading. Since the plant will be operational for 20 to 40 years, proper planning should be conducted so that future buildings or tree growth do not create new issues of shading. In addition, aerosols, dust, cooling tower vapor, or stack smoke can reduce Direct Normal Irradiance (DNI), affecting the plant's efficiency.

3.5.2 Infrastructure and Grid Connectivity

In addition to a suitable land area with sufficient solar resource, the standard of the surrounding infrastructure is of significant importance.

Electricity grid

The power generated by the plant needs to be transmitted, so it will have to connect to a high-voltage (HV) power line of a suitable voltage rating. For plants over 150 MW, this will usually mean getting onto a transmission line of between 132 kV and 400 kV, depending on grid code and network conditions.

It would entail the selection of an appropriate tie point by consulting with the grid operator, who would need to decide if the proposed location would fall within the overall network capacity plan. For large generation units, building an additional substation to tap into an HV line is possible, but in most cases, the connection would need to be made at one of the existing substations with adequate available capacity. Every nation has various methods of reserving capacity, and hence there is a need to adhere to local codes and regulations [114]. The distance to the grid should be as short as possible because each kilometre of transmission line adds extra cost. Larger projects can handle longer transmission lines since the cost is spread over a higher energy output.

Transmission line route planning requires careful consideration. Permissions and right of way through properties along the route must be acquired prior to and may be a laborious process since it includes regulatory approval as well as that of land owners. Environmental conditions also need to be taken into consideration as most countries stipulate a specific environmental impact study of transmission lines.

Road network

The road connection has two major roles. One, all the equipment, such as heavy machines, must be transported to the location using trucks when constructing the plant. This means that the road, together with road bridge capacity and ports for international transportation, must be properly planned. Some improvements, which are needed for transport during construction, may be temporary.

For smooth operation of the plant, access roads must be designed as permanent roads. The roads have to accommodate regular material hauling and maintenance work. Consider that throughout the 20–40-year operating life of the plant, major overhauls of steam turbines and generators can be necessary, as well as potential upgrades to the plant. The road design will depend on present needs and future requirements. The approval and the cost of building this road will also depend on how far it is from the nearest public road.

Fuel availability

CSP plants typically rely minimally on supplemental fossil fuels. However, assessing the accessibility and transportation cost of fuel to the project location remains important. In cases where significant fossil fuel input is required—such as in Integrated Solar Combined Cycle (ISCC) systems—the reliability of fuel supply becomes a critical factor in determining the project's feasibility. Such scenarios may necessitate placing the plant near infrastructure like pipelines or railway lines capable of transporting solid or liquid fuels.

3.5.3 Water Availability and Usage Constraints

A solar power facility necessitates a specific amount of water, which is primarily consumed in two main areas:

- Approximately 85–90% is utilized in wet cooling systems, mainly for compensating evaporative losses and blow-down/make-up requirements.
- The remaining 10–15% is allocated for operational processes such as equipment servicing, water demineralization, and cleaning of

mirrors. In systems employing dry cooling, transporting water by truck may also be considered a feasible solution.

Water-steam cycle

Demineralized water is essential for the water-steam cycle in steam-based power generation, a core process in all large-scale concentrated solar power (CSP) systems. In contrast, smaller CSP configurations—such as Stirling dish systems or compact solar towers—typically employ air or gas as the heat transfer fluid (HTF). To meet the specific purity standards required by steam turbine manufacturers, demineralized water must be produced on-site using a dedicated water treatment facility. Although the overall volume of water needed is relatively low, its purity must be meticulously maintained [100].

Process and service water

A power station normally needs process water for diverse uses: rotating equipment bearing cooling (pumps, motors, etc.), cleaning and washing the plant, etc.

Mirror cleaning

To maintain optimal reflectivity, mirrors must be cleaned regularly. The frequency of cleaning varies from one project to another, depending primarily on the amount of dust accumulation at the site and the cost-benefit balance of the cleaning process. Factors such as water and labor expenses, as well as the potential increase in energy output due to improved mirror reflectivity, influence this decision. It is essential to use demineralized water during cleaning to prevent stains on the mirror surfaces.

Condenser cooling system

The volume of water required varies based on the cooling system employed:

- Dry cooling systems use very little additional water, though they might require a larger condenser hot well. However, this does not significantly increase the overall water usage.
- Hybrid cooling towers, which integrate both dry and wet cooling techniques, spray a small amount of water on the exterior of condenser tubes. This water evaporates, aiding in cooling the condensate. Despite the evaporation, these systems consume much less water compared to traditional wet cooling setups.
- Wet cooling tower systems rely heavily on evaporative cooling, leading to water usage roughly ten times greater than that of dry systems. As the water evaporates, dissolved minerals and solids become more concentrated. To manage this buildup—restricted by technical or regulatory standards—a portion of the water is periodically discharged (blowdown) and replenished with fresh water [115].
- Once-through water cooling can be considered if the plants are situated near bodies of water, but for the majority of CSP projects, it is not a feasible option because such areas are typically water-scarce. The method uses the most water, though the water is heated by a few degrees Celsius only before it returns to the water source.

Water quality and volume requirements

Water quality plays a critical role in determining the quantity of water required and in designing appropriate treatment systems. At the early stages of a project, obtaining permits for both water withdrawal and discharge is typically necessary. Environmental regulations often impose restrictions not only on the volume of water used and released but also on the concentration of specific substances in the wastewater.

Several factors influence the total water demand for plant operations, including:

- Expected operational hours and the associated thermal load to be dissipated through the cooling system:
  - Higher efficiency in the power block results in a lower specific water requirement for cooling.
  - Seasonal and yearly variations in solar radiation must be considered. In years with increased sunshine, operational hours may rise by as much as 10% compared to assumptions based on the Typical Meteorological Year (TMY), necessitating updated calculations for plant performance.

To summarize, the quality of locally available water directly affects how much water is necessary for operating a solar thermal power plant, particularly when wet cooling is employed. Regulatory limits on water consumption may constrain plant operations if daily or routine usage exceeds permitted volumes under normal conditions.

3.5.4 Natural Hazards, Risks, and Mitigation

The risk from natural hazards in the chosen area shall be evaluated based on historical events and environmental conditions. The evaluation shall consider risks due to earthquakes, tsunamis, wildfires, floods from nearby rivers, severe storms (such as hurricanes, typhoons, hail, and thunderstorms), and volcanic eruptions, where relevant. Mitigation measures shall then be framed for any risks that are identified as being significant.

Risk management should also have technical protections as part of the design and build of the plant, as well as insurance coverage for any remaining risks. In case a natural hazard that is unique to the chosen location posing a major risk exists, one should check if insurance coverage exists for such an event. When insurance coverage does not exist, the financial risk will lie with the owner of the plant and finance banks. If this kind of risk is not tolerable, the site for the project may be considered inappropriate.

3.6 Overview of Global CSP Deployment

Since its inception in the 1990s, Concentrated Solar Power (CSP) has experienced significant growth, driven by the increasing demand for renewable energy and advancements in thermal energy storage. Over the past decade, CSP capacity has expanded substantially, increasing more than fivefold from below 1 GW in 2010 to approximately 5 GW by 2016. This growth trend has continued, with recent developments pushing global CSP capacity even higher. Fig. 3.6 shows the incremental trend of CSP installation all over the world.

As of 2023, global installed CSP capacity stands at approximately 8.1 GW, with 6.6 GW in operation and an additional 1.5 GW under construction according to the National Renewable Energy Laboratory (NREL). The world's largest CSP plant, Noor Energy 1 in the United Arab Emirates, added 400 MW in 2023, significantly contributing to the total installed capacity[116].

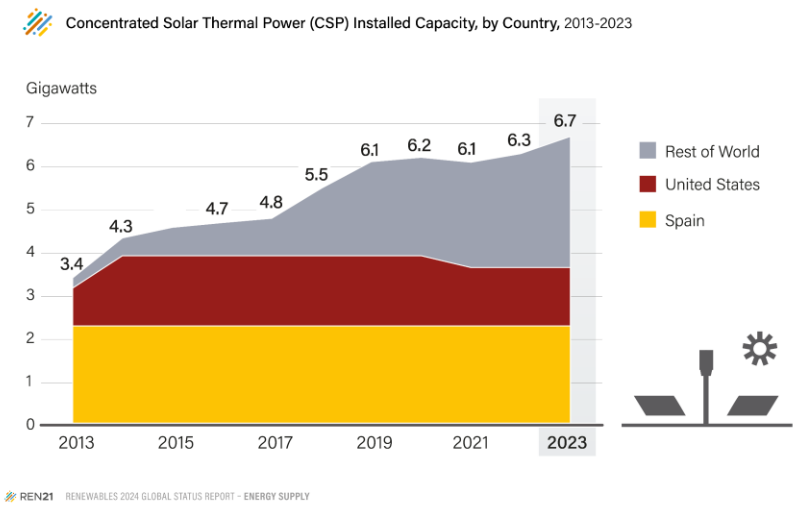

Fig. 3.6 The increment trend of CSP installation all over the world. Reproduced with Permission from [116].

CSP development is concentrated in several key countries, including:

- China: Rapidly emerging as a global leader, China had 40 new CSP projects under construction or commissioning by the end of 2023. The country has been actively investing in third-generation high-temperature CSP technologies to enhance efficiency and cost-effectiveness [117].
- United States: Home to some of the largest CSP plants, including Ivanpah (392 MW) and Crescent Dunes (110 MW), the U.S. has been a pioneer in commercial CSP deployment. However, growth has slowed due to increasing competition from photovoltaic (PV) solar [118].
- Spain: Despite regulatory restrictions limiting CSP facilities to 50 MW, Spain remains a global leader in CSP deployment, with a total installed capacity exceeding 2.3 GW [119].
- Middle East and North Africa (MENA): Countries such as the UAE, Morocco, and Saudi Arabia are investing heavily in CSP due to their high solar irradiation levels. The Dubai Electricity and Water Authority (DEWA) project, which combines 600 MW of parabolic trough and 100 MW of solar tower technology, set a record low CSP tariff of $73 per MWh in 2017 [120].
- Chile: The Atacama Desert, with its high DNI values, has become a hotspot for CSP projects. Recent auctions have seen CSP tariffs fall below $50 per MWh, making it one of the most cost-competitive locations for CSP [120].

3.7 Current Status of Power Generation in Bangladesh

Bangladesh, a rapidly developing country with a burgeoning population, is at a critical juncture in its energy sector development. As one of the most densely populated countries globally, with around 1,118 people per square kilometer, it faces unique challenges in meeting the escalating demand for electricity [121]. Classified as a lower middle-income country by the World Bank in 2018, Bangladesh has consistently achieved economic growth of above 6% since 1998. Its vision to transition to a high-income nation by 2041 hinges significantly on enhancing its energy infrastructure to support a forecasted net electricity demand of 61 GW [8].

The country's economic growth, urbanization, and industrialization have led to an unprecedented increase in energy demand. Currently, the power generation capacity stands at approximately 29,281 MW, with an electricity generation of 602 kWh per capita, markedly lower than that of developed countries. The reliance on fossil fuels is pronounced, with almost 40% of power primarily generated from natural gases and the remainder from coal, liquid fuel (imported), hydropower, and a nascent but booming renewable energy sector contributing around 4.16% to the total electricity generation, including off-grid capacity [122].

Despite achieving a milestone of connecting 100% of the population to the electricity network, the reality of load shedding underscores the persistent challenges of insufficient power plants and the need for a more diversified energy mix [12]. The frequent interruptions in electric power supply to end-users highlight the urgent need for strategic enhancements in the nation's energy policy. This is further underscored by projections suggesting the depletion of domestic fossil fuel reserves within the next decade, emphasizing the imperative to develop a sustainable energy strategy that reduces dependency on domestic natural gas and various imported fuels, including coal, liquefied natural gas (LNG), and imported hydropower.

Amidst these challenges, the global shift towards renewable energy sources offers a viable pathway for Bangladesh to diversify its energy mix, reduce dependence on fossil fuels, and align with international sustainability commitments. However, the integration of renewable energy into the national grid introduces complexities, including variability, storage, and infrastructure development. Thus, a numerical investigation into the optimal mix of energy resources becomes imperative to navigate these challenges and minimize operational costs while ensuring the grid's reliability and sustainability.

The significance of this study lies in its potential to contribute to the national energy policy, offering data-driven insights into cost-effective, sustainable energy solutions. By optimizing the energy mix, Bangladesh can achieve a balance between economic growth and environmental stewardship, paving the way for a resilient and sustainable energy future. Furthermore, this research aligns with the United Nations Sustainable Development Goals, particularly Goal 7: Affordable and Clean Energy, by exploring pathways to increase the share of renewable energy in the national grid.

The objective of this study is to analyze the current energy mix and its associated operational costs within Bangladesh's power system grid and employ numerical methods to investigate and identify an optimal mix of energy resources. This mix aims to minimize operational costs while considering environmental impacts, energy security, and scalability. Through this research, we seek to provide actionable recommendations for energy policymakers, stakeholders, and the scientific community, contributing to the strategic planning and development of Bangladesh's energy sector.

Energy Mix of Bangladesh

As Bangladesh strides towards meeting its growing energy demand amidst rapid economic and industrial expansion, the diversification of its energy mix becomes increasingly pivotal. The current electricity generation mix, as depicted in Table 3.3, showcases the reliance on a variety of fuel sources, with a notable lean towards non-renewable resources.

Table 3.3 Electricity Generation Mix of Bangladesh [88].

Fuel/Resource	Installed Capacity	Share
Coal	5412 MW	18.48%
Gas	11708 MW	39.98%
HFO	6492 MW	22.17%
HSD	490 MW	1.67%
Imported	1160 MW	3.96%
Renewable	1219.24 MW	4.16%
Captive	2800 MW	9.56%
Total	**29281 MW**	100%

Current Composition

- Coal and Gas: Dominating the energy landscape, coal and gas together account for approximately 58.46% of the total installed capacity, underscoring the nation's dependency on fossil fuels for electricity generation.

- Heavy Fuel Oil (HFO) and High-Speed Diesel (HSD): These sources further contribute 22.84% to the mix, highlighting the significant role of imported fuels in Bangladesh's energy sector.
- Renewables and Captive Power: Although renewable sources currently represent a smaller fraction (4.16%) of the total mix, the commitment to expanding this segment is evident. Captive power, often used by industries to ensure reliable supply, accounts for 9.56% of the total capacity.

The renewable energy sector, detailed in Table 3.4, illustrates the burgeoning capacity of solar, wind, hydro, and biomass technologies, both off-grid and on-grid.

Table 3.4 Renewable Energy Generation Summary Report [122].

Technology	Off-grid (MW)	On-grid (MW)	Total (MW)
Solar	370.26	614.91	985.17
Wind	2	0.9	2.9
Hydro	0	230	230
Biogas to Electricity	0.69	0	0.69
Biomass to Electricity	0.4	0	0.4
Total	**373.35**	**845.81**	**1219.16**

Challenges and Opportunities

This data underscores the challenges in balancing the energy mix towards more sustainable sources while managing the inherent variability and infrastructure needs associated with renewables. Yet, it also highlights the untapped potential within the renewable sector, especially in solar and hydro, offering pathways for substantial contributions to the national grid.

Future Directions

To transition to a more diversified and sustainable energy mix, Bangladesh must leverage its existing renewable resources and explore innovative technologies like as CSP and financing mechanisms to scale up renewable energy production. This strategic transition not only tackles environmental issues but also strengthens energy security and promotes economic growth.

