Comparative Performance of a Hydrogen Fuel Cell Integrated PV–Wind Hybrid Energy System with Gas-Turbine Backup Using NSGA-II and MOPSO

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A Thesis Submitted to the Academic Faculty in Partial Fulfillment of the Requirements for the Degree of

BACHELOR OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

Department of Electrical and Electronic Engineering

Islamic University of Technology (IUT)

Gazipur, Bangladesh

October 2025

Declaration of Authorship

We do hereby certify that the thesis titled "*Comparative Performance of a Hydrogen Fuel Cell Integrated PV–Wind Hybrid Energy System with Gas-Turbine Backup Using NSGA-II and MOPSO*" represents the original outcome of research conducted under the supervision of Dr. Ashik Ahmed, Professor, at the Department of Electrical and Electronic Engineering, Islamic University of Technology (IUT).

This work has been carried out in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering at IUT.

We affirm that this thesis, in whole or in part, has not been submitted previously for any other degree, diploma, or academic qualification at this or any other institution. All materials, data, figures, and published works of others used in this thesis have been properly acknowledged and cited in accordance with academic integrity and ethical standards.

We further declare that the contents of this thesis are the product of our own work, except where explicit references are provided, and that no portion of this document has been plagiarized.

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List of Acronyms

TCE	Total Carbon Emissions
LCOE	Levelized Cost Of Energy
HRES	Hybrid Renewable Energy Systems
NSGA-II	Non-dominated Sorting Genetic Algorithm II
MOPSO	Multi-Objective Particle Swarm Optimization
PSO	Particle Swarm Optimization
NPC	Net Present Cost
COE	Cost Of Energy and alternating current (AC)
PV	Photovoltaic
PEM	Proton Exchange Membrane
DC	Direct Current
STC	Standard Test Conditions
LHV	Lower Heating Value
GTs	Gas Turbines

GHI	Global Horizontal Irradiance
O&M	Operation and Maintenance
OBE	Outcome-Based Education
POs	Program Learning Outcomes
COs	Course Outcomes

Acknowledgements

First and foremost, all praise is due to Almighty Allah, whose blessings and guidance enabled us to complete this research successfully.

We want to express our sincere appreciation to our supervisor, Dr. Ashik Ahmed (Professor, Department of Electrical and Electronic Engineering, IUT), for his continuous guidance, insightful feedback, and encouragement throughout the research process.

We acknowledge the Department of Electrical and Electronic Engineering at Islamic University of Technology for providing the required facilities, technical resources, and a supportive environment necessary for conducting this study.

Finally, we express our heartfelt gratitude to our parents, family members, and friends for their constant support, motivation, and prayers, which helped us remain determined and focused throughout this journey.

Abstract

The intermittency of wind power and solar PV complicates grid stability and leads to higher curtailment of renewables; in order to minimize such challenges this study conceptualizes and designs an optimized hybrid large-scale renewable energy system comprising PV, wind, an electrolyzer, fuel cell, hydrogen storage, gas-turbine backup, and optional electrochemical storage to divide shortfall compensation below the turbine's minimum load. Biomass plant dispatch and system capacity optimized based on a life-cycle perspective, both the total CO_2 emissions (TCE) and levelized cost of energy (LCOE) were minimized based on NSGA-II and MOPSO in MATLAB R2021a. Pareto analysis produced apparent trade-offs: the cost-optimized solution had TCE ≈ 97,054 tCO_2 and LCOE of 0.1126 $/kWh (NSGA-II), and the optimized emission solution had its best TCE of 91,769 tCO_2 with an LCOE of 0.2119 $/kWh; a compromise solution did 0.1404 $/kWh and 93,325 tCO_2 (NSGA-II). Hydrogen storage with the gas turbine reduces curtailment and natural gas consumption considerably but incurs higher capital cost; addition of electrochemical storage maximizes turbine efficiency, minimizes fuel use, and maximizes overall economy. Compared results show NSGA-II provides more accurate cost estimation at endpoints, whereas MOPSO provides convergence and better distribution of Pareto front. Sensitivity analyses reveal that reducing discount rates and reducing capital costs reduce LCOE (and reduce TCE slightly), increased global horizontal irradiance increases cost and emissions, and increased ambient temperature decreases performance; increasing component efficiency reduces LCOE and TCE. The method gives a realistic decision-support tool for planning low-carbon, cost-efficient Hybrid Renewable Energy Systems (HRES) in Bangladesh and comparable emerging economies.

Chapter 1

Introduction

The world's energy demand continues to rise at a rapid pace due to industrialization, urbanization, and population growth. At the same time, increasing greenhouse gas emissions from fossil fuel-based power generation have exacerbated global warming and accelerated climate change. Most countries are now confronted with the double challenge of ensuring energy security and reducing the environmental footprint. Conventional energy systems reliant on a high proportion of coal, oil, and natural gas are proving to be both economically and environmentally unsustainable in the long term. As a result, hybrid renewable energy systems that integrate solar, wind, and emerging storage technologies are becoming a critical component of sustainable energy planning around the world.

Bangladesh provides a case in point for the transition towards cleaner and more reliable energy systems. With a population of more than 180 million, the country still struggles to meet its growing electricity demands. Although more than 70% of the citizens are technically connected to the national grid, the per capita consumption of electricity is about 417 kWh, which is much lower compared to the world average of approximately 3180 kWh per capita [1] . This comparison shows that access to energy does not denote energy sufficiency. Frequent power outages, voltage instability, and disruption of supply are common in urban and rural areas. In Dhaka city, the capital and principal economic hub, power disruption is common due to an aging and overstressed distribution system. Technical losses in the system are high, and growing demand in high-density areas keeps stressing system capacity.

One of the key causes of such instability is Bangladesh's dependence on fossil fuel-based generation. Natural gas has been the cornerstone of the country's energy mix for a long time, supplying the majority of the country's electricity. However, domestic gas reserves are dwindling, and the country has depended more and more on imported liquefied natural gas, coal, and furnace oil to keep power generation going. Dependence on imports has exposed Bangladesh to international price volatility, currency devaluation, and increased generation expenses. The economic expense of fuel importation, in addition to infrastructural limitations, has made electricity production excessively expensive and vulnerable to market fluctuations [2]. Additionally, combustion of fossil fuels continues to emit enormous amounts of greenhouse gas, driving climate change and environmental degradation. Being a climate change-vulnerable deltaic nation, Bangladesh is highly exposed to sea level rise, cyclones, and extreme weather events, and hence emission curtailment and energy transition become an urgent national agenda [3].

Despite these challenges, Bangladesh has a huge renewable energy potential. The geographical location of the country provides high solar irradiation throughout the year, with most locations receiving average 4.65 kWh/m² of solar energy daily [4]. This makes photovoltaic-based electricity generation extremely attractive. In addition to solar potential, certain coastal and offshore locations also have moderate wind potential for electricity generation. Rural areas that remain poorly connected or isolated from the national grid can benefit particularly from decentralized renewable energy technologies. However, integration challenges come from the intermittent nature of wind and solar energy, which requires systems that can ensure reliability and continuity of supply.

Hybrid renewable energy systems offer a sensible solution to these complexities by integrating more than one energy source with appropriate storage and backup systems. By integrating solar photovoltaic modules, wind turbines, hydrogen storage systems, fuel cells, and gas turbines, energy supply can be balanced in real time based on availability and load. When renewable power exceeds consumption, the surplus can be converted into hydrogen through electrolyzers for later use. Hydrogen stored can be converted back into electricity through fuel cells when there is a deficit in renewable generation. Gas turbines provide an additional layer of security during periods of extreme deficit or low hydrogen storage. This integrated approach minimizes renewable energy curtailment, maximizes utilization of storage, and maintains system reliability.

Hydrogen storage is particularly valuable for long-duration energy balancing. Unlike batteries, which are generally optimal for short-duration storage, hydrogen can be stored in large quantities and drawn upon over extended periods of time [5]. When produced from renewable energy, hydrogen is a zero-carbon storage medium enabling emission reduction targets. Fuel cells efficiently and cleanly convert stored hydrogen into electricity with little environmental impact. Hybridizing such technologies with conventional backup sources, such as gas turbines, provides a flexible and resilient hybrid renewable system with the potential to provide continuous electricity to grid-connected and off-grid communities. The benefits of introducing hydrogen storage to the stand-alone PV-based system have been reported by Tatti et al. found that the higher load reliability of 99% can be achieved by hydrogen storage than the battery storage (93%) [6].

Economic viability is always a first consideration in energy system planning. Levelized cost of energy (LCOE) is the most prevalent measure for determining the economic feasibility of different power system designs [7]. A system that has lower LCOE at high reliability has a higher chance of being implemented in reality [8]. Environmental performance is evaluated at the same time based on metrics such as total carbon emissions (TCE) [9]. A combined model that considers both LCOE and TCE allows decision-makers to balance economic and environmental objectives. An economic system that budgetsthe emissions without involving excessive costs can form the basis of long-term energy planning, policy, and climate commitment.

To create a good mix of energy sources for Bangladesh, we need to think hard about money and the environment. Putting together solar power, wind power, hydrogen storage, fuel cells, and gas turbines can help us depend less on fossil fuels and feel safer about energy. But to get the most out of each part, it takes good planning. These kinds of models can help us look at the pros and cons to find the best setups that meet what we need, like low costs and enough power [10].

The incorporation of hydrogen storage and fuel cells into hybrid renewable systems is highly compatible with Bangladesh's long-term objectives of greenhouse gas emissions reduction, diversification of energy sources, and improvement in reliability. The availability of gas turbines as backup ensures that even when there are low renewable output conditions and depleted hydrogen reserves, the system continues to meet demand. To create the right mix of energy sources for Bangladesh, we need to think carefully about money and the environment. Using solar, wind, hydrogen storage, fuel cells, and gas turbines together can help Bangladesh depend less on old-fashioned fuels and make its energy supply safer. Still, planning and getting the most out of each part needs some smart thinking. Using ways to find the best balance can help us see the trade-offs and find setups that hit the right spot for things like price, pollution, and how well the system keeps up with demand.

The subsequent chapters are organized as follows: Chapter 2 presents a comprehensive Literature Review; Chapter 3 details the Methodology employed in this study; Chapter 4 describes the proposed Optimization Framework. Chapter 5 elaborates on the Operational

Strategy of the System, followed by Chapter 6, which discusses the Results and Analysis. Chapter 7 demonstrates the Outcome-Based Education (OBE) Implementation, while Chapter 8 concludes the study and outlines Future Work. Finally, Chapter 9 lists all References cited throughout the thesis.

Chapter 2

Literature Review

Hybrid renewable energy systems are now a bigger deal in energy planning because they can help reduce the on-again, off-again nature of renewable sources and make the power supply more reliable. By bringing together different renewable sources like solar, wind, and hydrogen. These setups can keep the power flowing steadily while using less fossil fuel. Recent studies are looking at how to design these hybrid setups, find the best ways to run them, and check if they make sense from a tech and money point of view in different climates and regions. This chapter is all about relevant research works on hybrid renewable energy systems, how hydrogen fits in, and ways to get the most out of them, especially for energy in Bangladesh. Systems that mix more than one renewable source have been studied a lot because they're good for both the wallet and the environment. For instance, Liu et al. [11] put together and made the most of a renewable energy system with solar, wind, and fuel cells to depend less on the power grid and cut down on CO_2 emissions. Their results depicted a favorable sustainability index of 0.999 and LCOE of 0.3096 $/kWh, demonstrating the potential for hybridization with regard to cost-effectiveness and environmental benefit. Similarly, Danish et al. [12] formulated a multi-objective framework to analyze solar, wind, storage, and hydrogen-based component integration, with emphasis on operational stability enhancement and reduced environmental footprint.

Several works focused on specific hybrid configurations for islanded or grid-connected uses. Oueslati [13] likened PV/Wind/Battery-fed hydrogen refueling stations in twenty French cities and discovered that PV-led systems featured the most competitive LCOE and hydrogen costs. Anastasiadis et al. [14] examined the financial feasibility of a hybrid wind–photovoltaic system with an electrolyzer for the production of green hydrogen to provide energy for a small fleet of hydrogen cars. Their comparison provided an insight into the relationship between LCOE and hydrogen cost, validating the viability of hybrid systems for green distributed hydrogen production. Extending this, Oueslati and Fezai [15] optimized PV–Wind hydrogen refueling stations in twenty sites in Saudi Arabia and demonstrated how varying the proportion of solar and wind energy influences both the levelized cost of energy and hydrogen.

Bahri et al. [16] proposed a large-scale renewable-based hybrid system consisting of photovoltaic panels, a fuel cell, batteries, an electrolyzer, and a hydrogen storage tank that satisfied a given electrical load profile with reliability. Their system showed the synergy between hydrogen storage and battery storage for supply continuity. Shboul et al. [17] used Gaussian process regression and NSGA-II for the optimization of a hybrid photovoltaic–fuel cell system for green hydrogen and power generation. The optimum design achieved the reduction of CO_2 emissions by 13% and LCOE below 2 $/kWh. Alturki [18] modeled the economic barriers to hydrogen adoption and proposed modeling and optimization techniques to reduce the levelized cost of hydrogen, showing that the correct hybrid configuration choice is crucial for cost reduction.