3.8 Research Tools and Simulation Methodology

3.8.1 System Advisor Model (SAM) for Performance Analysis

The System Advisor Model (SAM) is a detailed tool for performance and financial modeling, created by the National Renewable Energy Laboratory (NREL) in partnership with Sandia National Laboratories and the University of Wisconsin. SAM is extensively utilized by researchers, engineers, policy analysts, project developers, and technology innovators to assess the feasibility, performance, and economic potential of renewable energy projects, such as Concentrated Solar Power (CSP) plants [85].

Key Features of SAM

SAM provides a robust framework for modeling grid-connected renewable energy systems and supports detailed performance predictions and cost analysis. The tool facilitates decision-making by offering a combination of:

- Technical Performance Modeling – Hourly and sub-hourly simulations of system performance based on site-specific weather data.
- Financial Analysis – Evaluation of costs, revenues, incentives, and financial metrics for different project types.

- Resource Database Integration – Automatic data retrieval from NREL's National Solar Radiation Database (NSRDB) and other sources.
- Sensitivity and Parametric Analysis – Variability assessment of input parameters and their impact on project economics.
- Optimization Capabilities – Fine-tuning system parameters for improved efficiency and economic performance.

Application of SAM in CSP Performance Analysis

SAM provides tailored performance models for various Concentrated Solar Power (CSP) technologies, including Parabolic Trough Collector (PTC), Solar Dish (SD), Linear Fresnel Reflector (LFR), and Solar Power Tower (SPT), making it highly effective for the design and optimization of CSP plants. The software employs a modular structure, where individual components like the solar field, receiver, heat transfer fluid (HTF), thermal energy storage (TES), and power block are modeled independently before being integrated for a thorough performance evaluation.

The modeling process in SAM involves the following steps:

1. Defining System Configuration – Selection of CSP technology, thermal storage, and power block parameters.
2. Specifying Site Conditions – Input of location-specific weather data including Direct Normal Irradiance (DNI), ambient temperature, and wind speed.
3. Defining Financial Parameters – Specification of capital costs, operation and maintenance (O&M) costs, financing structure, and incentives.
4. Running Performance Simulations – Execution of hourly simulations to evaluate power output, efficiency, and annual energy yield.

5. Analyzing Economic Feasibility – Calculation of key financial metrics such as Levelized Cost of Electricity (LCOE), Net Present Value (NPV), and Internal Rate of Return (IRR).

Integration of SAM in the Thesis Work

In this study, SAM has been utilized to evaluate the performance and techno-economic analysis of total 600 MW Parabolic Trough Collector (PTC), Solar Dish (SD), Linear Fresnel Reflector (LFR) and Solar Tower CSP plants in Bangladesh. The software was instrumental in:

- Optimizing key design parameters such as solar field size, receiver dimensions, and thermal storage capacity.
- Assessing plant performance under different DNI scenarios and climatic conditions.
- Comparing economic viability by analyzing various financial models and tariff structures.
- Investigating grid integration aspects to ensure stability and reliability in CSP-based power generation.

By leveraging SAM's simulation capabilities, the study aims to propose an optimized design for large-scale CSP implementation in Bangladesh, considering both technical efficiency and economic sustainability.

Flowchart of SAM-Based Techno-Economic Analysis and Optimization

The overall workflow for conducting techno-economic analysis and optimization using the System Advisor Model (SAM) is illustrated in Fig. 3.7. The process begins with the identification of prospective sites suitable for solar energy deployment, followed by the collection of meteorological data (e.g., DNI, temperature, wind speed) specific to each location. A comprehensive literature survey is then conducted to determine relevant techno-economic parameters, such as capital cost, O&M cost, and thermal storage characteristics.

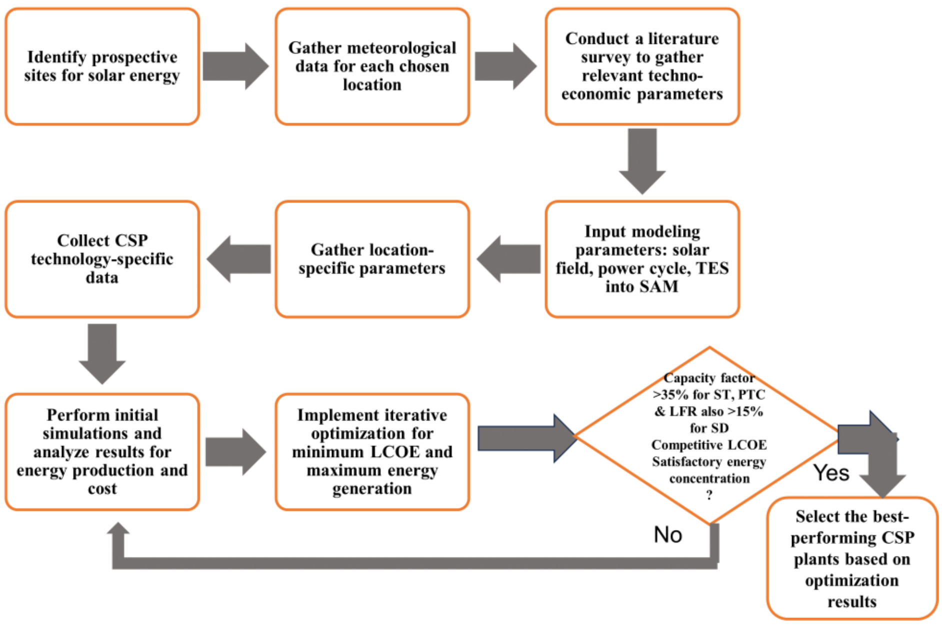

Fig. 3.7 Flow Chart The Detailed Workflow of Using SAM Software for Techno-Economic Analysis and Optimization.

Subsequently, modeling parameters including solar field design, power block configuration, and thermal energy storage (TES) specifications are input into SAM. Alongside this, location-specific parameters such as elevation and land availability, as well as technology-specific data (e.g., optical efficiency, receiver type, HTF selection), are integrated into the simulation environment.

Initial simulations are performed to assess energy yield, capacity factor, and Levelized Cost of Electricity (LCOE). Based on the preliminary results, an iterative optimization process is carried out to minimize the LCOE while maximizing annual energy generation. This includes refining design parameters and re-running simulations until optimal techno-economic performance is achieved.

Optimization Process in SAM Framework

The optimization process employed in this study is performed using the parametric analysis and manual iterative tuning features available in the System Advisor Model (SAM). SAM allows users to conduct extensive parametric sweeps across multiple input variables—such as solar multiple, TES capacity, heliostat field size, and receiver dimensions.

In this study, a multi-objective optimization approach is applied manually by balancing two key objectives: minimizing the Levelized Cost of Electricity (LCOE) and maximizing annual electricity generation. The tuning process involves the following steps:

1. Selection of key design parameters affecting performance and cost.
2. Running simulations over a defined range for each parameter using SAM's parametric analysis tool.
3. Analyzing trade-offs between LCOE and energy output, identifying the Pareto-optimal front.
4. Refining parameter ranges based on trends observed in initial runs.
5. Finalizing optimal design configuration where further reduction in LCOE leads to unacceptable loss in energy yield or vice versa.

3.8.2 Multi-Objective Optimization for Design Parameters

The CSP plants in this study were optimized using a multi-objective iterative optimization method. This method refines design variables through repeated iterations to achieve the best balance between conflicting objectives like cost and efficiency. During each iteration, potential solutions are assessed, and trade-offs are examined to strike a balance between the competing goals. The process is repeated until a set of solutions is found that most effectively meets the various objectives.

In this study, the key parameters for the CSP plants were energy concentration, solar multiple, and TES full load hours. The main goals of the optimization were to maximize annual energy generation and minimize the levelized cost of electricity (LCOE). A summary of the input parameters, objectives, and their units used in the iterative multi-objective optimization process is provided in Table 3.5. This optimization framework was designed to examine the trade-offs between these factors, aiming to achieve the best possible balance between economic viability and energy production.

Table 3.5: Input Variables, Objectives, and Unit of the Optimization Approach

Optimization Section	**Parameter**	**Unit**
Input Variable	Energy concentration	TWh/acre
	Solar multiple	-
	TES full load hour	Hours
Objectives	Minimizing LCOE	cents/kWh
	Maximizing annual energy	TWh

3.9 Summary

This chapter outlined the research methodology adopted in this study, detailing the tools and techniques used for analyzing CSP plant feasibility, performance, and optimization. The System Advisor Model (SAM) was identified as the primary simulation tool, enabling comprehensive techno-economic evaluations of various CSP technologies. SAM facilitated the assessment of system performance under different climatic conditions, financial structures, and grid integration scenarios.

Additionally, an iterative multi-objective optimization approach was employed to refine key design parameters, including energy concentration, solar multiple, and TES full load hours. The optimization process aimed to achieve a balance between maximizing annual energy output and minimizing the levelized cost of electricity (LCOE), ensuring economic and operational efficiency.

The findings from this methodological framework provide a solid foundation for the subsequent analysis of CSP deployment in Bangladesh. The insights derived from these simulations and optimizations will guide decision-making in the selection and design of CSP plants that align with the country's renewable energy goals.

Chapter 4: Results Analysis and Discussion

This chapter presents a comprehensive analysis of the results obtained from the optimization and design of Concentrated Solar Power (CSP) plants. Section 4.1 provides an introduction to the chapter, outlining the key aspects of the study. Section 4.2 discusses the selection of the design point based on climatic and geographical conditions. Section 4.3 focuses on the optimization and design of solar fields, detailing the receiver and collector configurations for different CSP technologies, including Parabolic Trough Collector (PTC), Solar Tower (ST), Linear Fresnel Reflector (LFR), and Solar Dish (SD). Section 4.4 evaluates the selection of Heat Transfer Fluids (HTF) for different CSP technologies, while Section 4.5 discusses the power cycle and Thermal Energy Storage (TES) systems incorporated in the plant designs. Economic modelling and cost estimation are covered in Section 4.6, followed by a detailed techno-economic analysis of the optimized CSP plants in Section 4.7. Section 4.8 provides a viability analysis of CSP plants in Bangladesh and recommends suitable locations for installation. A comparison of CSP with other energy sources in Bangladesh is discussed in Section 4.9, highlighting the feasibility of large-scale CSP deployment. Section 4.10 presents a comparative analysis of the CSP plants designed in this study with existing operational CSP plants worldwide. Finally, Section 4.11 summarizes the key findings and provides concluding remarks for Chapter 4.

4.1 Introduction

This chapter provides an in-depth analysis and optimization study of different Concentrated Solar Power (CSP) technologies tailored for potential deployment in Bangladesh. It starts by outlining the design parameters for several CSP systems, including Solar Tower (ST), Parabolic Trough Collector

(PTC), Linear Fresnel Reflector (LFR), and Solar Dish (SD). Each technology's performance is assessed through simulation, focusing on critical indicators such as capacity factor, annual energy output, levelized cost of electricity (LCOE), and net present value (NPV).

A comparative evaluation is carried out to determine the efficiency and practicality of these CSP technologies across regions in Bangladesh with high solar irradiance. The chapter also details the optimization strategies used to identify the most promising CSP configurations from both energy production and economic perspectives. Furthermore, a benchmarking analysis is performed, comparing the simulated CSP systems with established international projects like NOOR III (ST), NOOR II (PTC), Dhursar (LFR), and a Dish-Stirling project from Algeria. This comparison highlights both the opportunities and constraints involved in adopting CSP technologies in the Bangladeshi context.

The results and insights from this analysis form the basis for proposing the optimal location and configuration of a 600 MW CSP plant in Bangladesh, taking into account solar potential, land availability, and financial feasibility.

4.2 Selection of Design Point

Choosing the right design point is essential for maximizing the efficiency and performance of Concentrated Solar Power (CSP) plants. Although specific design parameters differ based on the CSP technology employed, two core factors—design point Direct Normal Irradiance (DNI) and design point temperature—are consistently relevant across all CSP technologies analyzed in this research.

A review of existing literature reveals that these parameters are often chosen arbitrarily, with limited justification or explanation. In many cases, researchers select the mean value of DNI for a given location as the design point. However, this approach can lead to inaccuracies in solar field sizing, resulting in overestimation or underestimation of the required solar field area. Specifically, selecting the mean DNI value tends to oversize the solar field, leading to increased capital costs, while selecting the most frequent DNI value tends to undersize the solar field, reducing the overall energy yield.

To minimize inefficiencies, the National Renewable Energy Laboratory (NREL) advises selecting the design-point Direct Normal Irradiance (DNI) within the 90–95% range of the probability density function (PDF) or cumulative distribution function (CDF) of the DNI at the specific site. This approach helps ensure the chosen value accurately represents typical operating conditions while achieving a balanced trade-off between system efficiency and economic feasibility.

For Cox's Bazar, the location chosen for this study, the design point DNI has been determined based on the DNI distribution curve shown in Fig. 4.1. According to the probability analysis, a DNI value of 801 W/m² has been selected, as it falls within the 90–95% range of the cumulative distribution function (CDF), ensuring a well-balanced system design.

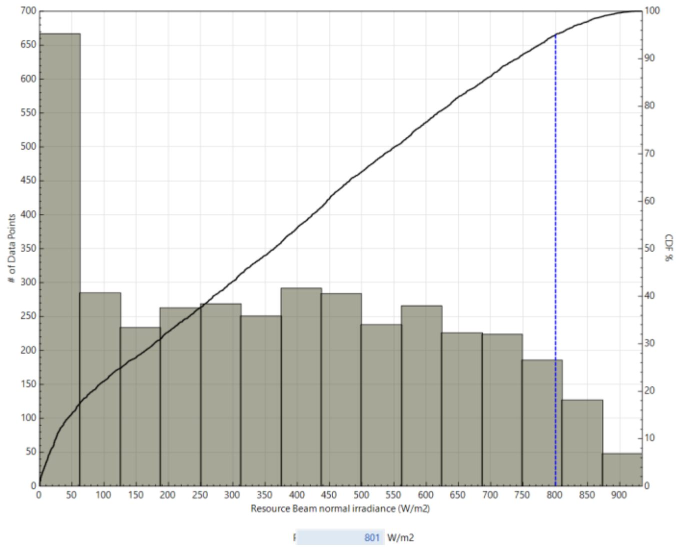

Fig. 4.1 Design Point DNI Selection.

By adopting this systematic approach, the CSP plant design avoids common pitfalls associated with arbitrary DNI selection, leading to improved efficiency, cost-effectiveness, and reliability in energy generation.

4.3 Optimization & Design of Solar Field

In a Concentrated Solar Power (CSP) system, the solar field contains mirrors or collectors that focus sunlight onto a receiver. For Parabolic Trough Collectors (PTC) and Linear Fresnel Reflectors (LFR), this receiver lies along a focal line, whereas in solar tower systems, the receiver is positioned at a central focal point. A Heat Transfer Fluid (HTF) circulates through the receiver, absorbs thermal energy, and then transfers the heat to water via a heat exchanger, generating steam for power production.

4.3.1 Solar Field and Receiver Design of PTC

The individual smallest unit in a parabolic trough solar field is called a module. Various modules joined up in series but driven by one drive system produce what is described as a solar collector assembly (SCA). The employed collector in the current research is the SkyFuel SkyTrough with an outer diameter (OD) of 80 mm of the receiver. The collector has been chosen to perform optimally for the Bangladesh climate, with high efficiency under typical moderate direct normal irradiance (DNI) conditions. The collectors are arranged in rows with 15 meters of space between them to prevent shading from neighbouring collectors. It might at first sight seem sensible to have greater curves on the collectors to capture more sunlight, but greater curvature reduces overall efficiency in terms of heat. This is because with greater curvature, the distance between the collector surface and its focal point is greater.

The optimal value of the aperture diameter can be obtained by equation (4.1)[123],

$$Optimum\ Aperture\ Diameter = \frac{Pgross}{DNI \times \eta, optical \times \eta, loop} \quad (4.1)$$

Where, $Pgross$ is the Gross Power Delivered to the Power Cycle (W), DNI is Direct Normal Irradiance (W/m2), $\eta, optical$ is Gross Optical Efficiency (%) and $\eta, loop$ is Loop Optical Efficiency (%).

In this configuration, the receiver consists of a metal tube enclosed within a vacuum and housed inside a glass envelope aligned with the focal axis of a parabolic trough collector (PTC). Bellows seal both ends of the tube, preserving the vacuum environment within the glass enclosure. The Solel UVAC 3 receiver is selected for its favorable thermal performance under the given climatic conditions.

To minimize solar radiation losses, the glass envelope is treated with an anti-reflective coating. Additionally, the metal tube is coated with specialized selective absorptive paint, which enhances heat absorption by effectively capturing and retaining solar energy.

For successful integration of the receiver and collector in this study, certain adaptations are necessary. These adjustments are aimed at ensuring optimal compatibility between the Solel UVAC 3 receiver and the SkyFuel SkyTrough collector. Possible modifications include altering the structure of the trough, such as repositioning components or reshaping the reflector, to more precisely focus solar energy onto the receiver.

4.3.2 Heliostat Field and Receiver Design of ST

Heliostats are flat mirrors capable of dual-axis rotation, primarily designed to follow the sun's movement and redirect its rays toward a designated target called the receiver within the solar field. In addition to this core functionality, heliostat systems must be configured with certain operational parameters, including stow and deploy angles, as well as a defined wind stow speed. The wind stow speed represents the threshold beyond which the system cannot safely operate. When wind speeds exceed this limit, heliostats automatically shift to a stowed position to prevent structural damage.

The overall performance of the solar field is influenced by various loss factors. Among the most significant are losses due to atmospheric attenuation and reduced heliostat availability, both of which contribute to diminished efficiency [30].

Atmospheric attenuation loss occurs due to solar radiation passing through the atmosphere and colliding with atmospheric particles such as air molecules, water vapor, and dust. In this process, the solar radiation is scattered and hence part of the reflected sun's light never reaches the receiver.

Heliostat availability loss, though, occurs due to circumstances like soiling (deposits of dirt on the mirrors) or component failure, reducing the overall output of the solar field.

Taking into account such operational parameters and losses in efficiency, the potential for a more successful optimization and understanding of heliostat efficiency in solar power plants exists. Energy collected by heliostat field, Hsf can be calculated by using equation (4.2) [29],

$$Hsf = DNI \times As \tag{4.2}$$

Where, Hsf is the Thermal Power Incident (W), DNI is Direct Normal Irradiance (W/m^2) and As is Surface Area of Heliostat (m^2).

Solar field is not 100% efficient due to various losses. The efficiency of solar field,ηsf can be calculated by using equation (4.3),

$$\eta sf = \frac{Hrec}{Hsf} \tag{4.3}$$

Where, Hsf is the solar field thermal Power Incident (W), $Hrec$ is the receiver thermal Power Incident (W) and ηsf is the efficiency of solar field (%).

The sun's rays are reflected by the heliostats onto a single point, called the receiver, located on top of a tower in the middle of the heliostat field. It is possible to improve performance by optimizing the tower's height and receiver's size.

Maximum receiver flux is the maximum amount of solar radiation the receiver may handle without being damaged, defined by the sunbeam after reflection from the heliostat field. The SAM optimizes the receiver size and heliostat locations so that the receiver flux never exceeds the maximum.

The performance of the receiver system can also be affected by piping losses, therefore piping losses must be added to the simulation. Piping losses depend on the pipe heat loss coefficient, constant length of the pipes, a length scaling factor, and the total piping length.

Efficiency of the receiver can be calculated by using equation (4.4) [29],

$$\eta rec = \frac{Hhtf}{Hrec} \tag{4.4}$$

Where, $Hhtf$ is the thermal Power transfer to HTF (W), $Hrec$ is the receiver thermal Power Incident (W) and ηrec is the efficiency of receiver (%).

$Hhtf$ can be calculated with equation (4.5) [29],

$$Hhtf = mhtf(ho - hi) \tag{4.5}$$

Where, $Hhtf$ is the thermal Power transfer to HTF (W), $mhtf$ is mass flow rate of HTF (kg/s), $ho\ is\ Enthalpy$ at the outlet of Receiver (J) and $hi\ is\ Enthalpy$ at the inlet of Receiver (J).

4.3.3 Solar Field and Receiver Design of LFR

LFR (Linear Fresnel Reflector) is a line focusing sun concentrating technology. LFR makes use of one-axis tracking of the sun through multiple reflectors and focuses sun onto tubes containing fluid. Two-axis tracking with mirrors is the method used in PTC and linear ground-fixed mirrors with one receiver tube floating above them for LFR. The receiver, in this case, is static, reducing initial investment compared to PTC facilities.

One of the significant advantages of a fixed receiver is that it simplifies the system by the use of a piping system with no moving parts, thereby making it more reliable and less expensive. In addition, LFR systems are versatile in the selection of heat transfer fluids (HTFs) such as water, thermal oil, or molten salt, which can increase the thermal energy storage (TES) capability.

According to IRENA's 2012 CSP report [124], LFR systems are cheaper since they use cheaper flat mirrors constructed of plain glass, which reduce the need for heavy steel and concrete supports. The construction is thus easier and less costly. An LFR solar field's design parameters are no different from a PTC solar field.

4.3.4 Collector and Receiver Design of SD

The collector in a solar dish-Stirling (SD) system consists of parabolic mirrors, a support structure, and a two-axis tracking system. The primary function of the mirrors is to concentrate direct normal solar radiation onto the aperture of the receiver. The aperture size is optimized to maximize solar energy absorption while minimizing convective and radiative losses.

The receiver, positioned at the focal point of the parabolic concentrator, absorbs the concentrated thermal energy and transfers it to the working fluid of the Stirling engine. The SD system employs direct illumination receivers, where solar radiation is directly absorbed by absorber tubes containing the working fluid. This receiver type is widely used in dish-Stirling systems due to its efficiency in thermal energy absorption and transfer.

For this study, four configurations of collector-receiver combinations were simulated:

- SES (Stirling Energy Systems)
- WGA (Wilkinson, Goldberg, and Associates)
- SAIC (Science Applications International Corporation)
- SBP (Schlaich Bergermann and Partner)

The results from the simulation for different collectors are presented in Fig. 4.2.

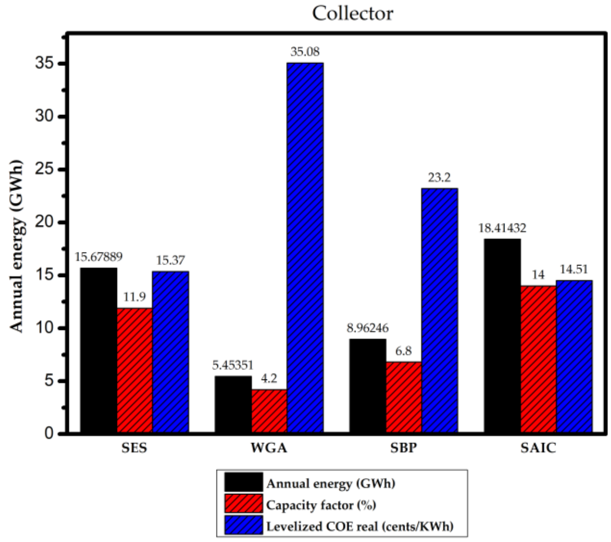

Fig. 4.2 Performance Evaluation of Different Collectors.

From the collector simulation results, the SAIC collector was found to have the highest annual energy generation (18.41 GWh) and the lowest Levelized Cost of Electricity (LCOE) at 14.51 cents/kWh, making it the optimal choice for this study. The results for different receiver configurations are presented in Fig. 4.3.

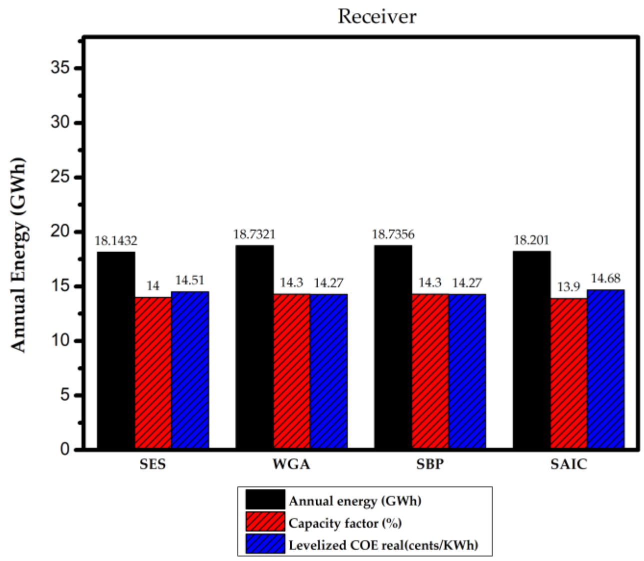

Fig. 4.3 Performance Evaluation of Different Receivers.

Among the receivers, SBP receiver demonstrated the highest annual energy output (18.7356 GWh) and the lowest LCOE (14.27 cents/kWh). Therefore, the SBP receiver was selected for this study.

Thus, the SAIC collector and SBP receiver combination is chosen for the solar dish-Stirling system as it provides the highest energy generation with the lowest LCOE, making it the most economically viable and efficient configuration.

4.4 HTF Selection for Different Technologies

Selecting an appropriate Heat Transfer Fluid (HTF) is crucial for ensuring the efficient operation and overall performance of a Concentrated Solar Power (CSP) plant. HTFs serve two primary purposes in CSP systems: they either directly drive the turbine or are used to generate steam through heat exchangers, which in turn powers the turbine. In addition to their role in power generation, HTFs are also vital for thermal energy storage (TES), where they are stored in insulated tanks to retain and transfer heat as needed.

When choosing an HTF, several key properties must be considered. These include a low freezing point, high boiling point, thermal stability over a wide temperature range, low viscosity, high thermal conductivity, and minimal corrosiveness—particularly when in contact with common metallic alloys used in CSP systems. Furthermore, a suitable HTF should have a high specific heat capacity to store large amounts of thermal energy, exhibit low vapor pressure (ideally below 1 atm) at elevated temperatures, and be cost-effective for large-scale implementation. Besides, it should have high heat capacity to store the maximum energy, low vapor pressure (<1 atm) at high temperatures, and economic feasibility.

As outlined by Pacio and Tian [125], HTFs used in CSP applications generally fall into six categories: (1) gases such as air, (2) water or steam, (3) molten salts, (4) synthetic oils, (5) liquid metals, and (6) organic compounds.

Operating CSP plants at elevated temperatures is critical for enhancing thermal-to-electric efficiency. Among the available HTF options, molten salts stand out for their favorable characteristics, including relatively low melting points, high operational temperature thresholds (often exceeding 500°C), substantial heat storage capacity, low vapor pressure, and strong resistance to corrosion.

4.4.1 HTF for PTC and LFR Power Plant

In the SAM model, Dowtherm RP and Hitec XL are two heat transfer fluids (HTFs) commonly utilized in Concentrated Solar Power (CSP) technologies like Parabolic Trough Collector (PTC) and Linear Fresnel Reflector (LFR). Between these two, Dowtherm RP is selected in this study for PTC as it has a greater thermal stability, providing greater energy quality to the power cycle. Hitec XL is selected in this study for LFR as it has a greater range of operating temperatures, providing greater energy quality to the power cycle.

Dowtherm RP operates at a range of 0°C to 330°C, while Hitec XL operates at a range of 120°C to 500°C. Hitec XL's broader operating range gives efficient operation because the temperatures below 263°C solidify the salt and can cause piping blockage or precipitation in the thermal storage tank. In order to avoid such issues, the minimum loop inlet temperature is 293°C and the heater temperatures in the cold HTF storage tank and the solar field are kept at 250°C. In addition, to avoid boiling and to facilitate effective heat transfer, the design maximum loop outlet temperature is kept at 500°C, which is same as the maximum operating temperature of the salt. If HTF were to vaporize and be turned into a gas, then heat transfer would be significantly cut down. For ease of use, the density of Hitec XL is assumed as 1901.92 kg/m^3 though it does slightly vary with temperature.

The velocity of the HTF in the receiver is also of utmost significance in the context of energy harvesting. Low velocity can lead to the HTF overheating and forming vapor, which leads to poor heat transfer efficiency. On the other hand, high velocity can hinder the desired energy transfer, which subsequently leads to the power plant efficiency reducing. These parameters are determined by variables like maximum mass flow rate ($Mloopmax$), minimum mass flow rate ($Mloopmin$), density ($Dhtf$), inner diameter of the absorber tube ($Dtubeinner$), and the inlet design loop temperature. The optimum flow velocity can be calculated from the equations (4.6) and (4.7) [100],

$$Minimum\ HTF\ Flow\ Velocity = \frac{4 \times Mloopmin}{Dhtf \times \pi x Dtubeinner^2} \tag{4.6}$$

$$Maximum\ HTF\ Flow\ Velocity = \frac{4 \times Mloopmax}{Dhtf \times \pi x Dtubeinner^2} \tag{4.7}$$

4.4.2 HTF for ST Power Plant

Molten salts are widely utilized as heat transfer fluids (HTFs) in solar tower (ST) power plants due to their favorable thermal properties. Among the various types, a mixture of nitrates and nitrites is most commonly employed in Concentrated Solar Power (CSP) systems. One such widely adopted blend is known as solar salt, composed of 60% sodium nitrate ($NaNO_3$) and 40% potassium nitrate (KNO_3), which is used as the HTF in this study. This formulation has been implemented in several installations, including the Solar Two central receiver project in California and various facilities in Spain [50]. The salt mixture has a melting temperature of 223°C and remains thermally stable up to 600°C. In the current research, the HTF operates within a temperature range of 288°C to 566°C [93]. Corrosion testing, conducted through immersion over approximately 7,000 hours, indicated that stainless steel 316—commonly used for piping—experiences a corrosion rate between 6 and 15 μm per year at temperatures below 570°C, which is considered acceptable for operational use.

4.5 Power Cycle and TES Design for CSP Plants

The energy block operates using a multi-stage steam Rankine cycle, incorporating two feedwater heaters, a preheater, and a superheater. This cycle includes three turbines—high-pressure (HP), intermediate-pressure (IP), and low-pressure (LP)—all mechanically linked to an electric generator. In this configuration, a single-pressure boiler generates high-pressure steam that initially expands through the HP turbine. The partially expanded steam is then reheated using hot Heat Transfer Fluid (HTF) before further expansion in the IP and LP turbines. After expansion, the steam is condensed back into liquid water and recirculated to the boiler. To enhance thermal efficiency, the system employs regenerative feedwater heating, where steam extracted from various turbine stages preheats the feedwater. This preheating step helps reduce the overall heat demand of the steam generator. Additionally, air cooling is used to improve system efficiency. Thermal Energy Storage (TES) is integrated to enable power generation during nighttime or cloudy periods when solar input is insufficient.

CSP systems typically employ two types of TES configurations: direct and indirect. In a direct TES setup, the same heat transfer fluid circulates through both the TES unit and the solar field. Conversely, indirect systems use a separate storage fluid and rely on a heat exchanger to transfer energy between the two circuits. This study adopts a direct TES system. A schematic representation of the power cycle for PTC, LFR, and ST systems is illustrated in Fig. 4.4.