In another study, Li et al. [19] optimized a co-located wind–hydrogen hybrid system with electrolyzers, hydrogen tanks, and fuel cells in a grid-connected wind network. The approach minimized system cost and improved operational flexibility. Boulmrharj et al. [20] examined a grid-connected photovoltaic–electrolyzer–fuel cell cogeneration system, which has the capacity to supply electricity and thermal energy to a building at the same time. Their results demonstrated the multifunctional potential of hybrid configurations for achieving improved energy efficiency. Likewise, Shaikh et al. [21] made a techno-economic evaluation of grid-connected renewable and hydrogen-to-power dispatch strategies. The study found that although the high initial cost and lower round-trip efficiency present a challenge, these systems remain economically attractive due to their long-term profitability and environmental gains.

Ahmed et al. [22] used the NSGA-II algorithm to optimize a hybrid system consisting of photovoltaic, wind, diesel generator, battery, and methanation subsystems designed for a remote island community. Their optimization minimized total cost while satisfying different energy demands, i.e., electricity, water, and gas, for various load conditions. Yan et al. [23] also explored the impact of design parameters on a microgrid integrating photovoltaic, wind, and fuel cell technologies, with a minimum cost of energy of 0.3458 $/kWh and an annual operating cost of $11,952. These findings collectively confirm that hybrid renewable systems, especially when supported by advanced optimization, can significantly enhance cost-effectiveness and sustainability.

Hydrogen energy storage has been the focus of significant interest for its use in stabilizing hybrid renewable-based systems. Its flexibility allows for excess renewable electricity to be converted into hydrogen via electrolysis with the possibility of storage and reconversion into electricity via fuel cells. This allows for long-term storage and ensures a stable power supply in periods of low renewable generation. Papers such as Oueslati [13] and Oueslati & Fezai [15] illustrated how the inclusion of hydrogen infrastructure in renewable systems benefits both transportation and power systems.

Anastasiadis et al. [14] emphasized that green hydrogen from electrolyzers powered by renewables can be utilized for numerous applications, from transportation to grid balancing, with significant CO_2 savings. Similarly, Bahri et al. [16] and Li et al. [19] illustrated that the combination of electrolyzers and fuel cells with PV and wind assets brings about improved reliability and flexibility of energy systems. These configurations represent a fundamental stepping stone to decarbonized hybrid systems with the ability to meet long-term energy and emission objectives.

Hybrid energy systems' complexity has increased reliance on multi-objective optimization algorithms to size optimally, cost-minimize, and emit less. Metaheuristic methods such as NSGA-II and MOPSO have gained popularity in solving nonlinear, multi-dimensional optimization problems in energy planning. NSGA-II, in particular, has seen extensive use in maintaining diversity among solutions and identifying Pareto-optimal configurations across large search spaces. MOPSO, being a swarm intelligence-based technique, offers faster convergence and computational efficiency through the balancing of multiple objectives.

Recent work has implemented these algorithms on various hybrid system configurations. Shboul et al. [17] integrated NSGA-II with regression modeling for hybrid PV–fuel cell optimization with cost and emission improvement. Ahmed et al. [22] applied NSGA-II to remote hybrid configurations with renewable and methanation processes, successfully minimizing cost while satisfying diverse energy demands. Comparative investigations of different worldwide studies have shown that NSGA-II tends to generate more diverse Pareto fronts, whereas MOPSO converges faster. The combination of these two algorithms in hybrid system modeling allows researchers to test solution robustness and identify environmental and economic trade-offs more effectively.

In Bangladesh, a number of studies of hybrid renewable energy systems suitable for rural and urban electrification have been conducted. Research has been concentrated on solar, wind, diesel, and biomass hybrids. A few examples include PV/Diesel/Battery [24], PV/Wind/Battery [25], PV/Wind/Diesel/Battery [26], and PV/Biomass/Diesel/Battery [27] systems. Das et al. [28] proposed a PV/Micro-hydro/Diesel/Battery system for an offshore location, with an energy cost of 0.206 $/kWh, about 28% lower than pure diesel systems. Nurunnabi et al. [29] made a comparison between on-grid and off-grid PV/Wind hybrid systems for different locations, including Sitakunda, achieving COE values of 0.477 $/kWh for off-grid and 0.064 $/kWh for on-grid systems.

Anjum et al. [30] compared the techno-economic feasibility of PV, wind, and fuel cell-based systems for grid-connected and stand-alone applications. The results demonstrated encouraging COE savings of up to 70% for off-grid installations. Islam et al. [31] applied the NSGA-II algorithm and HOMER Pro software for optimizing a hybrid power system with minimum net present cost (NPC), cost of energy (COE), and CO_2 emissions, showing the applicability of the algorithm to the Bangladeshi context. Ali et al. [32] analyzed a grid-connected PV–biomass system for a Bangladeshi university, which achieved a competitive COE of 0.0347 $/kWh and a payback period of 6.52 years. All these investigations cumulatively refer to the increasing interest in hybrid installations in Bangladesh, yet most have been limited to conventional renewable sources without any significant emphasis on hydrogen integration.

A review of existing research depicts substantial progress in hybrid renewable energy system development and optimization worldwide. Hybridization of PV, wind, and hydrogen storage technology has been demonstrated to reduce energy costs, enhance system reliability, and lower CO_2 emissions. Advanced optimization algorithms such as NSGA-II and MOPSO have been effectively utilized in examining trade-offs between economic and environmental objectives.

However, the majority of existing research remains region-specific and lacking in models applicable to varying climatic and economic conditions. Most have focused mainly on cost or reliability, with fewer addressing emissions or performing comparative analyses across optimization algorithms. Comprehensive integration of hydrogen storage in multi-objective frameworks is also scarce.

In the case of Bangladesh, most of the studies have considered PV, wind, diesel, and biomass hybrids with minimal work on hydrogen-based systems. Research work using advanced multi-objective optimization algorithms is scarce, and a comparison between NSGA-II and MOPSO has not been explored.

Thus, there is a clear research gap in the design of a hydrogen-integrated cost- and emission-optimized hybrid renewable system for the condition of Bangladesh. The present research bridges this gap using NSGA-II and MOPSO for the design of a balanced system with minimal LCOE and CO_2 emissions that will assist in the development of sustainable energy systems.

Chapter 3

Methodology

In the current research, the proposed hybrid renewable energy system uses a photovoltaic (PV) array and a wind farm as the primary renewable energy producing units. To supply a continuous power output and system reliability, a gas turbine and a fuel cell are considered as support and backup sources to meet load requirements in case of renewable energy shortages. The system also incorporates a proton exchange membrane (PEM) electrolyzer and hydrogen storage tank, allowing utilization of surplus renewable electricity for hydrogen production and storage for later use. For efficient power management between the portions, a bidirectional DC/AC inverter is included, offering efficient conversion and interaction among different system buses.

3.1 Photovoltaic cell modelling:

The photovoltaic (PV) subsystem is simulated, beginning with the calculation of its theoretical power generation. Under standard test conditions (STC), the rated power of a PV module can be expressed as

$$P_{\mathrm{PV},R} = A_c GI_{\mathrm{STC}} \eta_{\mathrm{PV,ref}} \tag{1}$$

where $P_{\mathrm{PV},R}$ is the rated power output of the PV array, A_c is the area of the panel surface (approximated as 1 m²), GI_{STC} is the solar irradiance at STC (1000 W/m²), and $\eta_{\mathrm{PV,ref}}$ is the reference efficiency of the PV module, approximated as 21.4% [33].

Under real operating conditions, the PV modules rarely achieve their theoretical rated power due to a number of practical limitations. The true power generation is therefore approximated by the following equation:

$$P_{\mathrm{PV}} = A_c GI_T \eta_{\mathrm{PV}} f_{\mathrm{PV}} \tag{2}$$

Where GI_T is the solar irradiance on the surface of the PV, η_{PV} is the module efficiency under ambient conditions, and f_{PV} is a derating factor encompassing physical and operational losses. The deviations from the theoretical maximum are caused by a variety of factors, such as temperature differences, shading, dust accumulation, and module aging. To compensate for these losses, a typical derating factor of 0.8 is used, as proposed in [34], considering the effects of environmental conditions (e.g., rain, snow, and dust) and differences in PV module performance.

The actual efficiency of a PV cell differs from its reference efficiency primarily due to the changes in temperature and wind speed. An empirical relationship is taken into account in order to compute the operating efficiency as:

$$\eta_{\mathrm{PV}} = \eta_{\mathrm{PV,ref}}\left[1 + \lambda\left(T_a - T_{c,\mathrm{ref}}\right) + \lambda G I_T \frac{\tau\alpha}{5.7+3.8v_1}\left(1 - \eta_{\mathrm{PV,ref}}\right)\right] \tag{3}$$

in which λ is the temperature coefficient of 0.41%/◦C [13], τα is the ambient temperature, $T_{c,\mathrm{ref}}$ is the PV cell temperature at STC with the value of 25 ◦C, τα is the transmittance-absorptance coefficient with the value of 0.9, and v_1 is the measured wind speed. [34] Finally, the power output can be measured as:

$$P_{\mathrm{PV}} = P_{\mathrm{PV},R}\frac{GI_T}{GI_{\mathrm{STC}}}\left[1 + \lambda\left(T_a - T_{c,\mathrm{ref}}\right) + \lambda G I_T \frac{\tau\alpha}{5.7+3.8v_1}\left(1 - \eta_{\mathrm{PV,ref}}\right)\right] f_{\mathrm{PV}} \tag{4}$$

3.2 Wind Turbine Modelling:

The performance of a WT is characterized through its power coefficient Cp that depends in a nonlinear way on two parameters, which are the tip speed ratio λ and the pitch angle of the blades β [33].

As shown in Fig. 1, a power curve is designed based on the empirical formulas of the wind-power utilization coefficient [33]:

$$c_p(\lambda, \beta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{12.5}{\lambda_i}} \tag{5}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \tag{6}$$

The functioning of a WT is divided into four broad operating regions, with each region having a certain wind speed limit. The regions are useful in describing the process of how the turbine gradually moves from zero operation to peak output and eventually shuts down when there is very high wind.

Region 1: Cut-in Region

If wind speed is less than cut-in speed ($v_{cut\text{-}in} < v < v_{rated}$), there is insufficient wind power to push the system out of inertia and begin rotating the turbine. Thus, the turbine cannot generate any significant power output, remaining essentially stationary in this region.

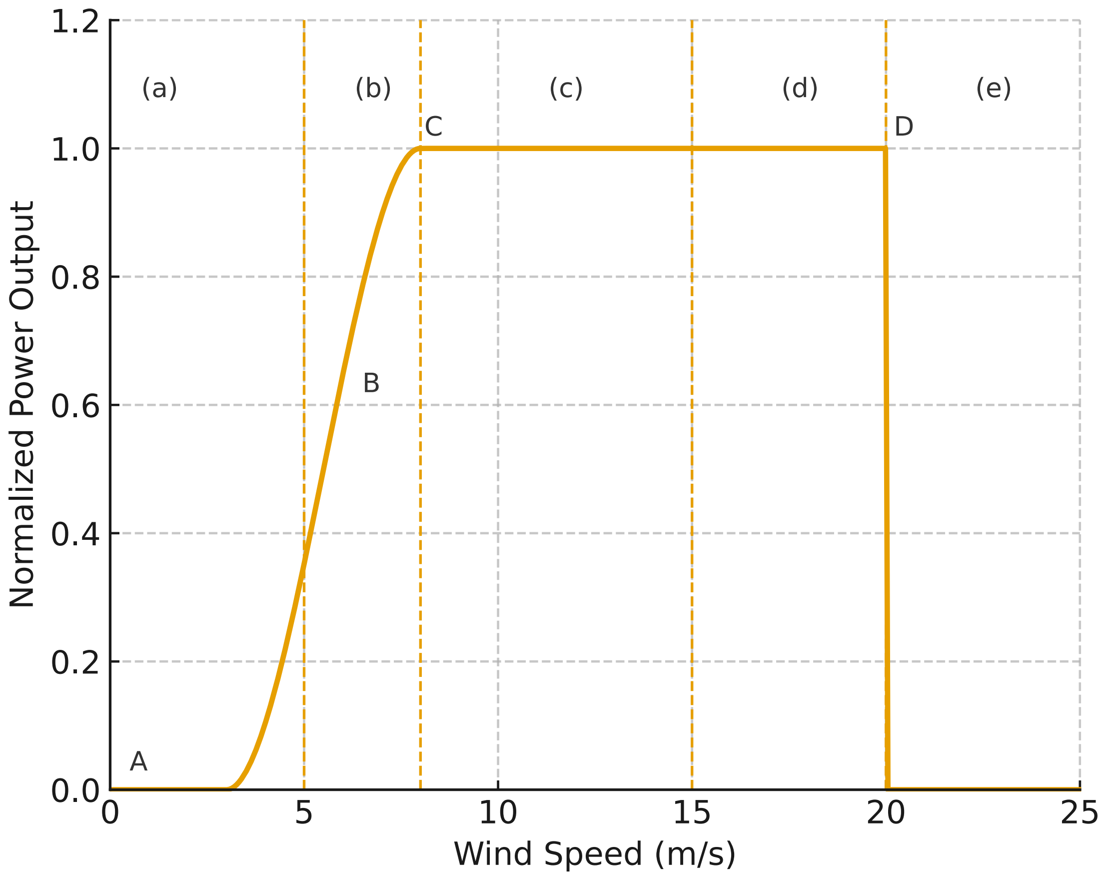

Fig. 1: Variation of Power output with wind speed for a typical wind turbine

Region 2: Variable Power Region

For this region, since the wind speed is within the cut-in speed and rated speed ($v_{cut\text{-}in} < v < v_{rated}$), the turbine starts producing electricity. The power output increases very quickly—typically with a cubic dependence on wind speed—since more energy is created. The output still increases up to the point that the turbine operates at its rated capacity.