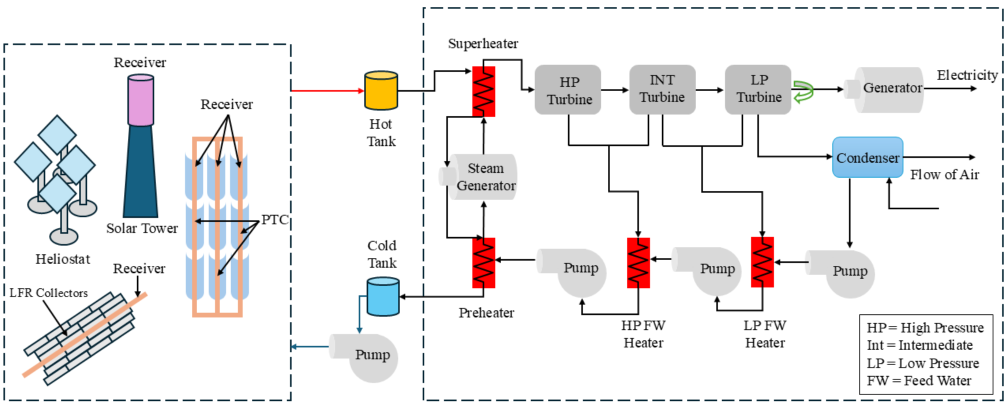

Fig. 4.4 The Schematic Diagram of Power Cycle of PTC, LFR and ST.

Volume of TES (Vt) system and thermal capacity (Tc) can be calculated from equation (4.8) and (4.9) [100], [126],

$$Vt = \frac{Cap \times 10^6 \times 3600}{Ch \times Dhtf \times \mu_e \times 1000 \times (To - Ti)} \tag{4.8}$$

$$Tc = \frac{tfull \times Pgross}{\eta des} \tag{4.9}$$

In this context, Cap represents the thermal energy storage capacity measured in megawatt-hours (MWh). Ch denotes the specific heat capacity of the heat transfer fluid in joules per kilogram per Kelvin (J/kg·K), and Dhtf refers to the density of the heat transfer fluid, expressed in kilograms per cubic meter (kg/m^3). The symbol μe signifies the effectiveness of the heat exchanger. To is the output temperature from the solar field (in Kelvin), while Ti stands for the turbine inlet temperature (also in Kelvin). tfull indicates the number of hours per day the plant operates at full load. Pgross is the gross power requirement of the power cycle in watts (W), and ηdes refers to the gross optical efficiency of the system.

The capacity factor (CF) and the overall efficiency are critical indicators of the performance of a concentrated solar power (CSP) plant. The overall efficiency (ηover) is defined as the ratio between the total useful energy extracted during operation and the total solar radiation received by the solar collectors over the specified period. This relationship is represented mathematically by Equation (4.10),

$$\eta over = \frac{En}{Hsf} \tag{4.10}$$

where E_n is Net Electrical Energy Generated (kWh) by the Solar and H_{sf} is Solar Field Thermal Power Incident (kWh_{th}).

The Capacity Factor (CF) is the ratio of the actual power generated by the power cycle during its operation to the maximum possible power it could generate if it operated continuously for the entire assessed period. This can be expressed by equation (4.11),

$$CF = \frac{En}{Efull} \tag{4.11}$$

where E_n is Net Electrical Energy Generated by the Solar Power Plant (kWh) and *Efull* is Amount of Power Produced by the Designed Power Cycle of the CSP Plants (kWh).

Solar Multiple (SM) is the ratio of the thermal energy collected by the solar field to the rated thermal energy supplied to the power cycle. It can be given by equation (4.12),

$$SM = \frac{Solar\ field\ capacity}{Power\ cycle\ capacity} \tag{4.12}$$

4.6 Economic Modeling

The economic structure of renewable energy plants differs markedly from that of conventional power generation facilities. Renewable energy systems generally demand higher initial capital investment due to technology and infrastructure requirements. However, they benefit from significantly lower operational costs, primarily because they do not rely on fuel inputs. Conversely, conventional power plants typically involve lower installation expenditures but face elevated operating costs driven by continuous fuel consumption. Consequently, the cost of electricity production in conventional systems is highly dependent on fuel price volatility [127].

In this research, the economic model was developed using the System Advisor Model (SAM) under the assumption of a single-owner power purchase agreement (PPA) structure, where a sole entity owns the entire project and possesses sufficient tax liability to fully benefit from available tax incentives [85]. This scheme is becoming increasingly popular, and the government of Bangladesh prefers this for new and innovative energy ventures.

This study employs two primary financial indicators: the Levelized Cost of Energy (LCOE) and the Net Present Value (NPV). The LCOE represents the average cost of producing a single unit of electricity over the operational life of the power plant. Conversely, NPV is used to evaluate the project's economic feasibility by comparing projected revenues against associated expenses. A positive NPV suggests the project is financially sustainable, whereas a negative NPV implies potential long-term unprofitability. The NPV in this evaluation is determined using Equation (4.13),

$$NPV = \sum_{n=0}^{N} \frac{Cn}{(1+D)^n} \tag{4.13}$$

Here, NPV stands for Net Present Value, Cn represents the cash flow at time period n, and D denotes the nominal discount rate.

The Levelized Cost of Energy (LCOE) can be determined using either the real or nominal approach. The real LCOE method is more suitable for long-term evaluations as it incorporates the effects of inflation, offering a more accurate reflection of costs over time. Conversely, the nominal LCOE approach is better suited for short-term assessments because it excludes inflation considerations. Given the extended duration of the project in this study, the real LCOE calculation method is adopted. The computation of the true LCOEs for the CSP systems is carried out using Equation (4.14),

$$LCOE(real) = \frac{-Co - \frac{\sum_{n=1}^{N} Cn}{(1+D)^n}}{\frac{\sum_{n=1}^{N} En}{(1+Dr)^n}} \tag{4.14}$$

Here, LCOE (real) refers to the Real Levelized Cost of Electricity measured in cents per kilowatt-hour. C_0 represents the initial capital investment in dollars, while C_n denotes the cash flow in year n. D is the nominal discount rate, D_r indicates the real discount rate, and E_n is the total amount of electricity, in kilowatt-hours, generated by the project during year n.

4.7 Techno Economic Analysis of CSP Plants

This study involved the design and evaluation of four types of Concentrated Solar Power (CSP) systems—Parabolic Trough Collector (PTC), Solar Tower, Linear Fresnel Reflector (LFR), and Solar Dish—to assess their techno-economic viability and compare their performance with conventional power generation methods. To ensure consistency in comparison, each CSP plant was designed with a capacity of 150 MW. The System Advisor Model (SAM) was used to simulate and analyze both the economic and operational performance of the systems.

Key parameters influencing CSP plant performance, such as the solar multiple (SM) and the duration of thermal energy storage (TES) in terms of full load hours, were optimized to enhance overall efficiency. Optimization focused on maximizing energy concentration and improving key financial indicators like Levelized Cost of Energy (LCOE), Net Present Value (NPV), and other relevant metrics.

For all CSP systems except the Solar Dish, the solar multiple was optimized by examining its impact on annual energy output, land use requirements, LCOE, minimum Debt Service Coverage Ratio (DSCR), and NPV. The optimal SM value for each technology was selected based on a balanced evaluation of these performance and financial indicators.

Parabolic Trough Collector (PTC) Optimization

For the Parabolic Trough Collector (PTC) plant, the highest energy concentration observed in Fig. 4.5 occurs at a solar multiple (SM) of 3.8, based on the graph depicting annual electricity generation relative to land area. An estimated 2,526 acres of land is required to ensure optimal operation of the 150 MW PTC power plant.

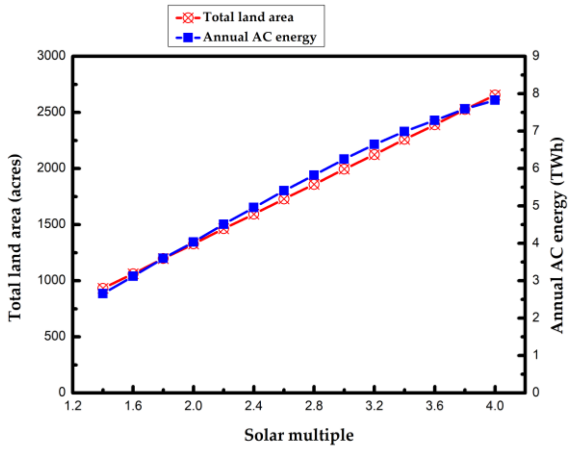

Fig. 4.5 Optimization of Solar Multiple (SM) for PTC Power Plant (Trend of Annual Energy Generation and Land Area).

Subsequently, the LCOE is lowest in Fig. 4.6, and the lowest value of real Levelized Cost of Energy found 9.56 cents/kWh.

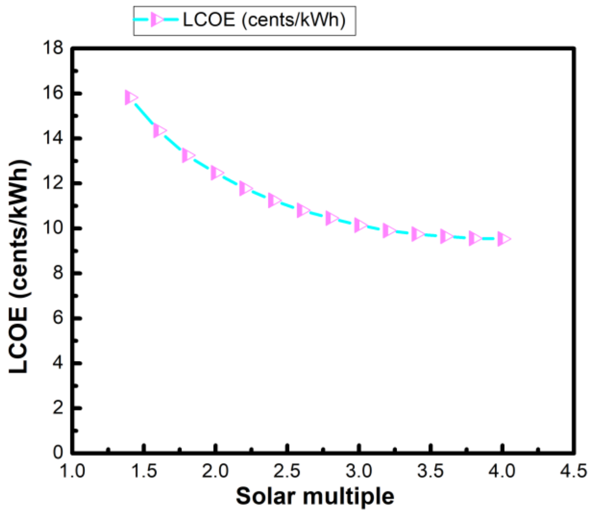

Fig. 4.6 Optimization of Solar Multiple (SM) for PTC power plant (Trend of LCOE).

Net Present Value (NPV) and lowest DSCR are both positive in Fig. 4.7, meaning that it is economically stable. The optimal SM of the PTC plant is therefore chosen to be 3.8. NPV obtained for the optimized PTC plant is $226,505,216.

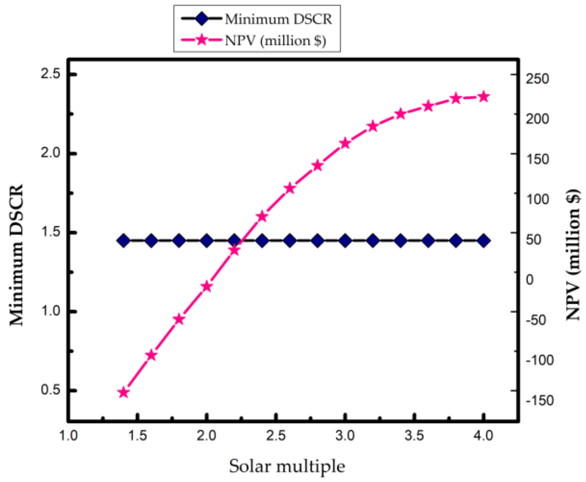

Fig. 4.7 Optimization of Solar Multiple (SM) for PTC Power Plant (Trend of Minimum DSCR and NPV).

For the optimum value of Solar Multiple (SM)= 3.8, highest amount of Annual AC energy is generated at the lowest LCOE shown in Fig. 4.8.

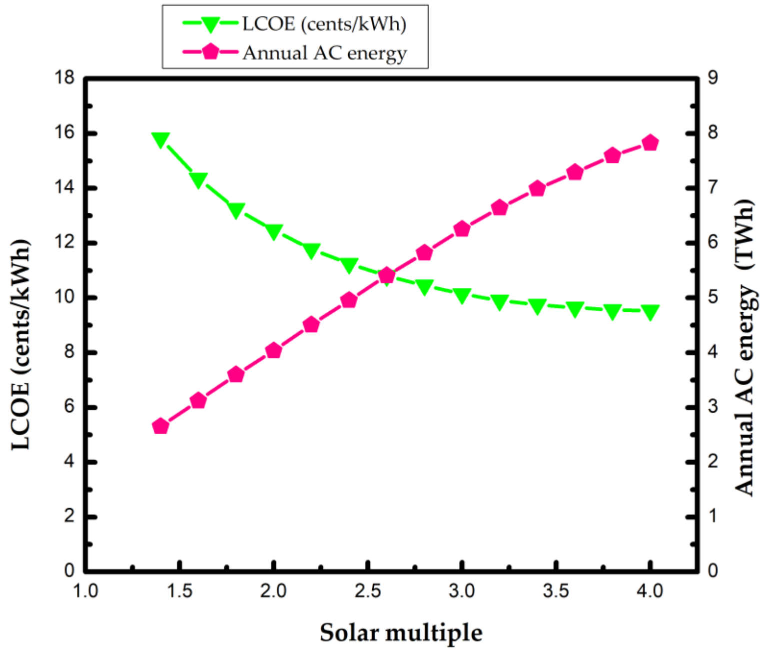

Fig. 4.8 Optimization of Solar Multiple (SM) for PTC Power Plant (Trend of Annual Energy Generation and LCOE).

After identifying the optimal solar multiple (SM) values, the subsequent step involved selecting the most effective number of full-load hours for the thermal energy storage (TES) system to enhance overall plant performance. To achieve this, the analysis considered variations in annual energy output, levelized cost of electricity (LCOE), and net present value (NPV) across different TES durations. Drawing from international CSP plant designs, which typically incorporate TES capacities ranging from 6 to 12 hours, the study evaluated this range for each configuration.

As illustrated in Fig. 4.9, the analysis revealed that for both parabolic trough collector (PTC) plants, the highest annual energy generation and lowest LCOE were achieved when the TES system was sized for 10 hours of full-load storage at the selected SM.

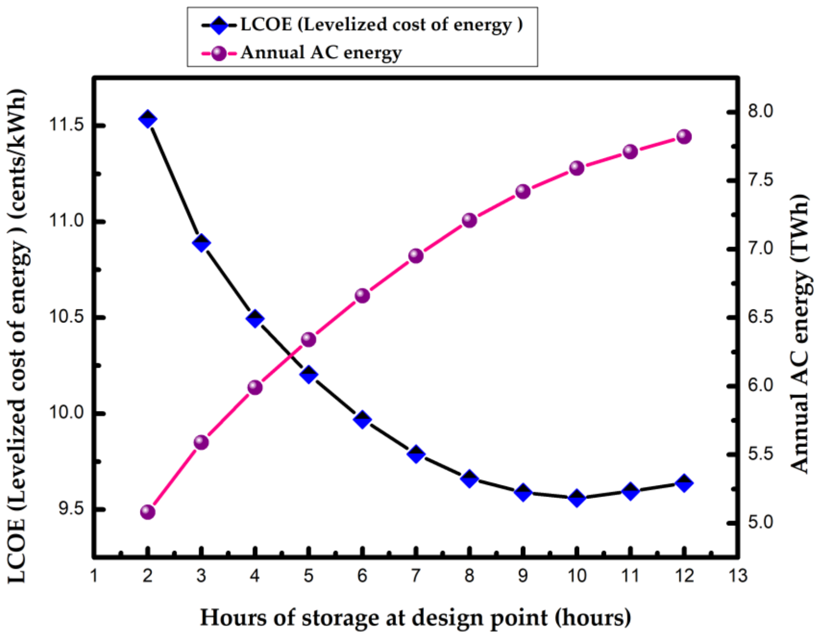

Fig. 4.9 Optimization Full Load Hour TES for PTC Power Plant (Trend of Annual Energy Generation and LCOE).

At optimized Solar Multiple=3.8 and Full load hour TES=10 hours annual energy generation is maximum and that is 759,288,640 kWh shown in Fig. 4.10.