Region 3: Constant Power Region

This region comprises wind speeds from the cut-off to the rated levels ($v_{rated} < v < v_{cut\text{-}off}$). Within this region, the turbine delivers the maximum power output at rated level. In order to prevent mechanical stress or damage, provisions are made to limit energy drawn from the wind. Consequently, the rate of power levels off and is fairly flat.

Region 4: Cut-off Region

When the canister speeds exceed the cut-off speed ($v > v_{cut\text{-}off}$), the turbine is automatically shut down to prevent damage. Extremely high winds result in a risk of structural damage, and shutting down preserves system integrity. Thus, the power output is brought to zero.

The calculation has been done using R=127 m For P_{rated} =2.8 MW

$$P_{\text{aero}} = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot v^3 \cdot C_p(\lambda, \beta) \tag{7}$$

$$P_{\text{norm}} = \frac{P_{\text{aero}}}{P_{\text{rated}}} \tag{8}$$

The turbine hub-height wind speed is calculated as [33]:

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{9}$$

where v_1 is the measured wind speed at height h_1 (10 m), v_2 is the wind speed at hub height h_2 (considered as 80 m), and α is the wind shear coefficient (1/7).

3.3 Gas Turbine Modelling

Gas turbines (GTs) play a vital role in hybrid renewable energy systems since they are capable of providing quick start-up, variable operation, and dynamic load-following capability. GTs are an essential backup power source that ensures system reliability during low renewable generation or high system demand. A 62 MW Siemens SGT-800 gas turbine is employed within this paper to meet the system peak load demand.

The gas turbine power output is primarily determined by the fuel mass flow rate ($\dot{m}$), its lower heating value (LHV), and the turbine efficiency (η_{gt}). The instantaneous energy output of the turbine can be expressed as [34]:

$$E_{gt} = \dot{m} \cdot LHV \cdot \eta_{gt} \cdot t \quad (10)$$

Where E_{gt} is the total energy produced (kWh), $\dot{m}$ is the mass flow rate of the input fuel (kg/s), LHV represents the energy content of the fuel (kWh/kg), η_{gt} denotes the gas turbine efficiency, taken as 57.3%, and t is the time duration (h).

The gas turbine model ensures stable operation during renewable shortfalls, providing fast ramping capability and supporting frequency regulation. It also serves as the final backup source when hydrogen reserves are insufficient, ensuring an uninterrupted energy supply within the system.

3.4 Modelling of Electrolyzer

The electrolyzer converts surplus renewable energy into hydrogen through electrolysis. When power generation from the PV and wind subsystems exceeds the load, the excess energy drives the electrolyzer to split water into hydrogen and oxygen.

The energy supplied to the electrolyzer at each time step is given by [35]:

$$E_{\text{Electrolyzer}}(t) = \left[E_{\text{PV}}(t) + E_{\text{WT}}(t) - \left(E_{\text{Elec}}(t)\right)\right] \times \eta_{\text{inv}} \quad (11)$$

The hourly hydrogen production is calculated as:

$$H_{\text{Electrolyzer}}(t) = \frac{E_{\text{Electrolyzer}}(t)\eta_{\text{ele}}}{\text{LHV}_{\text{H}_2}} \quad (12)$$

where $H_{\text{Electrolyzer}}(t)$ is the hydrogen produced (kg/h), η_{ele} is the electrolyzer efficiency, and LHV_{H_2} is the lower heating value of hydrogen. This process ensures efficient use of excess renewable energy for hydrogen generation.

3.5 Fuel Cell Modelling

The fuel cell provides backup power when renewable generation is insufficient. It converts stored hydrogen into electricity through an electrochemical reaction, producing only water as a by-product.

The electrical energy generated by the fuel cell is given by [35]:

$$E_{\mathrm{FC}}(t) = \left[E_{\mathrm{load}}(t) - \left(E_{\mathrm{PV}}(t) + E_{\mathrm{WT}}(t)\right)\right] \cdot \eta_{\mathrm{inv}} \tag{13}$$

The hydrogen consumption rate is expressed as:

$$H_{\mathrm{FC}}(t) = \frac{E_{\mathrm{FC}}(t)}{\eta_{\mathrm{FC}} \cdot \mathrm{HHV}_{\mathrm{H_2}}} \tag{14}$$

where $\eta_{\mathrm{FC}}$is the fuel cell efficiency (60%) and $\mathrm{HHV}_{\mathrm{H_2}}$is the higher heating value of hydrogen (39.4 kWh/kg). The fuel cell thus ensures a reliable supply with minimal emissions.

3.6 Hydrogen Storage Modelling

Hydrogen storage serves as an intermediate energy buffer between the electrolyzer and fuel cell. During periods of surplus generation, hydrogen is stored; during shortages, it is consumed by the fuel cell. The storage dynamics can be expressed as:

Hydrogen Inflow Condition:

$$H_{\mathrm{HS}}(t) = H_{\mathrm{HS}}(t-1) + H_{\mathrm{Electrolyzer}}(t) \tag{15}$$

Hydrogen Outflow Condition:

$$H_{\mathrm{HS}}(t) = H_{\mathrm{HS}}(t-1) - H_{\mathrm{FC}}(t) \tag{16}$$

Here, $H_{\mathrm{HS}}(t)$is the hydrogen stored at time t, $H_{\mathrm{HS}}(t-1)$is the previous storage level, $H_{\mathrm{Electrolyzer}}(t)$is hydrogen produced, and $H_{\mathrm{FC}}(t)$is hydrogen consumed. This model balances production and utilization of hydrogen within the system.

3.7 Modelling of Bidirectional Converter

The bidirectional inverter manages power exchange between the DC and AC buses, enabling two-way energy flow depending on supply and demand. Its operation is defined by:

$$P_{\text{out}} = P_{\text{in}} \cdot \eta_{\text{conv}} \tag{17}$$

where P_{in} is the input power and η_{conv} is the converter efficiency, assumed to be 95%. The inverter capacity is determined by the maximum expected power transfer between the DC and AC subsystems. This component enhances system flexibility and ensures efficient energy conversion across all operating conditions.

Chapter 4

Optimization Framework

The proposed optimization framework aims at finding the optimum configuration of the hybrid renewable energy system (HRES), which maximizes low cost and environmental impact with a guaranteed constant power supply. The optimization is conducted via a multi-objective Pareto frontier approach, taking into consideration economic and environmental performance criteria at the same time. The framework integrates in-depth system modeling, simulation, and optimization to balance economic feasibility and carbon emission reduction objectives.

4.1 Evaluation Metrics

The system performance is assessed using two primary indicators: Total Carbon Emissions (TCE) and Levelized Cost of Energy (LCOE). These two metrics represent the environmental and economic dimensions of the optimization problem.

4.1.1 Total Carbon Emissions (TCE)

Total carbon emissions encompass both operational and embodied emissions throughout the system's life cycle. The TCE can be expressed as:

$$TCE = CE_{OP} + CE_{MFG} \tag{18}$$

where CE_{OP} are operation-caused emissions, primarily due to fuel consumption in the gas turbine, and CE_{MFG} are manufacturing, transport, and disposal emissions of subsystems such as PV panels, wind turbines, fuel cells, and hydrogen storage equipment.

An integrated life-cycle model ensures that both direct and indirect emissions are accounted for in assessing environmental performance.

4.1.2 Levelized Cost of Energy (LCOE)

The LCOE quantifies the average cost per unit of electricity generated over the system's lifetime, incorporating all capital, operational, and replacement costs. It is formulated as follows:

$$LCOE = \frac{IC_{\text{sys}} + \sum_{t=1}^{N} \frac{AC_{\text{sys}}}{(1+i)^t} + \sum_{t=1}^{R} \frac{RC}{(1+i)^{tr}} - \sum_{t=1}^{R} \frac{SV}{(1+i)^{tr}}}{\sum_{t=1}^{N} \frac{E_{\text{grid}}}{(1+i)^t}} \quad (19)$$

where:

- IC_{sys}= initial investment cost,
- AC_{sys}= annual operation, maintenance, and fuel cost,
- RC= component replacement cost,
- SV= salvage value at the end of component life,
- E_{grid}= annual energy supplied to the grid (equal to demand under no-shortage condition),
- i= discount rate,
- t_r= replacement year, and
- N= total project lifetime.

This metric reflects the long-term economic viability of the HRES, incorporating the time value of money and the recurring expenditures associated with component maintenance and replacement.

4.1.3 Key Parameters of Subsystems

The techno-economic specifications of major subsystems—photovoltaic array, wind turbine, gas turbine, fuel cell, electrolyzer, and hydrogen storage—are taken from literature and given in Table 1. These are compared to a system life of 20 years.

Carbon emission factors for all the subsystems are listed in Table 2, where emissions from production and end-of-life disposal of PV panels, wind turbines, and hydrogen components are given. Small parts such as wiring, converters, and transformers are not included as their contribution to overall emissions is less.

During gas turbine operation, methane (CH_4) is assumed to be fully combusted, and carbon dioxide (CO_2) emissions are equal to 2.74 g CO_2 per gram of methane [34]. The environmental factors, such as ambient temperature, wind speed, and global horizontal irradiance (GHI) of one year of operation of Gazipur City, are provided in Fig. 2, and these are utilized as inputs to the system simulation.

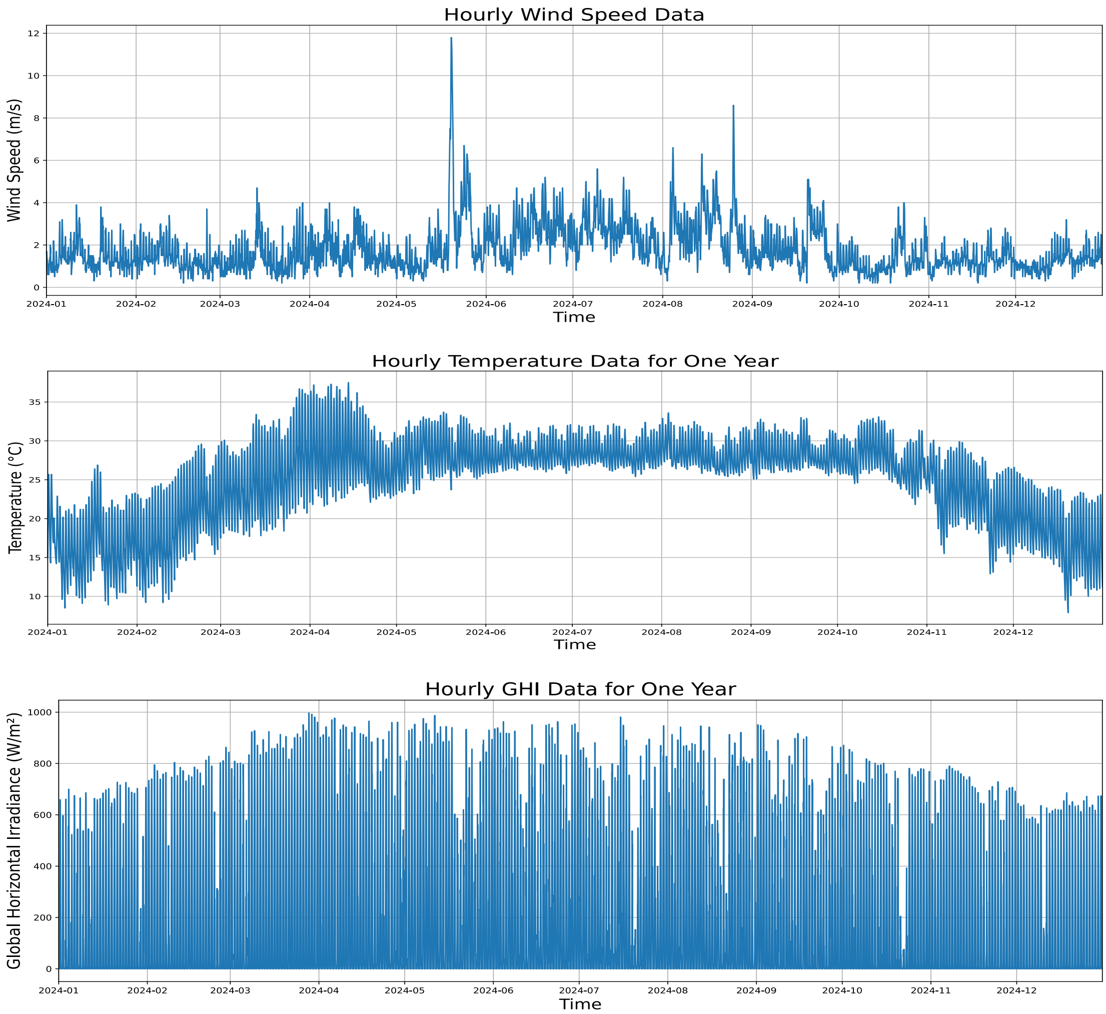

Fig. 2: Annual Weather Condition (Wind Speed, Temperature, and GHI)