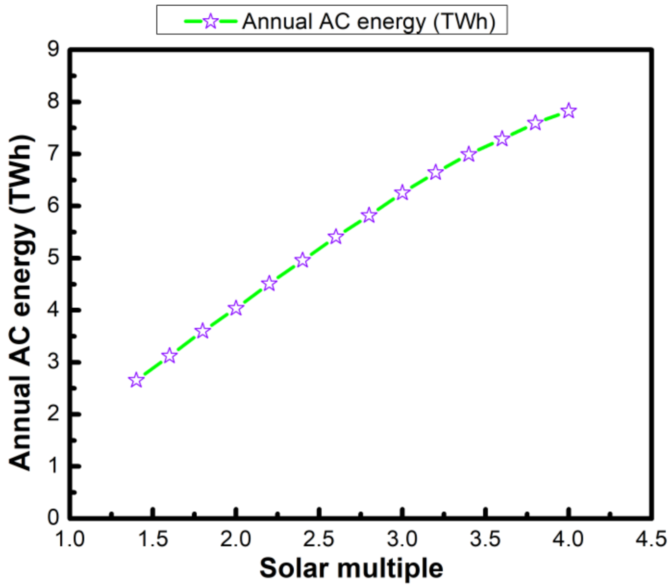

Fig. 4.10 Effectiveness of PTC Power Plant in Terms of Annual Energy Generation.

At optimized Solar Multiple=3.8 and Full load hour TES=10 hours PTC-CSP plant capacity factor is 57.7% and that is also maximum shown in Fig. 4.11.

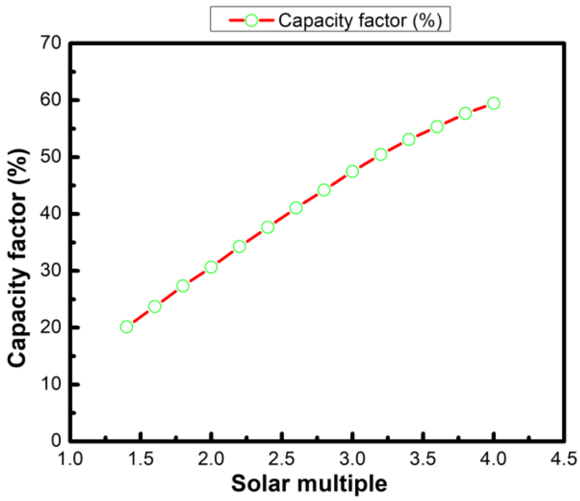

Fig. 4.11 Effectiveness of PTC Power Plant in Terms of Capacity Factor.

Liner Fresnel Reflector (LFR) Optimization

For the LFR plant, the most concentrated energy in Fig. 4.12 is when SM = 4, as shown in the graph of annual electricity generation vs land area. Total 1377 acres land is needed for optimum LFR 150 MW plant operation.

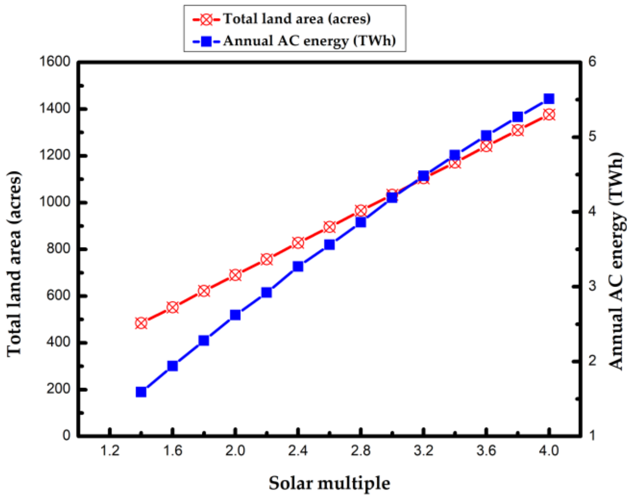

Fig. 4.12 Optimization of Solar Multiple (SM) for LFR Power Plant (Trend of Annual Energy Generation and Land Area).

Subsequently, the LCOE is lowest in Fig. 4.13, and the lowest value of real Levelized Cost of Energy found 13.44 cents/kWh.

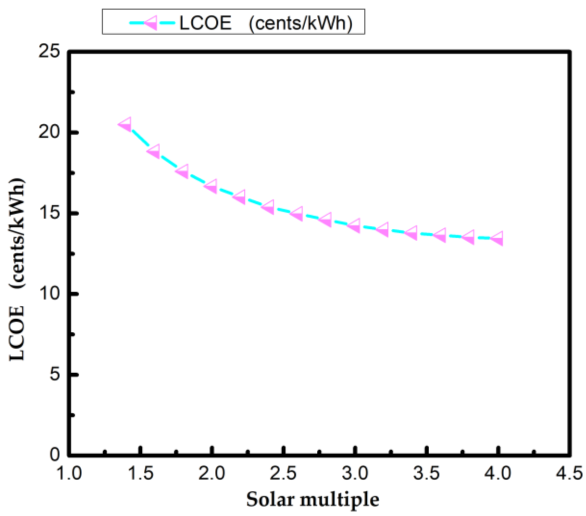

Fig. 4.13 Optimization of Solar Multiple (SM) for LFR power plant (Trend of LCOE).

Net Present Value (NPV) and lowest DSCR are both positive in Fig. 4.14, meaning that it is economically stable. The optimal SM of the LFR plant is therefore chosen to be 4. NPV obtained for the optimized LFR plant is $128,805,544.

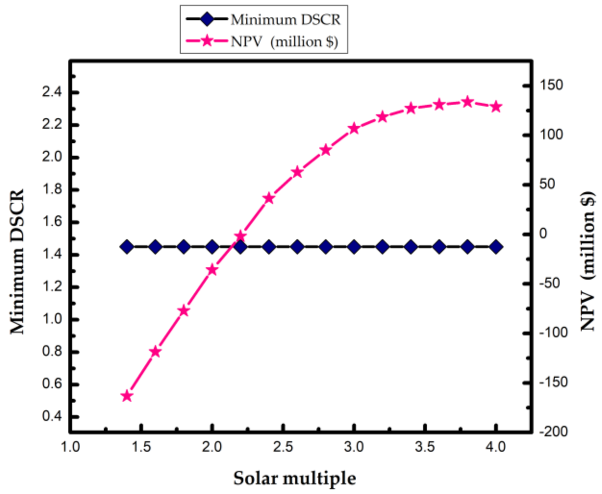

Fig. 4.14 Optimization of Solar Multiple (SM) for LFR Power Plant (Trend of Minimum DSCR and NPV).

For the optimum value of Solar Multiple (SM)= 4, highest amount of Annual AC energy is generated at the lowest LCOE shown in Fig. 4.15.

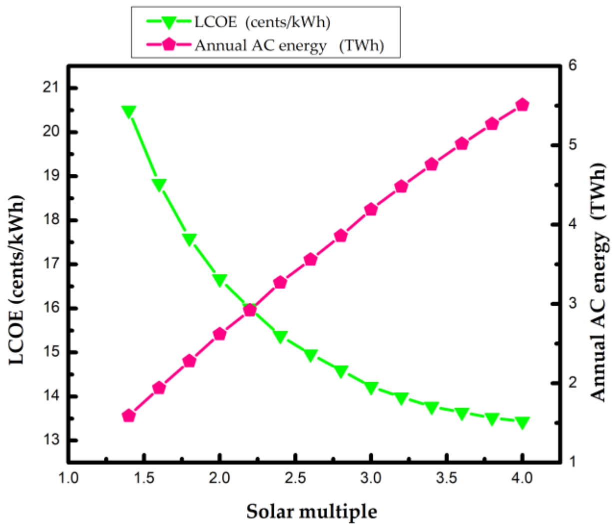

Fig. 4.15 Optimization of Solar Multiple (SM) for LFR Power Plant (Trend of Annual Energy Generation and LCOE).

In the analysis shown in Fig. 4.16, it can be seen that the annual electricity generation for both the LFR plants reaches its maximum at minimum LCOE when the TES (Thermal Energy Storage) system operates at 12 hours of full-load capacity for the selected storage medium (SM).

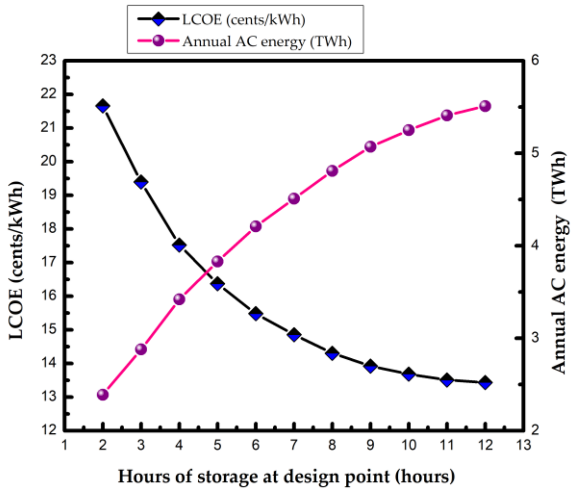

Fig. 4.16 Optimization Full Load Hour TES for LFR Power Plant (Trend of Annual Energy Generation and LCOE).

At optimized Solar Multiple= 4 and Full load hour TES= 12 hours annual energy generation is maximum and that is 551,230,272 kWh shown in Fig. 4.17.

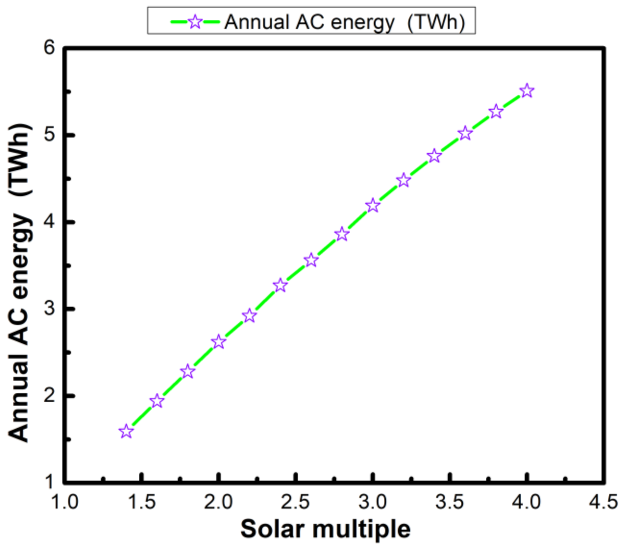

Fig. 4.17 Effectiveness of LFR Power Plant in Terms of Annual Energy Generation.

At optimized Solar Multiple= 4 and Full load hour TES= 12 hours LFR-CSP plant capacity factor is 41.9 % and that is also maximum shown in Fig. 4.18.

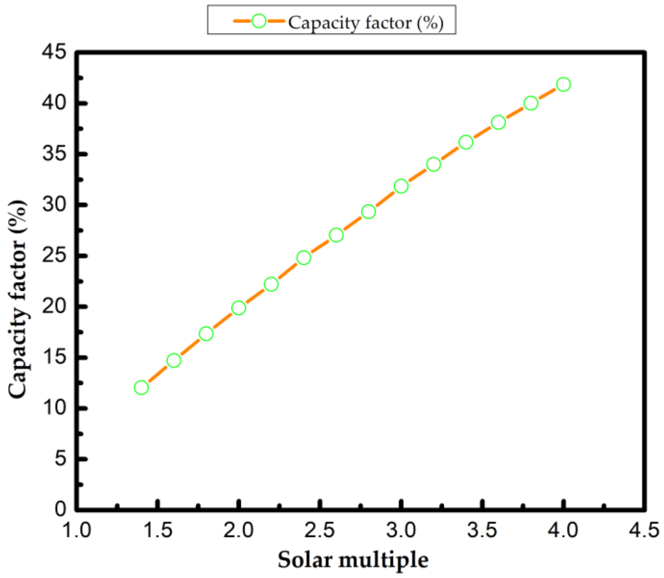

Fig. 4.18 Effectiveness of LFR Power Plant in Terms of Capacity Factor.

Solar Tower (ST) Plant Optimization

For the Solar Tower (ST) plant, the peak energy concentration, as illustrated in Fig. 4.19, occurs at a solar multiple (SM) of 1.6 based on the relationship between annual electricity output and land usage. An estimated 2,810 acres of land is required to ensure optimal performance of the 150 MW ST facility.

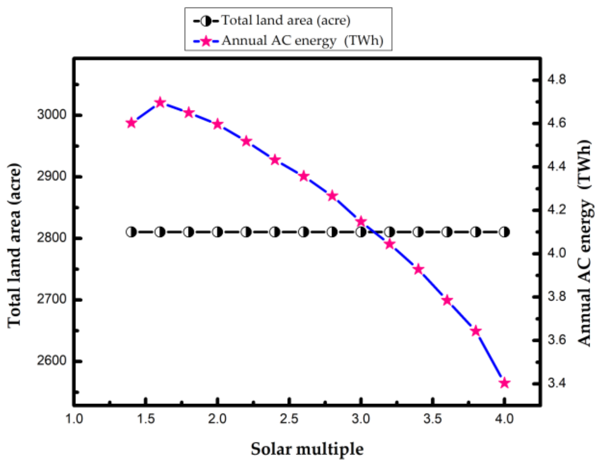

Fig. 4.19 Optimization of Solar Multiple (SM) for ST Power Plant (Trend of Annual Energy Generation and Land Area).

Subsequently, the LCOE is lowest in Fig. 4.20, and the lowest value of real Levelized Cost of Energy found 7.32 cents/kWh.

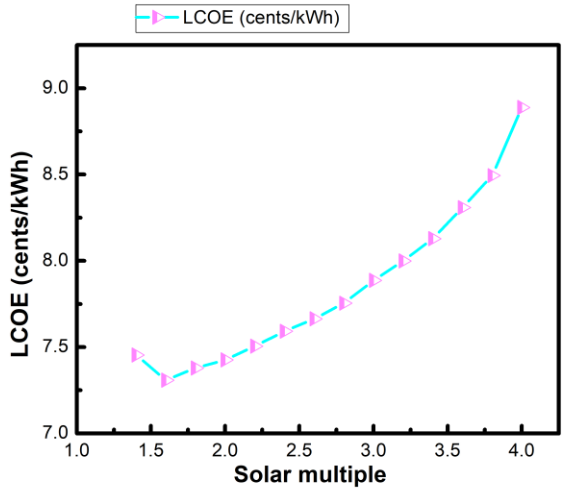

Fig. 4.20 Optimization of Solar Multiple (SM) for ST Power Plant (Trend of LCOE).

Net Present Value (NPV) and lowest DSCR are both positive in Fig. 4.21, meaning that it is economically stable. The optimal SM of the ST plant is therefore chosen to be 1.6. NPV obtained for the optimized ST plant is $78,294,312.

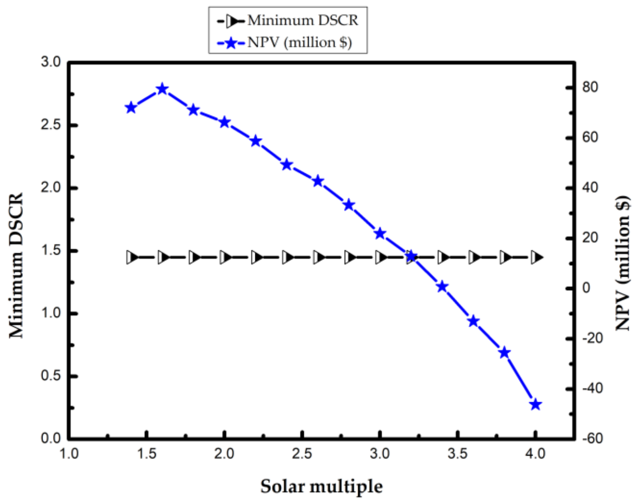

Fig. 4.21 Optimization of Solar Multiple (SM) for ST Power Plant (Trend of Minimum DSCR and NPV).