Table 1: Economic Characteristics of the Subsystems

Subsystem	**Investment Cost**	**O&M Cost**	**Lifetime (years)**

Wind farm	1600 $/kW [36]	42 $/kW/yr [18]	20 [37]
PV plant	1070 $/kW [37]	13 $/kW/yr [37]	20 [38]
Gas turbine power plant	475 $/kW	6 $/kW/yr	20 [34]
Electrolyzer	1200 $/kW [39]	24 $/kW/yr	10 [39]
Hydrogen storage tank	333 $/kg H_2 [39]	6.66 $/kg H_2/yr	20 [38]
Battery bank	320 $/kWh [40]	2.64 $/kWh/yr	5
Converter	300 $/kW [40]	2 $/kW/yr	10 [38]
Fuel cell	850 $/kW	8 $/kW/yr	10
Others	Water: 0.65 $/ton	—	—

Table 2: Carbon Emission Factors for Major Subsystems

Subsystem	**Carbon Emissions**
Wind farm	20 g CO_2-eq/kWh [34]
PV plant	35 g CO_2-eq/kWh [41]
Battery bank	16,100 g CO_2-eq/kWh [42]
Gas turbine power plant	2.74 g CO_2/g CH_4 [34]

4.2 Problem Formulation

The hybrid renewable energy system is formulated as a multi-objective optimization problem aimed at minimizing both life-cycle emissions and energy cost while ensuring complete load satisfaction. The optimization objectives are as follows:

4.2.1 Objective 1: Minimization of Life-Cycle Carbon Emissions

$$\text{Minimize } F_1 = TCE = CE_{OP} + CE_{MFG} \quad (20)$$

where CE_{OP}refers to operational emissions during energy production, and CE_{MFG}includes emissions from material extraction, component fabrication, transportation, and decommissioning.

4.2.2 Objective 2: Minimization of Levelized Cost of Energy

$$\text{Minimize } F_2 = LCOE \quad (21)$$

This objective accounts for all financial aspects of system operation, including capital investment, operation and maintenance (O&M), component replacement, salvage value, and potential carbon-credit revenues.

Constraints

The optimization process is governed by several physical and operational constraints to ensure system feasibility and reliability:

Energy Balance Constraint:

The total energy supplied must always meet or exceed the energy demand at any time step:

$$E_{supply}(t) \geq E_{demand}(t); \forall t \quad (22)$$

Component Capacity Constraints:

The output of each subsystem, including PV panels, wind turbines, electrolyzers, and fuel cells, must remain within their rated capacities as specified in the system design parameters.

Hydrogen Storage Constraint:

The stored hydrogen level must not exceed the maximum storage capacity of the tank nor fall below zero:

$$0 \leq H_{HS}(t) \leq H_{HS,max} \tag{23}$$

These constraints collectively ensure technical feasibility and prevent unrealistic system operation scenarios.

4.3 Optimization Strategy

The optimization approach adopts a Pareto frontier-based multi-objective approach, which is implemented by NSGA-II and MOPSO algorithms. Both the algorithms yield a set of non-dominated solutions that represent trade-offs between economic and environmental performance.

All of the solutions cover a specific set of subsystem capacities (PV, wind, electrolyzer, fuel cell, and gas turbine) and operational modes. The Pareto front of the latter allows one to identify optimal configurations—cost-optimized to emission-optimized designs—which permits decision-makers to select the most suitable system on the basis of priority criteria.

This multi-criteria analysis provides a balanced evaluation of energy cost and sustainability, making the incorporation of cleaner and more economically viable hybrid renewable systems suitable for the Bangladesh environment possible.

4.3.1 Non-Dominated Sorting Genetic Algorithm II (NSGA-II)

The Non-Dominated Sorting Genetic Algorithm II (NSGA-II) is a well-known evolutionary optimization technique to address multi-objective problems. It minimizes or maximizes several conflicting objectives at the same time by producing a set of Pareto-optimal solutions. The algorithm employs genetic operators such as selection, crossover, and mutation, and non-dominated sorting and crowding distance calculation mechanisms to maintain solution diversity. The entire optimization procedure is illustrated in Fig. 3, the flowchart of the NSGA-II algorithm.

Step 1: Initialization

Generate an initial population:

$P_0 = \{x_1, x_2, \dots, x_N\}$

Step 2: Fitness Evaluation

Each solution is assessed using objective functions such as:

$f_1 = \text{LCOE}, f_2 = \text{TCE}$

Step 3: Non-Dominated Sorting

Solutions are classified into fronts based on dominance:

$$x_a \prec x_b \text{if} \begin{cases} f_i(x_a) \leq f_i(x_b)\ \forall i, \\ f_j(x_a) < f_j(x_b) \text{ for at least one } j \end{cases} \tag{24}$$

Step 4: Crowding Distance

To preserve diversity, crowding distance is computed for each solution:

$$CD_i = \sum_{m=1}^{M} \frac{f_m(i+1) - f_m(i-1)}{f_m^{\max} - f_m^{\min}} \tag{25}$$

Step 5: Selection

Binary tournament selection is performed using rank and crowding distance.

Step 6: Crossover and Mutation

Offspring are created using:

Simulated Binary Crossover (SBX)

$$\text{child}_1 = 0.5[(1+\beta)x_1 + (1-\beta)x_2] \tag{26}$$

$$\text{child}_2 = 0.5[(1-\beta)x_1 + (1+\beta)x_2] \tag{27}$$

Polynomial Mutation

$$x_i' = x_i + \Delta \cdot (x^{\max} - x^{\min}) \tag{28}$$

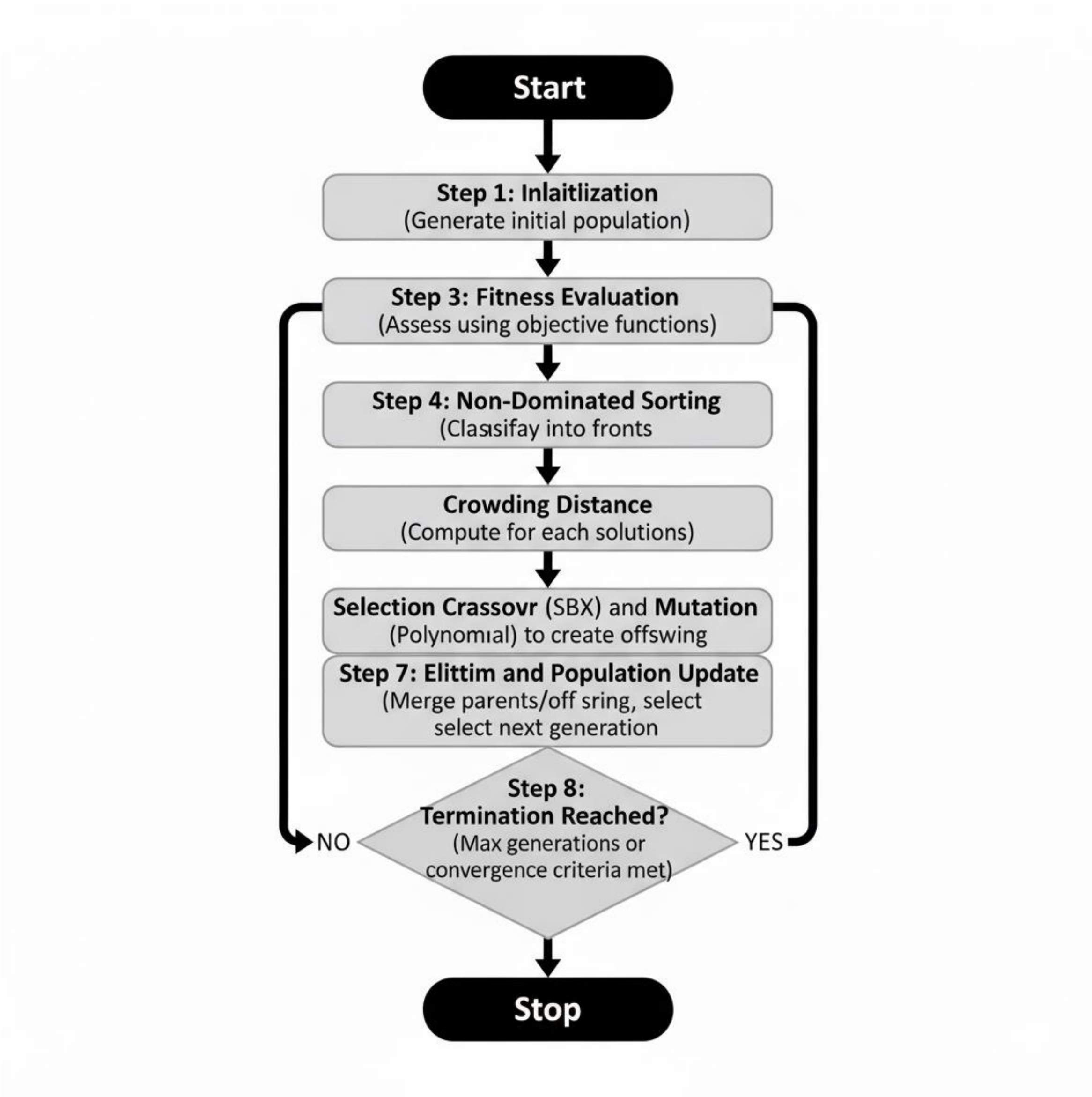

Fig. 3: Flowchart of the NSGA-II Algorithm

Step 7: Elitism and Population Update

Parent and offspring populations are merged:

$$R_t = P_t \cup Q_t \tag{29}$$

The next generation is:

$P_{t+1} =$ Best N solutions from R_t

Step 8: Termination

Stop when the maximum generations or the convergence criteria are reached.

4.3.2 Multi-Objective Particle Swarm Optimization (MOPSO)

Multi-Objective Particle Swarm Optimization (MOPSO) is an improvement over the conventional Particle Swarm Optimization (PSO) technique, altered for solving multiple conflicting objectives. MOPSO uses a population of particles that search in aggregate in the search space while maintaining an external archive that stores non-dominated solutions. The technique allows fast convergence towards the Pareto front with enhanced diversity maintenance. Fig. 4 represents the working flow of the MOPSO algorithm.

Step 1: Initialization

Initialize each particle with a random position and velocity:

$x_i^0 \in [x_{\min}, x_{\max}]$

and $v_i^0 \in [v_{\min}, v_{\max}]$

Step 2: Objective Evaluation

Evaluate:

$f_1(x_i), f_2(x_i)$

Step 3: Personal and Global Best

Personal best:

$p_i^{best} = x_i$; if non − dominated

Global best selected from the archive via the crowding or grid method.

Step 4: Velocity Update

$$v_i^{t+1} = w\, v_i^t + c_1 r_1 (p_i^{best} - x_i^t) + c_2 r_2 (g^{best} - x_i^t) \quad (30)$$

Step 5: Position Update

$$x_i^{t+1} = x_i^t + v_i^{t+1} \quad (31)$$

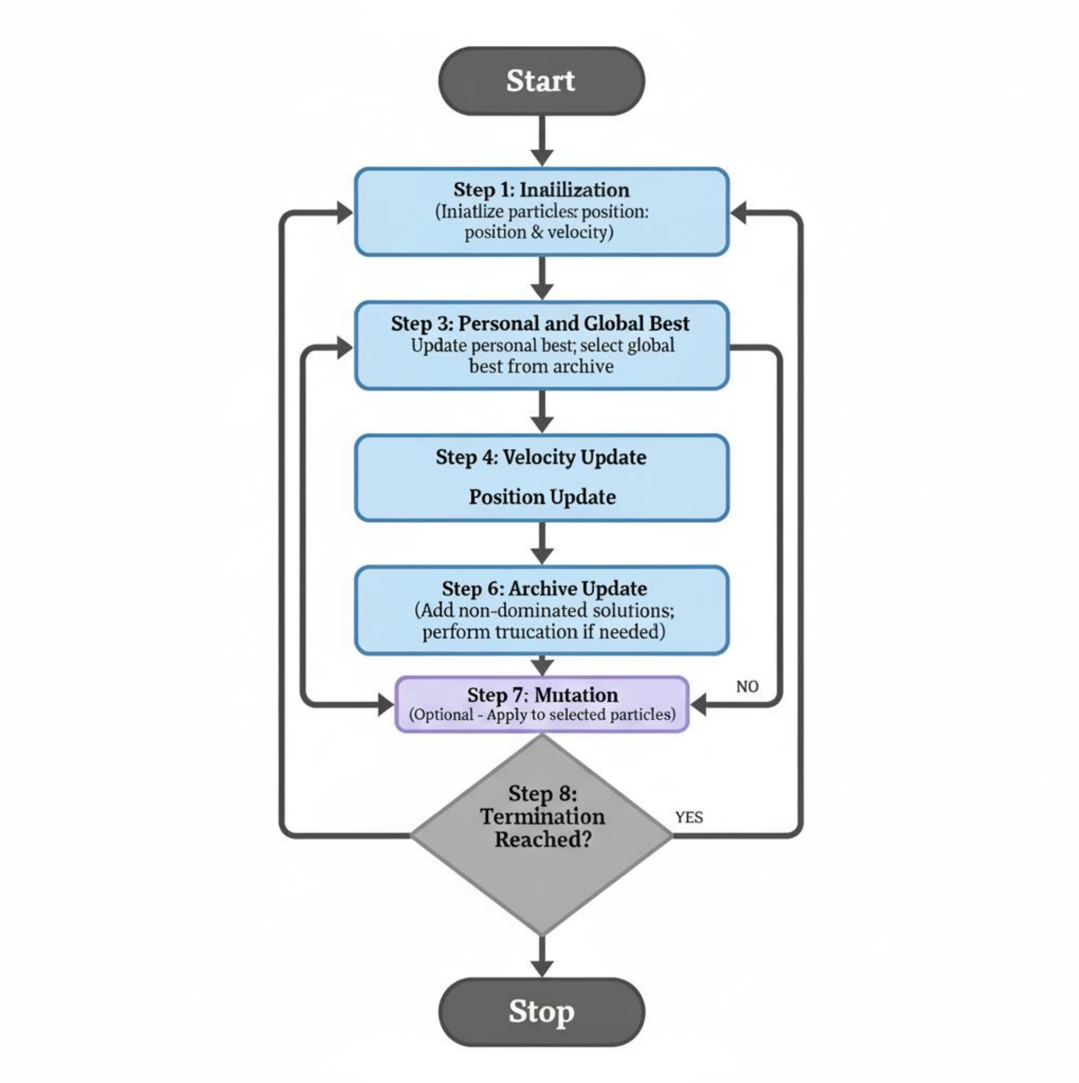

Fig. 4: Flowchart of the MOPSO Algorithm

Step 6: Archive Update

Add non-dominated solutions to the external archive. If the archive exceeds size limits, truncation is performed using crowding distance.

Step 7: Mutation (Optional)

A random mutation is applied in selected particles:

$$x_i' = x_i + \delta \cdot (x_{\max} - x_{\min}) \quad (32)$$

Step 8: Termination

Stop after maximum iterations or if the Pareto front stabilizes.

4.4 OPERATIONAL STRATEGY OF THE SYSTEM

The operation policy dictates how the proposed HRES regulates the operation of its various components—PV panels, wind turbines, electrolyzer, hydrogen storage unit, fuel cell, and gas turbine—to ensure a continuous, uniform, and optimized supply of power. The configuration of the system is outlined in overall Fig. 5 and represents the interconnection of the renewables through AC and DC buses supplemented with backup from hydrogen storage and gas turbine subsystems.

System operation sequence is demonstrated in Fig. 6, which indicates the control logic exercised at each time step. The system dynamically operates based on variation in renewable generation, load, and storage availability. Optimal use of renewable resources is the primary goal of the control strategy, with system stability, curtailment reduction, and emissions reduction.

At each instant of time, the control sequence begins with the comparison of the summation of power demand and the available power from the renewable sources. When the renewable energy production—PV array power and wind farm power—is greater than the electrical load, the surplus power is found and directed to the PEM electrolyzer. The surplus power is utilized by the electrolyzer to perform electrolysis, splitting water molecules into hydrogen and oxygen. The hydrogen thus generated is then stored in the hydrogen storage tank to be utilized later on during low-generation time.

During this phase, both AC and DC bus voltages are continuously monitored to assess the distribution of accessible excess power. Dual-bus monitoring avoids the loss of energy conversion waste and enables any excess power from either bus to be effectively diverted for hydrogen generation. Through the conversion of wasted energy to hydrogen, the system achieves its maximum overall efficiency and sustainability and creates a renewable energy reservoir in the process.

On the other hand, when there is insufficient renewable generation to meet demand, the system resorts to stored energy sources. The controller begins by examining the amount of hydrogen available in the storage tank. If the fuel cell system contains sufficient hydrogen, it activates the fuel cell system. The fuel cell converts stored hydrogen into electrical energy through an electrochemical reaction, generating power without combustion and producing only water vapor as waste. Not only does this compensate for the energy deficit, but it also provides low-emission performance.

If the available hydrogen is not enough to compensate for the deficit, the gas turbine is used as the last standby device. The gas turbine operates from an assigned minimum output rate to ensure stable combustion and best operating efficiency. This helps to guarantee that even during periods when low renewable generation durations are prolonged and hydrogen storage is low, demand for load is still fulfilled. But in exceptional circumstances, where all the renewable sources, hydrogen storage, and the gas turbine cannot completely meet the demand, then the leftover is taken as unmet load, and it is used as a measure of system reliability for measuring performance.

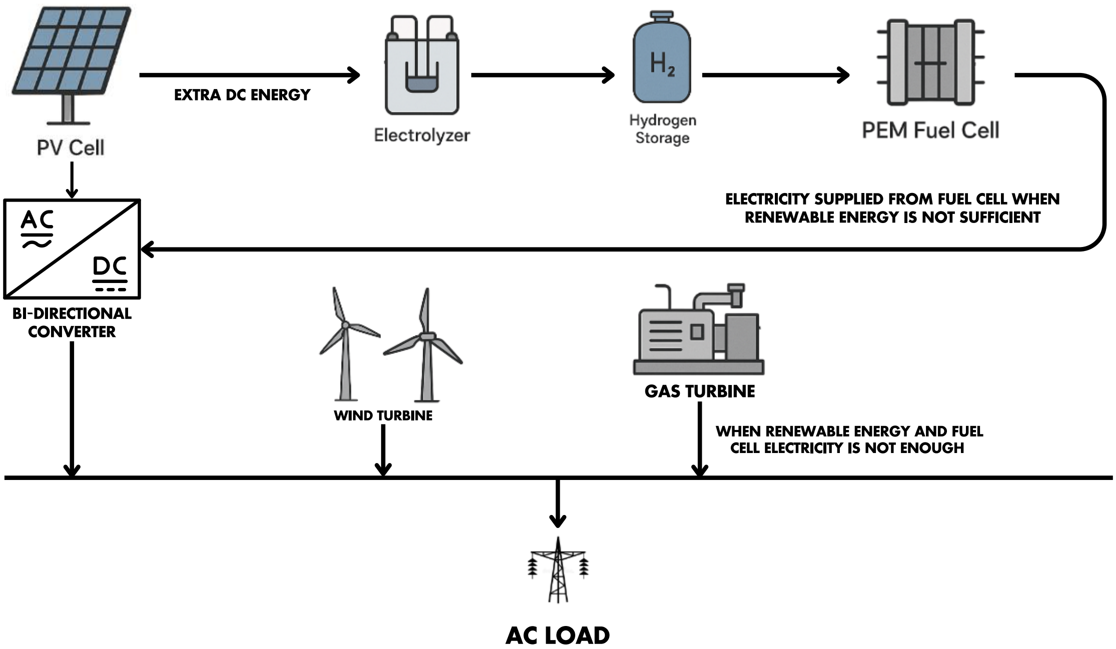

Fig. 5: Schematic Diagram of a Hybrid Renewable Energy System

The energy balance of the system is continuously updated in all instances with hydrogen production by the electrolyzer, hydrogen consumption by the fuel cell, and varying hydrogen storage levels taken into account. With iterative feedback, precise coordination of multiple subsystems is achieved so that the energy generation, conversion, and utilization processes are always balanced.

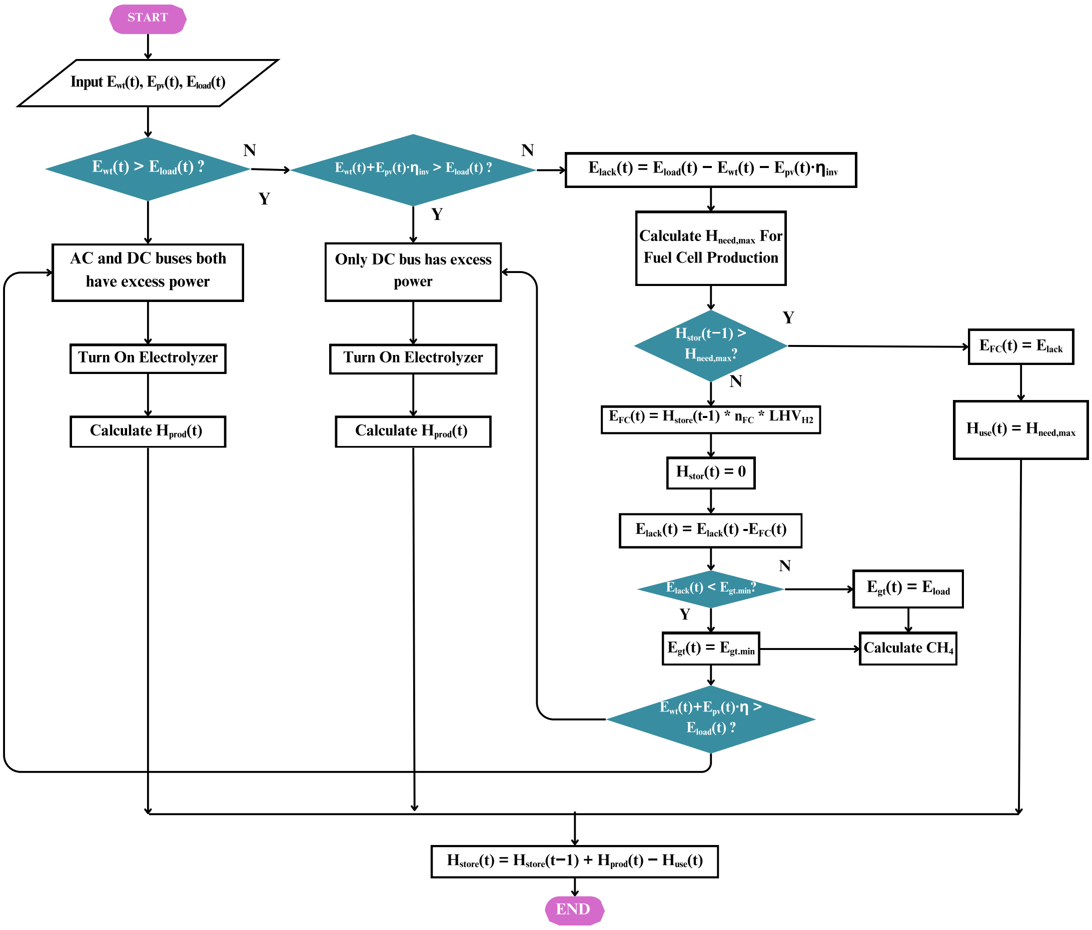

Fig. 6: Flowchart of Energy Management Strategy for a Hybrid Renewable Energy System

The economic logic also targets the reduction of renewable energy waste—that is, not wasting current renewable energy capability by routing excess energy into hydrogen production instead of letting it go to waste. In doing so, the system attempts to achieve maximum utilization of renewable sources first before supplementing with fossil-based generation, and hence reducing greenhouse gas emissions inherently. The gas turbine is used as a backup, attempting to move away from fossil fuel use without compromising reliability.

In general, this operation strategy possesses a coordinated dispatch program between the hydrogen energy storage unit, units of renewable energy, and the gas turbine standby unit. Intelligent energy management and control logic, the hybrid system is endowed with an optimal economic efficiency, operation reliability, and environmental sustainability. Through the utilization of hydrogen as an intermediate-level energy carrier, the system provides short-term flexibility in combination with long-term storage, placing it firmly in the position of alleviating renewable energy intermittency in grid-supply or stand-alone applications.

Chapter 5

Results and Discussion

The HRES suggested in this research, comprising a PV plant, wind farm, electrolyzer, hydrogen storage, fuel cell, and gas turbine, was optimized by two multi-objective optimization algorithms—NSGA-II and MOPSO—to compare their relative performance in cost-effective and environmentally friendly power generation. The optimization was done using MATLAB R2021a with a population of 200 and a maximum iteration number of 200 for both algorithms.