For the optimum value of Solar Multiple (SM)= 1.6, highest amount of Annual AC energy is generated at the lowest LCOE shown in Fig. 4.22.

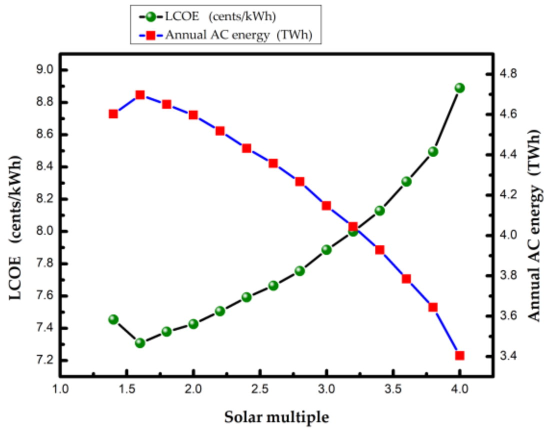

Fig. 4.22 Optimization of Solar Multiple (SM) for ST Power Plant (Trend of Annual Energy Generation and LCOE).

In the analysis shown in Fig. 4.23, it can be seen that the annual electricity generation for both the ST plants reaches its maximum at minimum LCOE when the TES (Thermal Energy Storage) system operates at 6.5 hours of full-load capacity for the selected storage medium (SM).

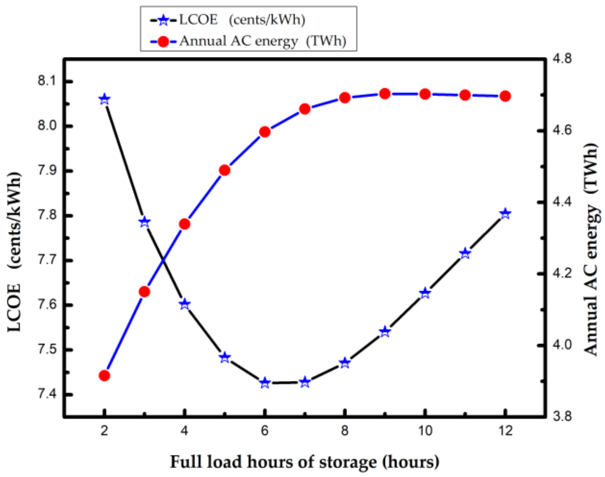

Fig. 4.23 Optimization Full Load Hour TES for ST Power Plant (Trend of Annual Energy Generation and LCOE).

At optimized Solar Multiple = 1.6 and Full load hour TES = 6.5 hours annual energy generation is maximum and that is 472,094,784 kWh shown in Fig. 4.24.

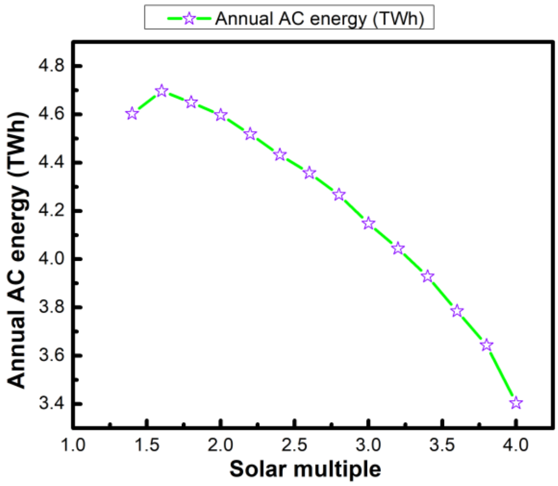

Fig. 4.24 Effectiveness of ST Power Plant in Terms of Annual Energy generation.

At optimized Solar Multiple = 1.6 and Full load hour TES = 6.5 hours ST-CSP plant capacity factor is 35.6% and that is also maximum shown in Fig. 4.25.

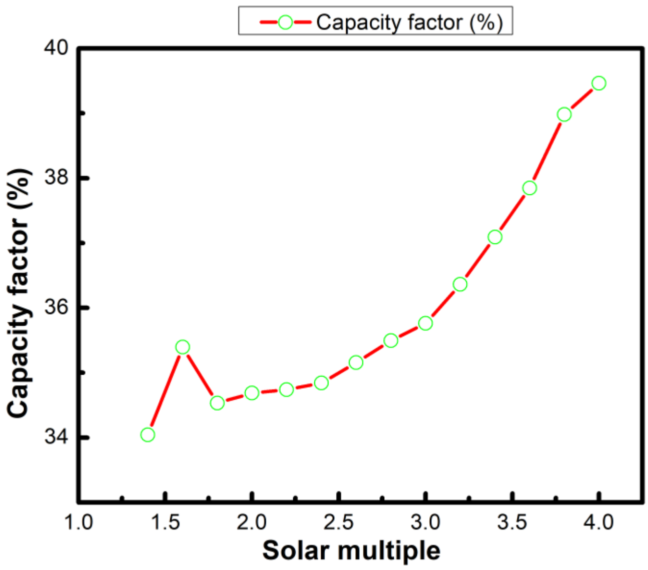

Fig. 4.25 Effectiveness of ST Power Plant in Terms of Capacity Factor.

Solar Dish (SD) System Optimization

Unlike the other CSP technologies, the Solar Dish system operates as an off-grid solution and does not support TES. Instead, this study optimized the most efficient collector, receiver, and engine combination for standalone applications

The Solar Dish-Stirling (SD) system is optimized by evaluating different collector-receiver-Stirling engine configurations to identify the most efficient and cost-effective model. While the SAIC collector and SBP receiver were initially identified as optimal based on energy generation and LCOE, their corresponding Stirling engines were not available in the SAM (System Advisor Model) library. Therefore, the analysis was conducted using available Stirling engine configurations.

The performance of four different receiver-Stirling engine combinations was evaluated, as presented in Fig. 4.26.

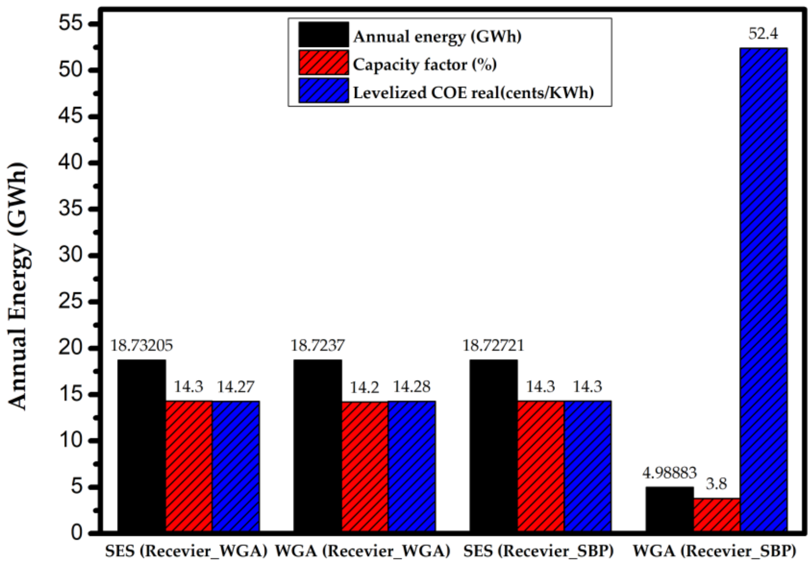

Fig. 4.26 The Performance Evaluation of Four Different Receiver-Stirling Engine Combinations.

From the analysis, the (Receiver_WGA) SES configuration demonstrated the highest annual energy generation (18.7320 GWh) and the lowest Levelized Cost of Electricity (LCOE) at 14.27 ¢/kWh, making it the most optimized configuration for economic feasibility. Additionally, it maintains a high-capacity factor of 14.3%, ensuring stable performance over time.

Thus, the Receiver_WGA with SES Stirling engine was selected as the optimized Solar Dish-Stirling (SD) system model due to its superior net present value (NPV) and lower LCOE, ensuring better financial viability and energy efficiency.

4.8 Viability Analysis and CSP Plants Placement Recommendations

To assess the feasibility of Concentrated Solar Power (CSP) in Bangladesh, four optimized CSP configurations—Solar Tower (ST), Solar Dish (SD), Parabolic Trough Collector (PTC), and Linear Fresnel Reflector (LFR)—were analyzed across the top three Direct Normal Irradiance (DNI) regions: Cox's Bazar (3.92 $kWh/m^2/day$), Bandarban (4.19 $kWh/m^2/day$), and Chapainawabganj (4.27 $kWh/m^2/day$). The evaluation considered key performance indicators, including capacity factor, annual energy generation, Levelized Cost of Electricity (LCOE), Net Present Value (NPV), and land area requirements. Based on this analysis, recommendations for a 600 MW CSP plant have been proposed to maximize energy yield, economic feasibility, and land efficiency.

Performance Comparison of CSP Technologies

Solar Tower (ST):

- Chapai Nawabganj is the most suitable location with the highest NPV ($113.15 million) and a competitive LCOE (7.49 ¢/kWh).
- Cox's Bazar offers the highest energy generation (472.09 GWh) but with a slightly lower NPV ($78.3 million).
- Capacity factor ranges from 34–35.6%, making it a reliable option for large-scale deployment. Table 4.1 shows the viability analysis of the optimized ST plant for condition of Bangladesh.

Solar Dish (SD):

- Chapai Nawabganj again performs best, with the highest capacity factor (15.3%) and annual energy generation (200.82 GWh) at the lowest LCOE (13.34 ¢/kWh).
- SD systems require only 334 acres, making them suitable for decentralized applications like Bandarban and Islands of Cox's Bazar. Table 4.2 shows the viability analysis of the optimized SD plant for condition of Bangladesh.

Table 4.1 The Viability Analysis of The Optimized ST Plant for Condition of Bangladesh.

Parameters	**Cox's Bazar (21.45 °N, 91.98°E)**	**Bandarban (22.21°N, 92.22°E)**	**Capai Nawabganj (26.93°N, 81.22 °E)**
Capacity factor (%)	35.6	34	35.1
Annual Energy generation (GWh)	472.09	451.327	465.758
LCOE real (cents/kWh)	7.32	7.62	7.49
NPV (million $)	78.3	70.6	113.15
Land Area (Acres)	2,810	2,810	2,810

Parabolic Trough Collector (PTC):

- Chapai Nawabganj shows the highest energy generation (889.26 GWh) and highest NPV ($418.69 million).
- Bandarban has the lowest LCOE (9.08 ¢/kWh), making it the most economically viable option.

- Capacity factor ranges from 57.7–67.5%, making it the best-performing technology overall. Table 4.3 shows the viability analysis of the optimized PTC plant for condition of Bangladesh.

Table 4.2 The Viability Analysis of The Optimized SD Plant for Condition of Bangladesh.

Parameters	**Cox's Bazar (21.45 °N, 91.98°E)**	**Bandarban (22.21°N, 92.22°E)**	**Capainawabganj (26.93°N, 81.22 °E)**
Capacity factor (%)	14.3	15	15.3
Annual Energy generation (GWh)	187.32	197.567	200.82
LCOE real (cents/kWh)	14.27	13.56	13.34
NPV (million $)	15.112	15.078	15.068
Land Area (Acres)	334	334	334

Linear Fresnel Reflector (LFR):

- Chapai Nawabganj is the best site for LFR, with the highest annual energy generation (683.74 GWh) and NPV ($382.24 million).
- Bandarban has the lowest LCOE (12.07 ¢/kWh) and a high-capacity factor (47.4%), making it a competitive alternative. Table 4.4 shows the viability analysis of the optimized LFR plant for condition of Bangladesh.

Table 4.3 The Viability Analysis of The Optimized PTC Plant for Condition of Bangladesh.

Parameters	**Cox's Bazar (21.45 °N, 91.98°E)**	**Bandarban (22.21°N, 92.22°E)**	**Capainawabganj (26.93°N, 81.22 °E)**
Capacity factor (%)	57.7	60.3	67.5
Annual Energy generation (GWh)	759.28	794.44	889.26
LCOE real (cents/kWh)	9.56	9.08	8.98
NPV (million $)	226.51	311.02	418.69
Land Area (Acres)	2,526	2,424	2,771

Table 4.4 The Viability Analysis of The Optimized LFR Plant for Condition of Bangladesh.

Parameters	**Cox's Bazar (21.45 °N, 91.98°E)**	**Bandarban (22.21°N, 92.22°E)**	**Capainawabganj (26.93°N, 81.22 °E)**
Capacity factor (%)	41.9	47.4	51.9
Annual Energy generation (GWh)	551.23	623.94	683.74
LCOE real (cents/kWh)	13.44	12.07	12.08
NPV (million $)	128.8	293.16	382.24
Land Area (Acre)	1,377	1,320	1,515

Land Use Impact and Mitigation Strategies

The proposed 600 MW Concentrated Solar Power (CSP) plant, comprising a 150 MW Linear Fresnel Reflector (LFR) and a 150 MW Solar Tower at two separate sites (each mirrored for duplication), will require substantial land—estimated between 4 to 6 acres per MW, depending on technology type and layout efficiency. This translates to 2,400–3,600 acres (approx. 10–15 km^2) in total, which may overlap with existing agricultural or unused rural land.

To address this, the following strategies are proposed to minimize adverse effects on farmland and local communities:

- **Site Selection on Non-Arable or Marginal Lands:** Locations are prioritized based on low agricultural productivity, proximity to transmission lines, and high DNI (Direct Normal Irradiance), avoiding fertile croplands wherever possible.
- **Agrovoltaics and Dual-Use Approaches:** In areas where farmland use is unavoidable, integrated land use models such as agrovoltaics can be adopted. For example, crops compatible with partial shading (e.g., legumes or shade-tolerant vegetables) may be cultivated between rows of heliostats or reflectors.
- **Farmer Compensation and Land Leasing Models:** Instead of permanent land acquisition, long-term lease agreements with farmers or cooperatives can be implemented. This ensures income continuity for landowners and maintains social acceptability.
- **Community Engagement and Benefit Sharing:** Establishing transparent dialogue with affected communities, ensuring

local employment during construction and operation, and implementing profit-sharing schemes can enhance project sustainability and reduce opposition.

4.9 Comparison With Other Energy Sources of Bangladesh

The price of generating electricity from different sources in Bangladesh is as follows: natural gas power plants costing 4 cents per kWh, coal power plants costing 9.6 cents per kWh, furnace oil power plants costing 16 cents per kWh, and diesel power plants costing 33 cents per kWh [128]. Compared to other energy technologies currently deployed in Bangladesh, the CSP power plant configurations analyzed in this study demonstrate more competitive electricity generation costs—surpassed only by natural gas-based plants. Furthermore, conventional fossil fuels like diesel and coal are finite resources, and their future scarcity is likely to drive up market prices. In contrast, CSP systems utilize solar energy, a renewable and inexhaustible resource. A visual comparison of electricity generation costs across various technologies in Bangladesh is presented in Fig. 4.26.

The comparative study illustrates that CSP power plants would be a viable source of diversification of Bangladesh's energy mix with the inclusion of renewable solar energy. CSP technologies are economically and environmentally friendly methods of meeting the growing demand for electricity in Bangladesh as opposed to non-renewable and renewable sources.

The CSP systems proposed in this study demonstrate a more cost-effective performance compared to recently installed photovoltaic (PV) facilities in Teknaf and Rangpur, Bangladesh. While the PV installations produce electricity at rates of approximately 13 and 15 cents per kilowatt-hour, respectively, the modeled CSP configurations—particularly the PTC and Solar Tower designs—offer generation costs that are nearly 50% lower [129].