5.1 Decision Variables and Optimization Setup

The optimization considered four primary decision variables—PV capacity, wind capacity, electrolyzer capacity, and fuel cell capacity—whose upper and lower bounds are presented in Table 3. These variables were selected to represent the system's core design flexibility, influencing both cost and emission performance.

Table 3: Decision Variable Lower and Upper Boundaries

VARIABLES (MW)	LOWER LIMIT	UPPER LIMIT
PV	0	65
WIND	0	65
ELECTROLYZER	0	40
FUEL CELL	0	60

The two objective functions utilized to compare the system were LCOE and TCE. Optimization was conducted to minimize both simultaneously, generating a Pareto-optimal front that will illustrate the trade-off between economic and environmental objectives. Pareto fronts generated with the two algorithms are shown in Fig. 7, and Fig. 8, where each point is a viable system configuration that optimizes between cost and emission rates.

5.2 Pareto Front Analysis

From the Pareto fronts in Fig. 7 and Fig. 8, the cost-emissions trade-off is nonlinear. On the left side of the curve, the solutions contain lower TCE values, indicating good environmental performance due to high penetration of renewables and utilization of hydrogen storage. However, this comes at the expense of more expensive LCOE values since greater capacity of renewable and storage results in increased capital and operational expenses. However, the right part of the curve represents economically optimal configurations with lower LCOE but higher carbon emissions, which are primarily due to higher utilization of gas turbine operation.

This characteristic trade-off is typical of hybrid renewable systems, where achieving minimal emissions often comes at the expense of higher investment, while focusing solely on economic performance increases fossil fuel dependency.

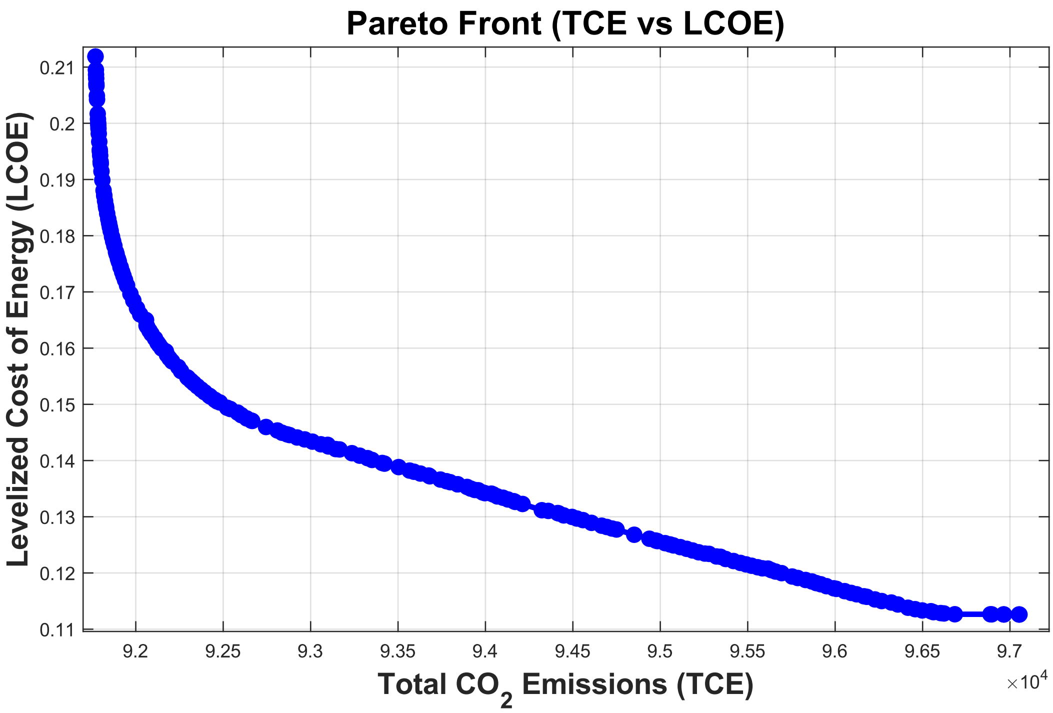

Fig. 7: Pareto Front of the Optimized Hybrid Renewable Energy System using NSGA-II

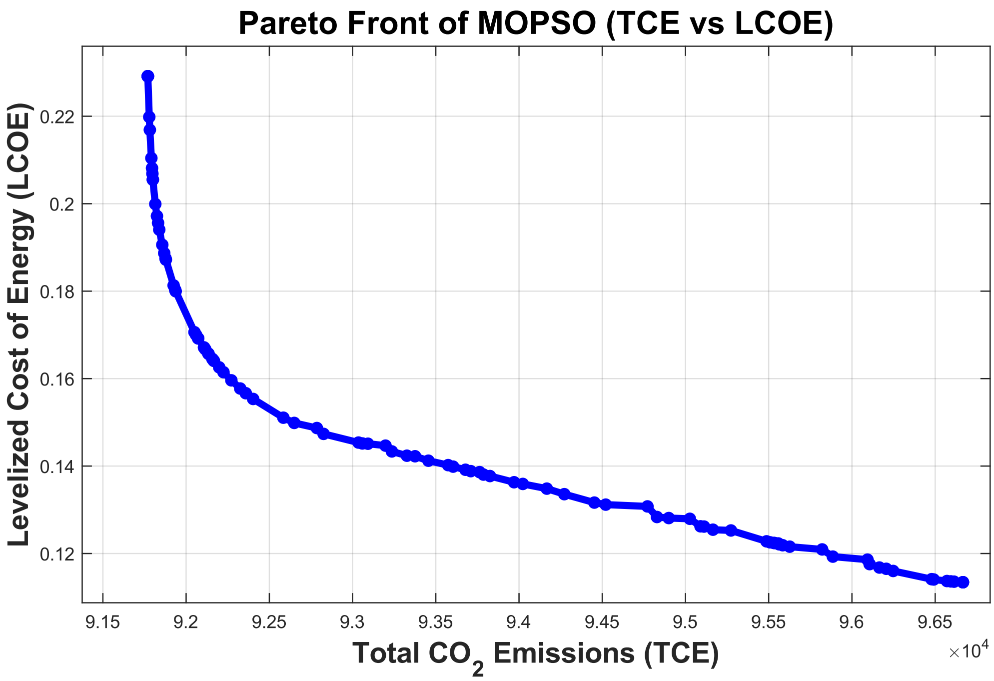

Fig. 8: Pareto Front of the Optimized Hybrid Renewable Energy System using MOPSO

5.3 Comparative Analysis of NSGA-II and MOPSO

To assess the comparative efficiency of NSGA-II and MOPSO, three representative solutions—Lowest LCOE (cost-optimal), Balanced, and Lowest TCE (emission-optimal)—were selected from the Pareto fronts generated by both algorithms, as shown in Fig. 9, Fig. 10, and Fig. 11. These representative points are listed in Table 4.

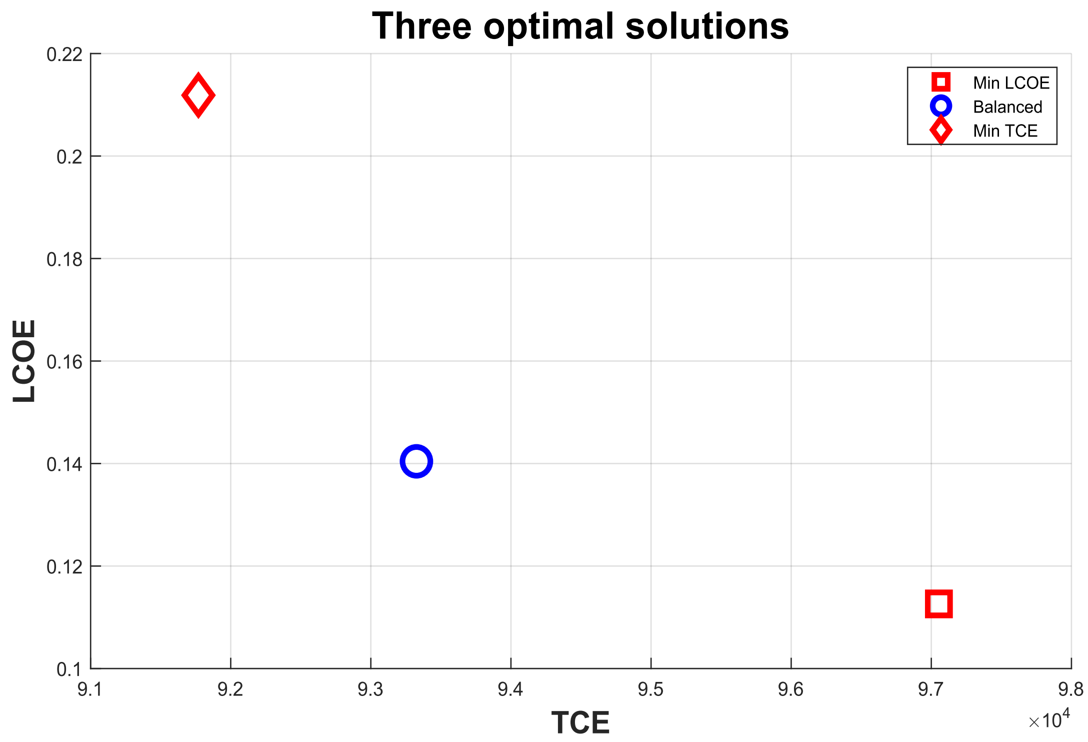

Fig. 9: Three optimal solutions of NSGA-II

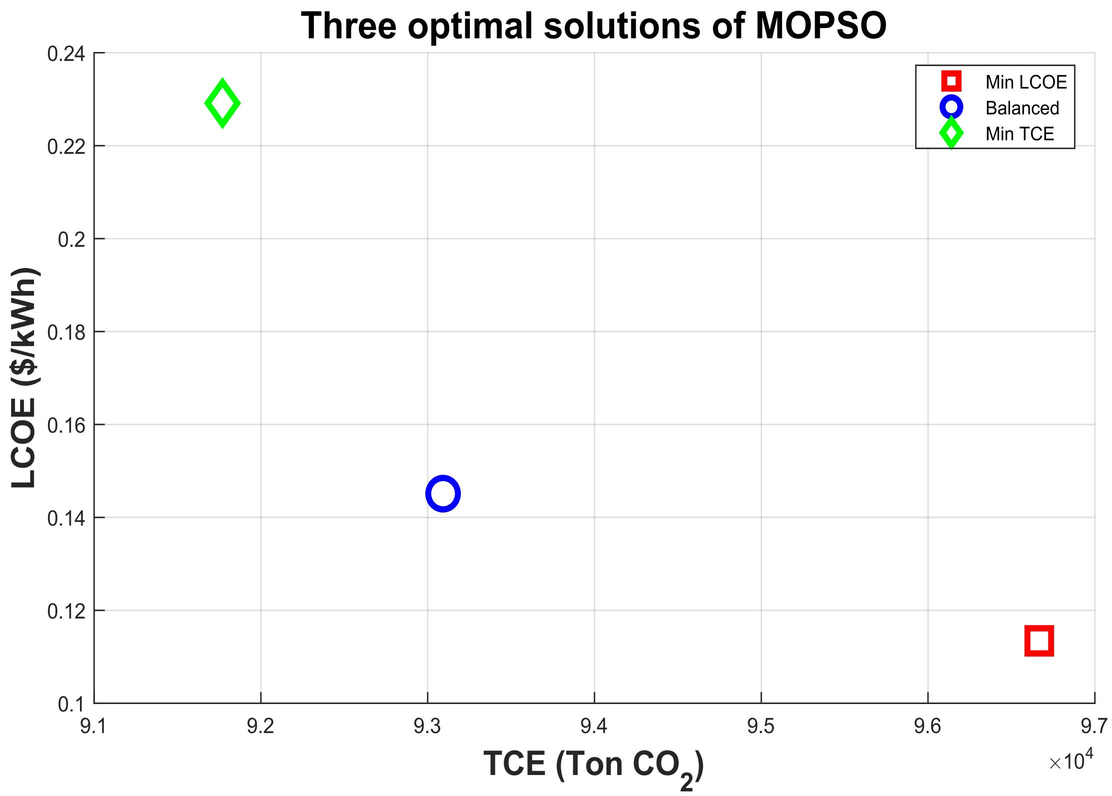

Fig. 10: Three optimal solutions of MOPSO

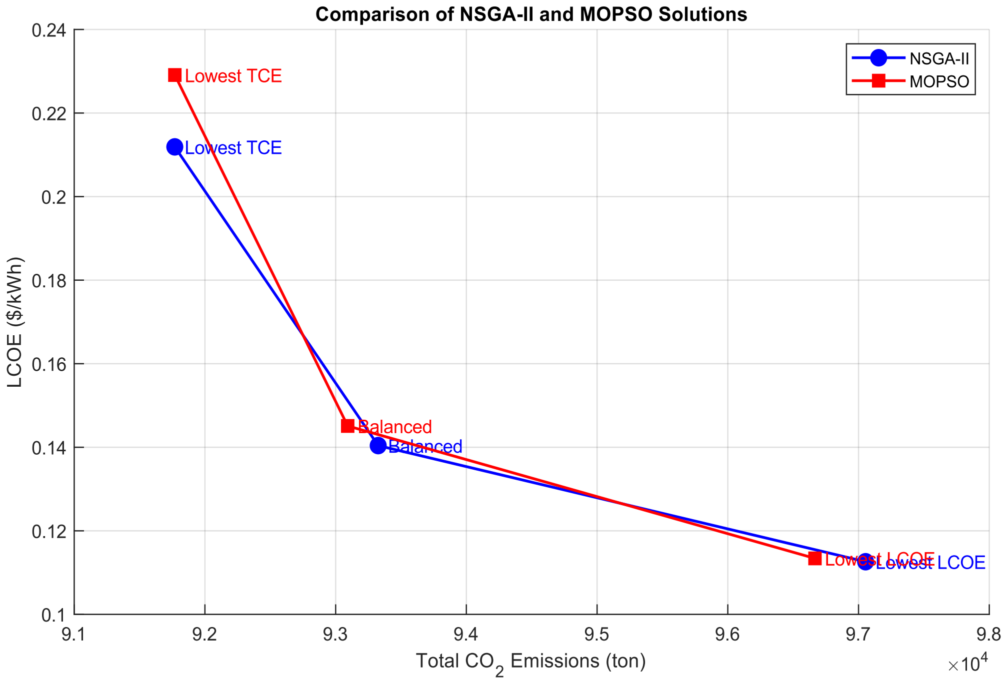

Fig. 11: Comparison of NSGA-II and MOPSO Solutions

5.4 Interpretation of Optimal Solutions

5.4.1 Minimum LCOE (Cost-Optimal Configuration)

The cost-optimal solution obtained based on NSGA-II has the minimum LCOE of 0.1126 $/kWh, and PV capacity is 43.25 MW with minimum dependence on wind generation. The corresponding TCE of 97,054.15 tons of CO_2 is the maximum among the three configurations due to sufficient gas turbine operation.

MOPSO establishes a very comparable configuration with LCOE = 0.1134 $/kWh and also marginally lower emissions of 96,666.89 tons CO_2. That slight improvement demonstrates MOPSO's capability for marginally optimal environmental performance at no cost trade-off.

5.4.2 Balanced Solution

The optimal solution is a balance of economic and environmental outcomes. Under this case, NSGA-II achieves LCOE = 0.1404 $/kWh and emissions = 93,325.53 tons CO_2, while MOPSO does almost as well with LCOE = 0.1451 $/kWh and TCE = 93,092.25 tons CO_2.

This setup emphasizes a middle-range use of hydrogen storage (electrolyzer size of ~25 MW and fuel cell size of ~40 MW) and middle-range wind penetration (about 25–30 MW). It effectively reduces the dependence on fossil fuel operation while keeping the cost increase within manageable levels. This type of setup is technically and financially feasible for nations looking to reduce emissions without significantly impacting cost.

Table 4: Comparative Optimal Solutions Obtained from NSGA-II and MOPSO

Decision Variables	**Algorithm**	**PV Capacity (MW)**	**Wind Capacity (MW)**	**Electrolyzer Capacity (MW)**	**Battery Capacity (MW)**	**TCE (ton CO_2)**	**LCOE (\$/kWh)**
Lowest LCOE	NSGA-II	43.25	0	10.7	23.025	97,054.1477	0.1126
	MOPSO	43.13	0	9.8	21.18	96,666.8934	0.1134
Balanced Solution	NSGA-II	65	24.87	25.547	40.327	93,325.5337	0.1404
	MOPSO	65	28.59	21.45	43.22	93,092.2462	0.1451
Lowest TCE	NSGA-II	65	65	40	60	91,769.506	0.2119
	MOPSO	65	65	40	60	91,769.9345	0.2291

5.4.3 Lowest TCE (Emission-Optimal Configuration)

The emission-optimal solution maximizes the highest possible renewable integration and storage use with 65 MW PV, 65 MW wind, 40 MW electrolyzer, and 60 MW fuel cell capacities. The NSGA-II algorithm yields the lowest TCE of 91,769.51 tons CO_2 and a matching LCOE of 0.2119 $/kWh, while MOPPS yields nearly equal emissions (91,769.93 tons CO_2) but with increased cost (0.2291 $/kWh).

This arrangement is the environmentally optimal option, even though the huge investment required makes it unsuitable for near-future deployment. Yet, it demonstrates the system's ability for deep decarbonization with advanced renewable penetration and hydrogen energy storage.

5.5 Comparison of Optimization Objectives

The comparative performance of the NSGA-II and MOPSO algorithms in terms of the two most critical objectives—LCOE and TCE—is represented in the form of two bar charts. The bar charts provide a close-up, side-by-side view of the performance of each algorithm at the three representative operating points: Lowest LCOE, Balanced, and Lowest TCE.

5.5.1 Cost Comparison (LCOE Analysis)

The initial bar chart separates the LCOE target in order to make a point-to-point economic performance comparison between the two algorithms. NSGA-II has uniformly lower LCOE values in all three operating points, as indicated in Fig. 12**.**

At the Lowest LCOE point, NSGA-II records the minimum cost of 0.1126 \$/kWh, outperforming MOPSO’s 0.1134 \$/kWh. This confirms NSGA-II’s capability to fine-tune decision variables to reach the absolute cost minimum. At the Balanced point, NSGA-II demonstrates a noticeable cost advantage with 0.1404 \$/kWh compared to MOPSO’s 0.1451 \$/kWh, indicating better optimization precision near the trade-off region between cost and emissions. The gap is largest at the Lowest TCE setting, at which NSGA-II discovers a system design of 0.2119 \$/kWh, a mere fraction of one cent per unit less than MOPSO's analogous 0.2291 \$/kWh.

These results collectively suggest that NSGA-II’s elitism-based selection and non-dominated sorting mechanisms allow it to achieve superior cost efficiency while maintaining stable convergence, especially in complex multi-objective environments.

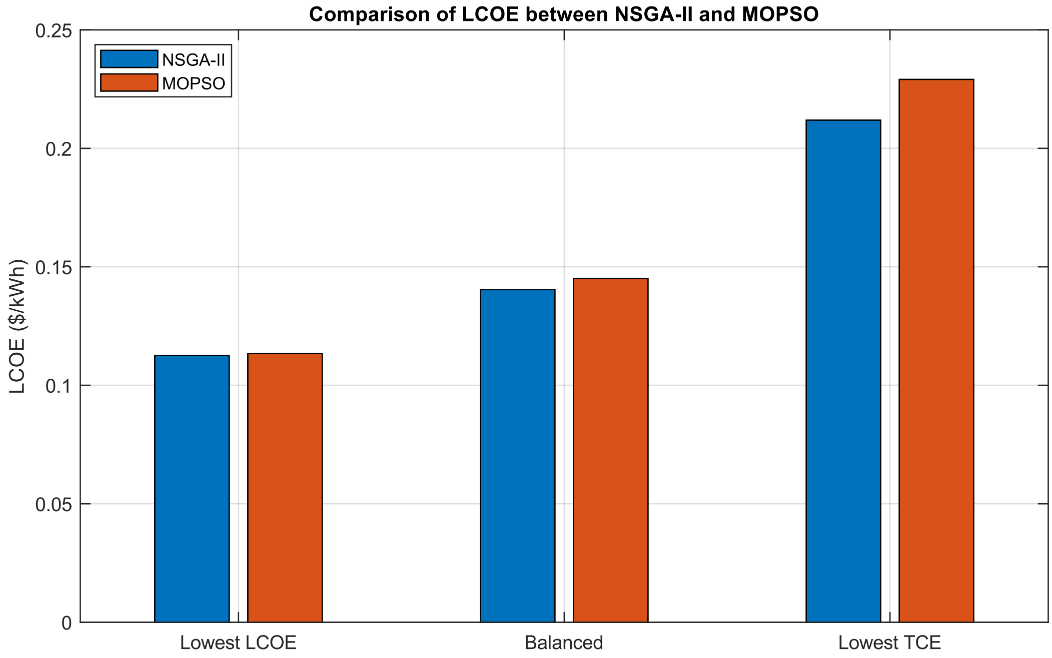

Fig. 12: Comparison of LCOE between NSGA-II and MOPSO

5.5.2 Comparison of Emissions (TCE Analysis)

The second bar chart of Fig. 13 takes the TCE objective into consideration, showing the environmental outcomes for every algorithm. The result shows that MOPSO achieves slightly lower emission levels in the Lowest LCOE and Balanced cases—96,666 tons CO_2 and 97,054 tons CO_2, and 93,092 tons CO_2 and 93,325 tons CO_2, respectively. The variations are small, however, constituting less than 0.5% variation. Both of the algorithms at the Lowest TCE arrangement are at nearly identical emission levels (~91,770 tons CO_2), which confirms that they arrived on the same lowest possible emission frontier.

Whereas MOPSO possesses slightly improved emission optimization, NSGA-II achieves the same optimizations at a lower cost. Therefore, NSGA-II displays improved economic-environmental trade-off and is a frontrunner in cost-sensitive uses of hybrid energy systems.

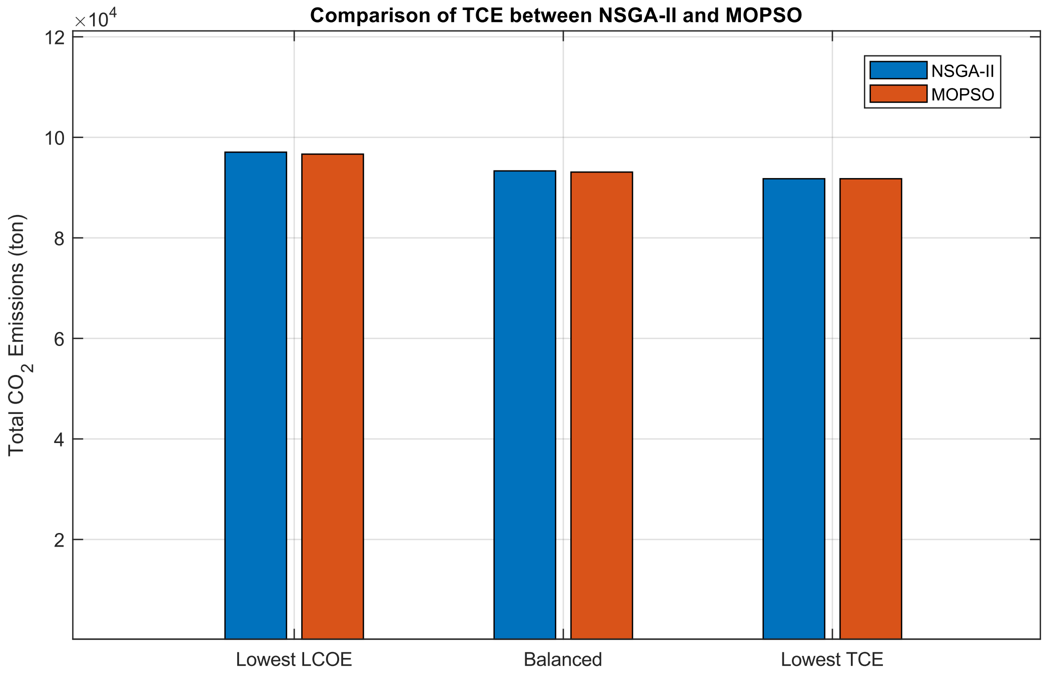

Fig. 13: Comparison of TCE between NSGA-II and MOPSO

5.6 Sensitivity Analysis

5.6.1 Influence of Interest Rate on Optimization Performance

Fig. 14 is a graph of the effect on the Pareto front of hybrid renewable energy system optimization of varying the interest (discount) rate, where the Levelized Cost of Energy (LCOE) is on the y-axis and the Total CO_2 Emissions (TCE) is on the x-axis. The research supposes three scenarios representing 5%, 7%, and 10% interest rates as represented by the blue, red, and purple curves, respectively.

The results evidently indicate that the discount rate affects overall system economics significantly while impacting emissions marginally. With a rise in the interest rate, the LCOE rises across the entire Pareto front, and the curve shifts upward. This is because a higher discount rate increases the net present value of capital-intensive investments such as solar, wind, and hydrogen storage components. Consequently, renewable-dominated configurations become less economic compared to more traditional generation-based systems, e.g., gas turbines.

For a 5% interest rate, the system shows the lowest LCOE (about 0.11 $/kWh) with the emission level also being relatively low, indicating very good economic sustainability for high-renewable setups. For a higher discount rate of 7%, cost increases moderately but the system remains in a competitive range as investment and operating costs are well balanced. However, at 10%, LCOE increases sharply from 0.20 $/kWh to illustrate that more rates place tremendous economic weight on capital-intensive hybrid systems while overall emissions are nearly unaffected.