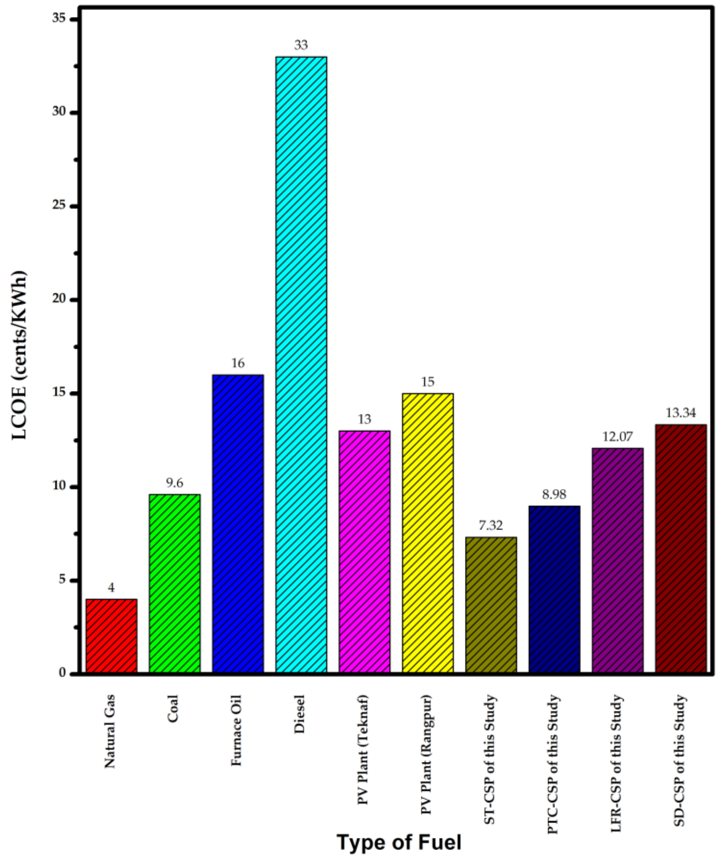

Fig. 4.27 Graphical Comparison of The Cost of Electricity Production from Different Sources Being Used in Bangladesh and The Plant Optimized in This Study.

One of the primary requirements during the planning and development of a Concentrated Solar Power (CSP) plant is securing adequate land. In densely populated countries such as Bangladesh, land availability poses a significant challenge that can impact the feasibility of CSP installations. The four CSP technologies evaluated in this study vary in their land requirements due to differences in their solar collector configurations.

Among the CSP technologies evaluated, the Solar Tower plant requires the largest area—around 2800 acres—mainly due to the extensive heliostat field needed to concentrate sunlight onto the receiver. In contrast, the Linear Fresnel Reflector (LFR) system demands the smallest footprint, using only about 1350 acres, which is one of its notable advantages. The Parabolic Trough Collector (PTC) system occupies an intermediate land area, approximately 2700 acres.

The analysis suggests that there is no universally superior CSP technology; each has its own strengths and limitations. The Solar Tower system, while offering the lowest Levelized Cost of Electricity (LCOE), does so at the expense of high land usage. On the other hand, the LFR plant is the most land-efficient, but it exhibits the lowest performance in terms of efficiency and has the highest LCOE. The PTC system represents a middle ground—it requires less land than the Solar Tower but more than the LFR, and its LCOE falls between the two.

For decentralized or small-scale power generation, Solar Dish systems could be considered due to their modular nature. When land availability is limited, the LFR system becomes a practical choice despite its higher cost. However, if reducing energy cost is the primary objective and sufficient land is available, the Solar Tower technology is the most suitable option. The PTC system offers a balanced compromise and can be considered an optimal solution for large-scale CSP deployment in Bangladesh.

Furthermore, the LCOE outcomes derived from this study support the objectives of Sustainable Development Goal (SDG) 7 by promoting affordable and clean energy. These findings hold critical implications for advancing renewable energy initiatives in Bangladesh.

4.10 Comparative Analysis

Comparative analysis is essential in evaluating the performance, feasibility, and economic viability of a newly designed power plant against existing operational projects. By comparing key parameters such as capacity factor, annual energy generation, levelized cost of electricity (LCOE), and land requirements, it is possible to assess the strengths and weaknesses of different CSP technologies.

Comparison of ST in This Study with NOOR III

This section presents a comparison between the simulated Solar Tower (ST) CSP plant designed in this study and the NOOR III CSP plant in Morocco, which is a well-established and operational CSP facility. NOOR III is a 150 MW power tower CSP plant located in Ouarzazate, Morocco, utilizing molten salt as a heat transfer and storage medium. The plant benefits from a high solar resource (DNI of 2508 kWh/m²/year) and has been operational since 2018. The designed ST CSP plant in this study, also with a 150 MW capacity, is optimized for Cox's Bazar in Bangladesh. While the NOOR III plant achieves a capacity factor of approximately 20.3% and an LCOE of around 15 cents/kWh, the ST CSP plant in this study demonstrates a comparable capacity factor ranging between 34% and 35.6% and an LCOE 7.32 cents/kWh. Despite the lower DNI in Bangladesh compared to Morocco, the proposed ST plant achieves a competitive economic performance, demonstrating the potential feasibility of CSP technology in Bangladesh under optimized design conditions. Comparison of Solar Tower (ST) in This Study with NOOR III shown in Table 4.5.

The lower LCOE of the proposed ST plant in Bangladesh (7.32 cents/kWh) compared to Morocco's NOOR III (15 cents/kWh) can be attributed to several key factors.

Firstly, construction and labor costs in Bangladesh are substantially lower than those in Morocco. According to the International Labour Organization and global cost benchmarking reports, average labor costs in Bangladesh can be 50–70% lower than in North African countries, significantly reducing capital expenditures, especially for civil and structural work [128 -132].

Table 4.5 Comparison of Solar Tower (ST) in This Study with NOOR III.

Parameters	**NOOR III** [135]	**ST plant (In this study)**	**ST-NOOR III diff (%)**
Capacity (MW)	**150**	**150**	
Annual energy (GWh)	500	472.09	-5.74
Aperture area (m^2)	1,312,000	1,999,013.5	-41.49
Capacity factor (%)	20.3	35.6	54.74
Nominal LCOE (cents/kWh)	15	7.32	61.8172
Storage capacity (Hours)	7	6.5	-7.41

Secondly, the proposed plant design benefits from recent advancements in thermal energy storage (TES) technologies and more cost-effective heliostat field configurations, leading to reduced system cost per kWh. For instance, smaller tower heights and optimized receiver dimensions help reduce material usage and installation costs. Additionally, the use of locally available construction materials and components where feasible further contributes to cost savings.

Lastly, the techno-economic modeling in this study incorporated site-specific cost and performance assumptions tailored for Cox's Bazar, optimizing for the local environment and economy rather than applying default SAM library values.

Therefore, while Bangladesh has a lower DNI (1900–2100 kWh/m^2/year vs. Morocco's ~2500–2800 kWh/m^2/year), the combined effect of lower capital expenditures, improved design strategies, and lower financing costs justifies the achieved lower LCOE. This finding is in line with recent literature, such as

IRENA (2023) and IEA CSP Roadmap, which emphasize the rapid global decline in CSP costs driven by learning curves and regional advantages [134 - 135].

Comparison of PTC in This Study with NOOR II

NOOR II is a 200 MW parabolic trough CSP plant located in Ouarzazate, Morocco, which became operational in 2018 [136]. The plant utilizes a solar resource of 2503 kWh/m²/year and has a thermal storage capacity of 7 hours. In comparison, the parabolic trough collector (PTC) CSP plant designed in this study is optimized for Bangladesh's top DNI locations, with a capacity of 150 MW and a storage capacity of 10 hours.

The comparative analysis reveals that the designed PTC plant significantly outperforms NOOR II in terms of capacity factor and annual energy generation. While NOOR II has a capacity factor of 40% and an annual energy generation of approximately 600 GWh, the PTC plant in this study achieves a capacity factor of up to 67.5% and an annual energy output of 889.26 GWh, representing a 51.16% and 65.6% increase, respectively.

The optimized aperture area of the designed plant (2,920,512 m²) is also considerably larger than NOOR II's (1,779,900 m²), leading to a higher solar energy capture efficiency. Additionally, the LCOE of the simulated PTC plant is 8.98 cents/kWh, which is significantly lower than NOOR II's 16 cents/kWh, making the proposed plant more economically competitive.

The improved performance is attributed to enhanced thermal storage capacity (10 hours compared to NOOR II's 7 hours) and an optimized collector field design tailored for the specific solar conditions in Bangladesh. Comparison of PTC in This Study with NOOR II shown in Table 4.6.

Table 4.6 Comparison of PTC in This Study with NOOR II.

Parameters	**NOOR II** [136]	**PTC plant (In this study)**	**PTC-NOOR II diff (%)**
Capacity (MW)	**200**	**150**	
Annual energy (GWh)	600	889.26	65.6
Aperture area (m^2)	1,779,900	2,920,512	-74.52
Capacity factor (%)	40	67.5	51.16
Nominal LCOE (cents/kWh)	16	8.98	56.2
Storage capacity (Hours)	7	10	35.29

Comparison of LFR in This Study with Dhursar

The Dhursar CSP plant, located in Rajasthan, India, is a 125 MW Linear Fresnel Reflector (LFR) plant that has been operational since 2014. It utilizes a solar resource of 1742 kWh/m^2/year and does not incorporate thermal storage. In contrast, the LFR CSP plant designed in this study is optimized for Bangladesh, with a higher capacity of 150 MW and an integrated 12-hour thermal storage system [137].

A comparative analysis indicates that the LFR plant in this study significantly outperforms Dhursar in terms of capacity factor and annual energy generation. The designed plant achieves a capacity factor of 51.9% compared to Dhursar's 24.1%, marking a 73.16% improvement. Additionally, the annual energy generation of the proposed plant reaches 683.74 GWh, which is 68.2% higher than Dhursar's 280 GWh output. The aperture area of the optimized plant is also slightly larger (4,003,193.6 m^2 vs. 3,400,000 m^2), enhancing solar energy absorption.

Despite its superior performance, the simulated LFR plant has a slightly higher LCOE of 12.08 cents/kWh compared to Dhursar's 11 cents/kWh. However, the inclusion of 12-hour thermal storage in the proposed plant, absent in Dhursar, greatly enhances grid stability and dispatchability, making it a more reliable power generation option. Comparison of LFR in This Study with Dhusar shown in Table 4.7.

Table 4.7 Comparison of LFR in This Study with Dhusar.

Parameters	**Dhusar** [138]	**LFR plant (In this study)**	**LFR- Dhusar diff (%)**
Capacity (MW)	**125**	**150**	
Annual energy (GWh)	280	683.74	68.2
Aperture area (m^2)	3400000	4,003,193.6	1.9
Capacity factor (%)	24.1	51.9	73.16
Nominal LCOE (cents/kWh)	11	12.08	-9.36
Storage capacity (Hours)	0	12	100

Comparison of SD in This Study with Abbas et al.'s Study

Since large-scale Dish-Stirling (SD) power plants are still in the research and development phase, direct comparisons with operational plants are limited. Therefore, this study compares its optimized Dish-Stirling design with the 100 MW Dish-Stirling plant proposed by Abbas et al.[139] for Algeria, which utilizes hydrogen as a working fluid.

The comparison reveals that while the plant designed in this study has a larger capacity of 150 MW compared to Abbas et al.'s 100 MW plant [139] , its performance in terms of capacity factor and annual energy generation is lower. The simulated plant achieves an annual energy output of 200.82 GWh, which is 49.1% less than the 221 GWh estimated in the Algerian study. Additionally, the capacity factor in this study is 15.3%, significantly lower than the 24% reported by Abbas et al., marking a 44.27% reduction. Comparison of SD in This Study with Abbas et al. [139] shown in Table 4.8.

Table 4.8 Comparison of SD in This Study with Abbas et al. [130].

Parameters	**Abbas et al.** [139]	**SD plant (In this study)**	**SD- Abbas et al. diff (%)**
Capacity (MW)	**100**	**150**	
Annual energy (GWh)	221	200.82	-49.1
Aperture area (m²)	900000	1350000	0
Capacity factor (%)	24	15.3	-44.27
Nominal LCOE (cents/kWh)	11.5	13.34	-14.81

One reason for this difference may be the specific solar resource availability and technological configurations. The Algerian study also achieves a lower levelized cost of electricity (LCOE) at 11.5 cents/kWh compared to 13.34 cents/kWh in this study, indicating a 14.81% cost disadvantage. However, the aperture area remains consistent, with both studies utilizing large reflective surfaces to concentrate solar energy efficiently.

Despite the differences, this study highlights the feasibility of Dish-Stirling technology for Bangladesh. With further optimization and integration of advanced working fluids or hybridization strategies, performance improvements and cost reductions could be achieved to make Dish-Stirling CSP a more competitive renewable energy solution.

4.11 Summary

This chapter provided a comprehensive analysis of CSP technologies optimized for Bangladesh, evaluating their technical and economic feasibility. The study considered four CSP technologies—ST, PTC, LFR, and SD—simulated under the top three solar-rich districts of Bangladesh. Performance metrics such as capacity factor, annual energy generation, LCOE, and NPV were analyzed to determine the most suitable CSP configurations for large-scale deployment.

The comparative analysis with existing CSP plants demonstrated that the designed ST, PTC, and LFR systems show competitive performance with globally established plants, such as NOOR III (ST), NOOR II (PTC), and Dhursar (LFR). However, SD technology remains in the research phase, and its comparison with Abbas et al. [139] 's study highlights areas for further improvement.

Based on these findings, recommendations were made for the strategic deployment of a 600 MW CSP plant in Bangladesh, focusing on maximizing energy output while ensuring economic viability. This study establishes a foundation for future CSP development in the country, emphasizing the potential for sustainable and efficient solar energy utilization.

Chapter 5: Conclusions and Future Study

Thus far, this thesis has explored the design, optimization, and techno-economic analysis of Concentrated Solar Power (CSP) plants in Bangladesh, presenting findings chapter by chapter. This chapter consolidates the study by summarizing its key insights, contributions, limitations, and recommendations for future research. It provides an overview of the major conclusions drawn from the analysis and discusses their implications for sustainable energy development in Bangladesh. Section 5.1 presents a concise summary of the study, outlining its objectives and major findings. Section 5.2 highlights the key insights gained from the research, while Section 5.3 discusses the specific contributions of this study to the field of CSP technology and energy planning. Ethical concerns related to the implementation of CSP projects are addressed in Section 5.4. Section 5.5 identifies the study's limitations, including constraints in data availability, modeling assumptions, and real-world applicability. Finally, Section 5.6 provides recommendations for further research, focusing on areas such as real-world validation, hybrid renewable energy integration, advanced storage solutions, and policy-driven economic studies to enhance the feasibility of CSP deployment in Bangladesh.

5.1 Summary

This study focused on the techno-economic analysis and optimization of Concentrated Solar Power (CSP) plants for sustainable energy development in Bangladesh. Four CSP technologies—Parabolic Trough Collector (PTC), Solar Tower (ST), Linear Fresnel Reflector (LFR), and Solar Dish (SD)—were designed and evaluated at the three highest Direct Normal Irradiance (DNI) locations in Bangladesh: Cox's Bazar, Bandarban, and Chapainawabganj. The optimization process considered solar field design, receiver configurations, heat transfer fluid selection, power cycle integration, and thermal energy storage to enhance plant efficiency and economic feasibility.

A detailed comparison of the designed CSP plants with existing operational CSP plants worldwide provided insights into the performance and cost-effectiveness of different technologies. The study also assessed the viability of CSP deployment in Bangladesh by evaluating land requirements, levelized cost of electricity (LCOE), net present value (NPV), and capacity factors. Recommendations for suitable plant placement were provided based on the results.

The findings indicate that CSP technology has the potential to contribute significantly to Bangladesh's renewable energy mix, particularly for grid stability and large-scale power generation. However, economic challenges, land constraints, and technological advancements must be addressed to ensure successful implementation. The next sections summarize key insights, contributions, ethical considerations, study limitations, and recommendations for future research.

5.2 Key Insights

The study provides several key insights into the feasibility and optimization of Concentrated Solar Power (CSP) plants in Bangladesh:

- Technology Performance Variation – Among the four CSP technologies analyzed, Parabolic Trough Collector (PTC) and Solar Tower (ST) exhibited the highest efficiency and capacity factors, making them the most suitable for large-scale power generation. The Linear Fresnel Reflector (LFR) showed moderate efficiency but had a lower land requirement, while the Solar Dish (SD), though highly modular, had the lowest capacity factor and highest LCOE.

- Economic Viability – The levelized cost of electricity (LCOE) for CSP plants in Bangladesh is competitive with global benchmarks but remains higher than conventional power sources. The NPV analysis indicates that locations with higher DNI, such as Chapai Nawabganj, offer better economic feasibility.
- Optimal Plant Locations – The three highest DNI regions—Cox's Bazar, Bandarban, and Chapai Nawabganj—are suitable for CSP deployment, with Chapai Nawabganj showing the best performance in terms of energy generation and financial return. However, land availability and infrastructure must be considered when selecting sites.
- Thermal Energy Storage (TES) Benefits – The inclusion of TES systems in CSP plants significantly improves dispatchability, allowing power generation during non-sunny hours and enhancing grid stability. Solar Tower CSP benefits the most from TES integration due to its high operating temperature and storage efficiency.
- Comparison with Existing CSP Plants – The designed CSP plants were compared with operational projects such as NOOR II, NOOR III, and Dhursar CSP plants, revealing that optimized CSP plants in this study can achieve higher energy generation and capacity factors under Bangladesh's solar conditions. However, cost competitiveness remains a challenge.
- Land Requirement and Scalability – CSP plants require significant land area, with PTC and ST having the largest footprint, making land acquisition a critical factor. LFR has a smaller land requirement, making it a potential option for regions with land constraints.
- Potential for a 600 MW CSP Plant – Based on the findings, a 600 MW CSP plant could be developed by combining multiple CSP technologies,

leveraging their strengths, and optimizing thermal storage to enhance capacity utilization.

5.3 Contribution

The implementation of Concentrated Solar Power (CSP) technology in Bangladesh remains a challenge due to the lack of detailed optimization models and feasibility studies tailored to the country's unique solar and economic conditions. Previous research has primarily focused on photovoltaic (PV) solutions, often overlooking the potential of CSP for large-scale energy generation and grid stability. Additionally, most existing studies on CSP development focus on global projects without offering a localized and technically optimized solution for Bangladesh.

This thesis presents a comprehensive design and optimization for four major CSP technologies—Solar Tower (ST), Parabolic Trough Collector (PTC), Linear Fresnel Reflector (LFR), and Solar Dish (SD)—considering Bangladesh's solar resource availability, land constraints, and economic feasibility. The optimized CSP models are designed to maximize energy output, reduce LCOE, and enhance reliability through the integration of Thermal Energy Storage (TES).

The proposed CSP plant designs are evaluated and compared with existing operational plants, such as NOOR II, NOOR III, and Dhursar, to validate their performance. Additionally, this study provides a strategic roadmap for deploying a 600 MW CSP plant in Bangladesh, offering insights into site selection, financial viability, and technological implementation.

By addressing the key technical and economic challenges of CSP deployment in Bangladesh, this research contributes to sustainable energy development, renewable energy policy planning, and future large-scale CSP projects, ensuring a viable alternative to conventional fossil-fuel-based power generation.

5.4 Ethical Concerns

The whole writing process followed the Chittagong University of Engineering and Technology's writing format for the thesis. A licensed version of SAM (System Advisor Model) software was used for simulation purposes. All the calculations related to the thesis were done by myself. All of the historical data for analysis purposes was taken from the following sources: (1) http://www.sreda.gov.bd/; (2) https://www.idcol.org/; and (3) http://www.nrel.gov. The set of data mentioned in the procedure was done for this detection process by myself.

5.5 Limitations of The Study

While this study provides a comprehensive techno-economic analysis and design optimization of Concentrated Solar Power (CSP) plants for Bangladesh, certain limitations must be acknowledged:

- The study relies on simulated data rather than real-world operational data, which may introduce discrepancies in actual plant performance.
- Variability in Direct Normal Irradiance (DNI) and seasonal changes can impact the efficiency of CSP systems, requiring further adaptive strategies.
- The study assumes ideal operating conditions and does not fully account for grid fluctuations, land constraints, or socio-economic challenges in implementation.
- Limited availability of high-resolution climate data for Bangladesh may have affected the accuracy of solar resource assessment.

5.6 Recommendations for Further Study

Future research can build on this work to enhance the feasibility and optimization of CSP plants in Bangladesh. Key areas for further exploration include:

- Real-world performance validation by integrating actual operational data from existing CSP plants to refine simulation models.
- Hybridization with other renewable sources, such as photovoltaic (PV) systems or wind power, to ensure continuous energy generation and grid stability.
- Advanced thermal energy storage (TES) optimization, including phase change materials (PCMs) and molten salt storage for improved efficiency.
- Integration of artificial intelligence (AI) and machine learning for predictive maintenance, optimal dispatch, and dynamic performance enhancement of CSP plants.

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Appendices

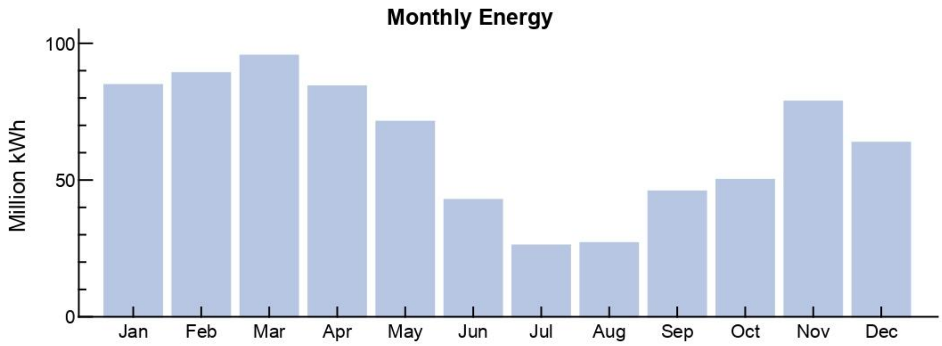
Appendix A: PTC Plant Design Report by SAM

System Advisor Model Basic Report

Parabolic Trough System	150 MW Nameplate Capacity
Single Owner	$1,225,263,630 Installed Cost
City and state unknown	21.45 N, 91.98 E GMT +6

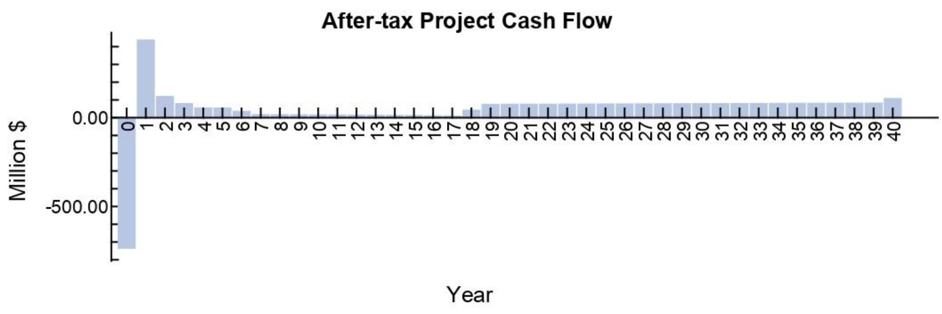
Performance Model

Annual Output in Year 1	759,288,640 kWh
Capacity Factor	0.58



Financial model

Levelized Cost of Energy	14 cents/kWh
Net Present Value	$125,901,776



System Advisor Model Standard Report generated by SAM 2024.12.12 on Tue Feb 25 02:54:31 2025

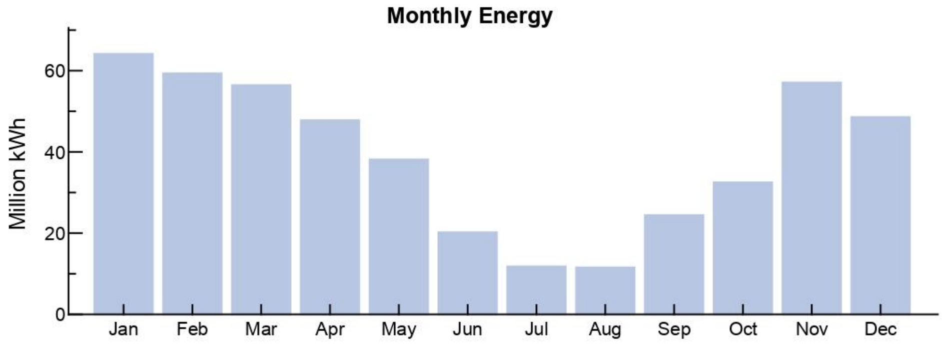
Appendix B: ST Plant Design Report by SAM

System Advisor Model Basic Report

Power Tower System	151 MW Nameplate Capacity
Single Owner	$480,375,025 Installed Cost
City and state unknown	21.45 N, 91.98 E GMT +6

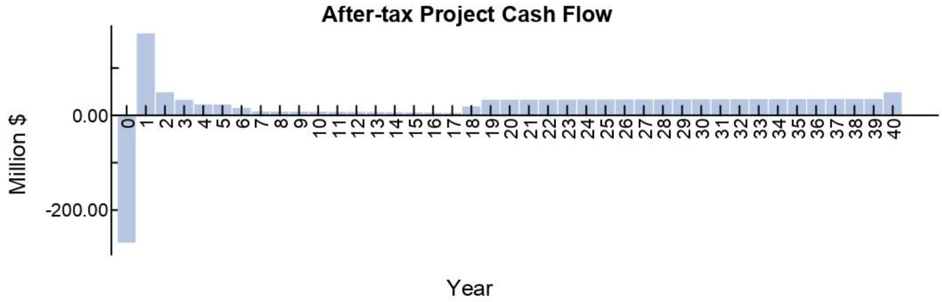
Performance Model

Annual Output in Year 1	472,094,784 kWh
Capacity Factor	0.36



Financial model

Levelized Cost of Energy	9.8 cents/kWh
Net Present Value	$78,294,312



System Advisor Model Standard Report generated by SAM 2024.12.12 on Wed Mar 5 06:34:07 2025

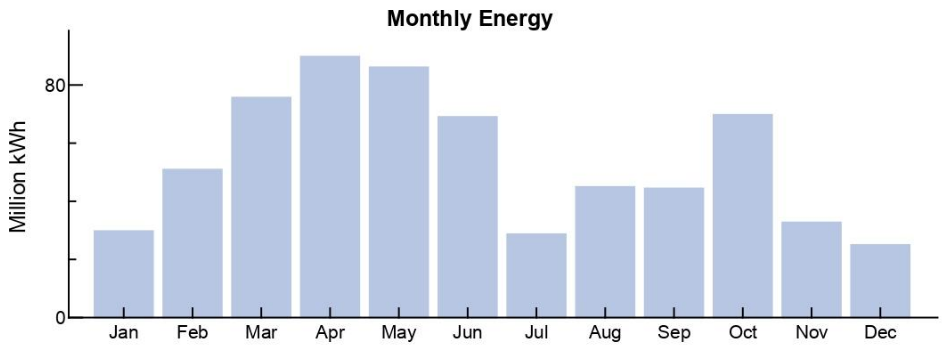
Appendix C: LFR Plant Design Report by SAM

System Advisor Model Basic Report

Linear Fresnel System	150 MW Nameplate Capacity
Single Owner	$1,165,186,595 Installed Cost
City and state unknown	26.93 N, 81.22 E GMT +5

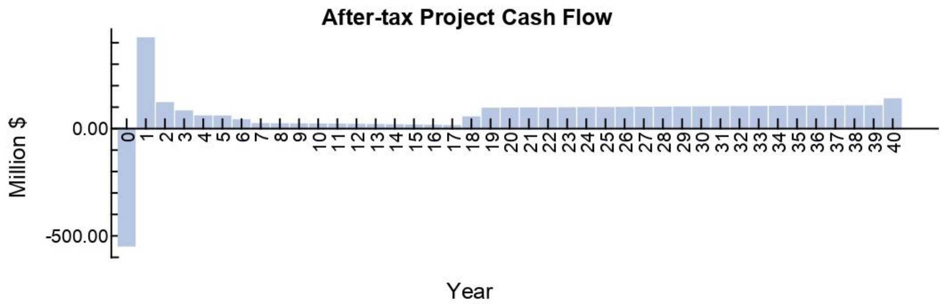
Performance Model

Annual Output in Year 1	646,491,648 kWh
Capacity Factor	0.49



Financial model

Levelized Cost of Energy	16.2 cents/kWh
Net Present Value	$383,551,840



System Advisor Model Standard Report generated by SAM 2024.12.12 on Wed Mar 5 06:28:18 2025

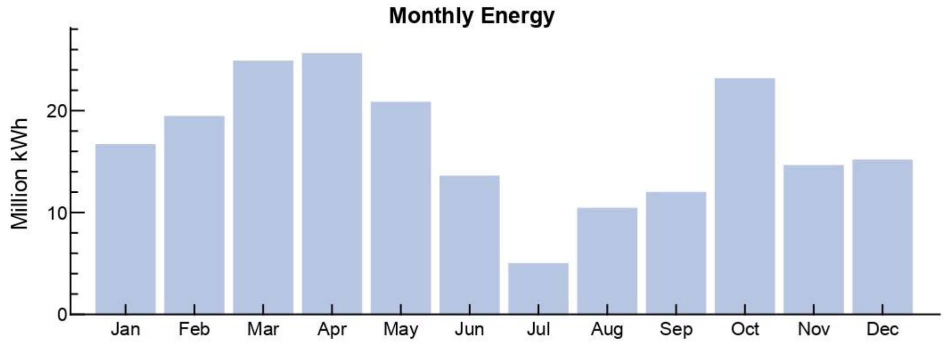
Appendix D: SD Plant Design Report by SAM

System Advisor Model Basic Report

Dish Stirling System	150,000 kW Nameplate Capacity
Single Owner	$418,349,952 Installed Cost
City and state unknown	26.93 N, 81.22 E GMT +5

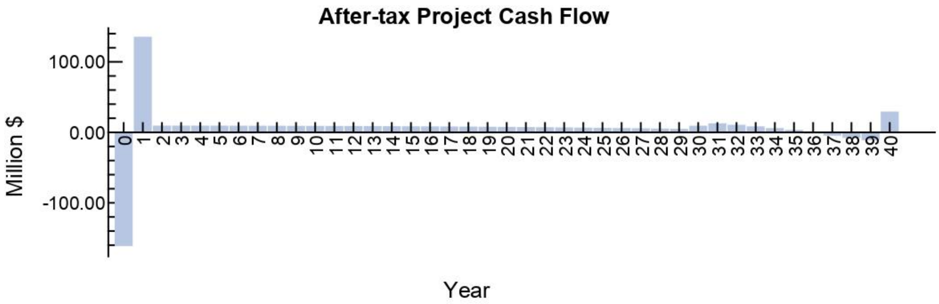
Performance Model

Annual Output in Year 1	200,820,512 kWh
Capacity Factor	0.15



Financial model

Levelized Cost of Energy	23.6 cents/kWh
Net Present Value	$15,068,197



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