In entirety, the graph indicates the susceptibility of system cost to economic conditions, and therefore it goes without saying that reducing discount rates have importance-weighted positive effect on positioning clean energy systems within economic circles. Therefore, policy incentives and favorable financing conditions are of paramount priority to enable widespread use of renewable–hydrogen-based hybrid systems in target energy markets such as Bangladesh.

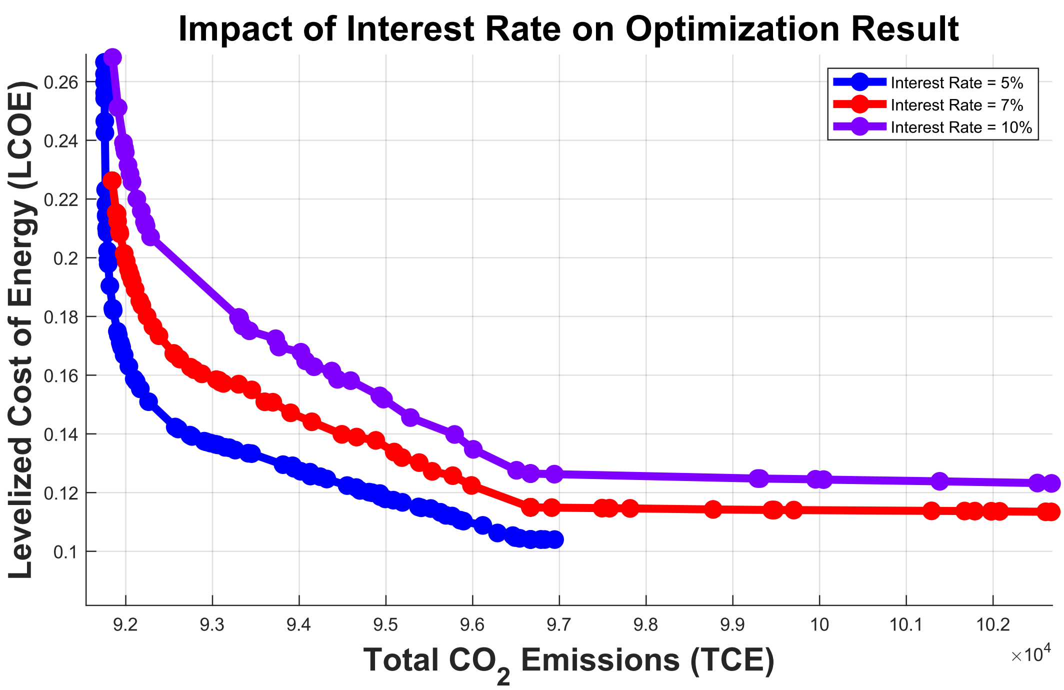

Fig. 14: Impact of Interest Rate on Optimization Result

5.6.2 Impact of Component Investment Costs on Optimization Result

Fig. 15 illustrates the sensitivity of the hybrid energy system's optimization results to variations in component investment costs, including the PV array, battery storage, and inverter systems. The LCOE is plotted against the TCE for three scenarios:

- Blue curve: Base case using the cost parameters adopted in this study.
- Red curve: High-cost scenario (using upper values from Table 5).
- Purple curve: Low-cost scenario (using lower values from Table 5).

As expected, TCE is robust to changes in capital cost, while LCOE varies. The red line (high-cost scenario) illustrates an extensive upward shift of the Pareto front, showing that increased capital investment translates directly to increased total energy cost. While the emission rate of the system is not dramatically altered, the penalty in cost decreases the economical potential of renewable-dominant configurations.

Table 5: Typical Cost Parameters for PV Plant, Battery, and Inverter

LITERATURE	PV ($/KW)	BATTERY ($/KWH)	INVERTER ($/KW)
XIONG ET AL. [43]	400	255	210
HE ET AL. [44]	1040	200	–
OGUNJUYIGBE ET AL. [45]	630	300	–
MA ET AL. [46]	450	–	110
BHAYO ET AL. [47]	900	320	300
AGUILAR-JIMÉNEZ ET AL. [48]	600	260	248
GUO ET AL. [49]	1040	500	–
MOKHTARA ET AL. [50]	1600	180	700

Conversely, the purple line (low-cost scenario) is far below the baseline, illustrating that reductions in PV, battery, and inverter costs greatly increase system affordability. In this case, LCOE falls by up to 30–40%, rendering renewable-dominant installations economically viable and sustainable. The blue line (base case) represents an intermediate stance between these two, reflecting the benchmark performance under existing cost assumptions.

Overall, this sensitivity analysis underscores the critical role of technology cost reductions—particularly in PV and battery technology—in making hybrid renewable-hydrogen systems economically feasible. Continuous manufacturing efficiency and scale economy enhancements could thus be the deciding factor in facilitating quick take-off in new energy sectors such as Bangladesh.

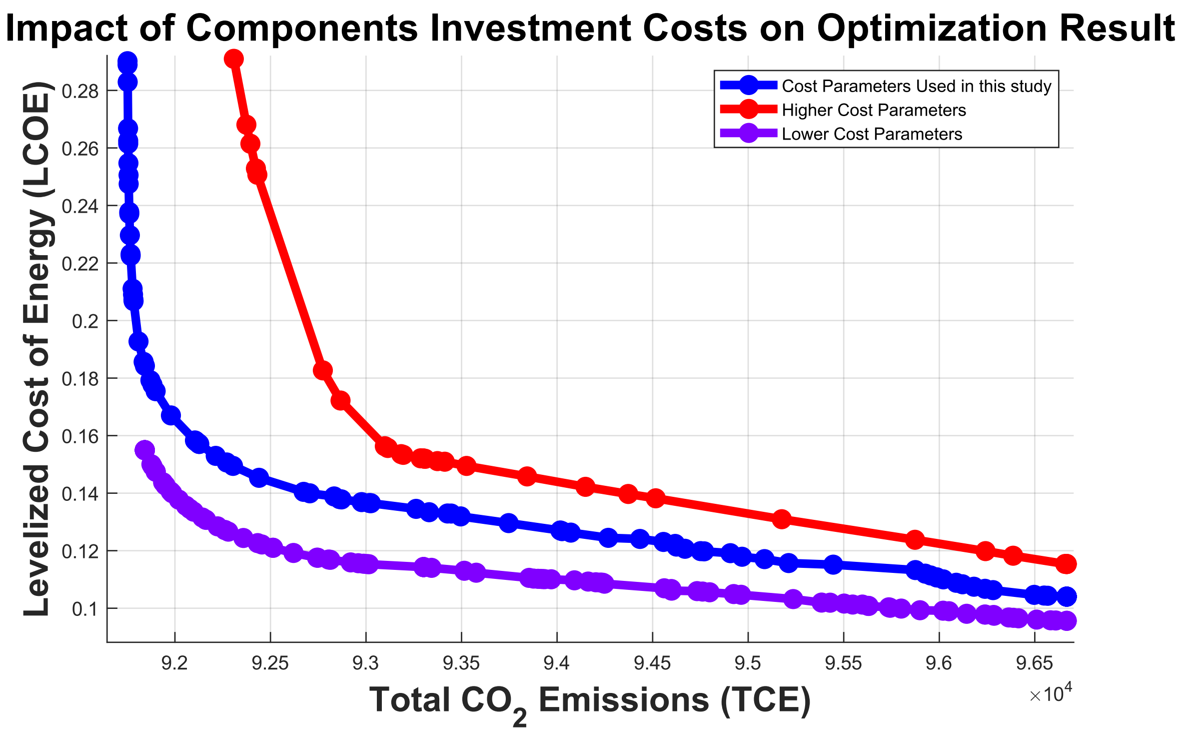

Fig. 15: Impact of Components Investment Costs on Optimization Result

5.6.3 Impact of Ambient Temperature and GHI on System Output

Fig. 16 illustrates the sensitivity of the hybrid renewable energy system's performance to variations in ambient temperature and GHI. The LCOE is plotted against TCE for three scenarios:

- Blue curve: Base case, representing current measured ambient temperature and GHI.
- Red curve: A 10% increase in both temperature and GHI.
- Purple curve: A 10% decrease in both temperature and GHI.

As observed, the red curve (increased GHI and temperature) exhibits the lowest LCOE and lowest emissions, indicating that enhanced solar irradiance significantly boosts PV generation, thereby improving the overall system efficiency and reducing dependency on fossil-based backup power. Despite a slight rise in temperature, which marginally reduces PV cell efficiency, the overall power output remains higher due to the dominant influence of increased irradiance.

Conversely, the purple curve (decreased GHI and temperature) reflects a deterioration in both performance metrics. The LCOE rises considerably, and TCE shifts upward, demonstrating higher operational reliance on the gas turbine to meet the load demand during renewable shortfalls.

The blue curve, corresponding to current climatic conditions, lies between these two extremes, representing the baseline system performance.

Overall, this analysis confirms that solar irradiance variations have a stronger influence than temperature changes on system efficiency. Even moderate increases in GHI yield substantial cost and emission benefits, underlining the importance of high-irradiance site selection and solar resource forecasting in hybrid renewable system planning.

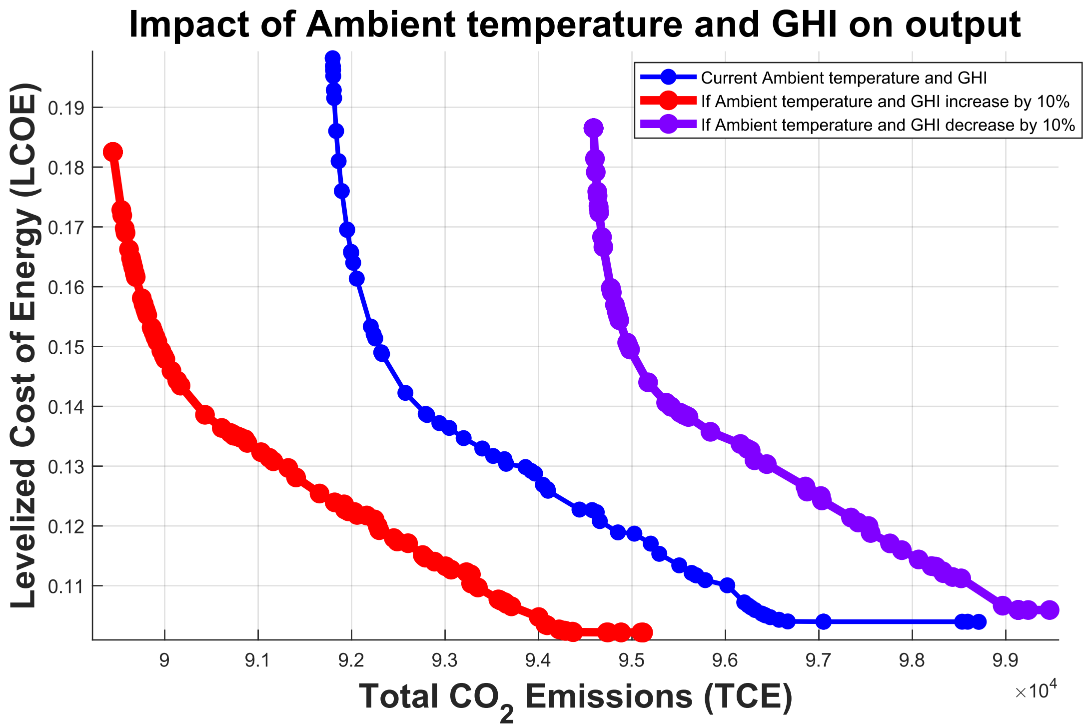

Fig. 16: Impact of Ambient temperature and GHI on output

5.6.4 Sensitivity to Hardware Efficiency Improvements

Fig. 17 compares two optimization scenarios to assess how changes in component efficiencies influence the trade-off between LCOE and TCE. In the baseline case (blue curve), the system uses the lower efficiency values applied in the main model:

- Gas turbine efficiency: 0.59
- Electrolyzer efficiency: 0.60
- PV module efficiency: 21.4%
- Converter efficiency: 0.95

In contrast, the improved scenario (green curve) incorporates higher efficiency assumptions based on projected technological advancement:

- Gas turbine efficiency: 0.70
- Electrolyzer efficiency: 0.75

- PV module efficiency: 30%
- Converter efficiency: 0.98

The higher-efficiency case shifts the Pareto front downward and leftward, indicating simultaneous reductions in both LCOE and TCE. For similar emission levels, the improved-efficiency designs consistently achieve 0.02–0.04 $/kWh lower LCOE. Likewise, reduced system losses lead to lower fuel use and less dependence on the gas turbine, resulting in measurable declines in total CO_2 emissions.

In contrast, the baseline efficiency case shows higher costs and steeper increases in LCOE at the low-emission end of the curve, reflecting the additional renewable and storage capacity required to compensate for performance losses.

Overall, the results clearly demonstrate that enhancing component efficiencies—particularly in conversion and hydrogen subsystems—substantially improves both economic and environmental outcomes. This confirms that continued technological development is a key enabler for the large-scale adoption of hybrid renewable-hydrogen systems.

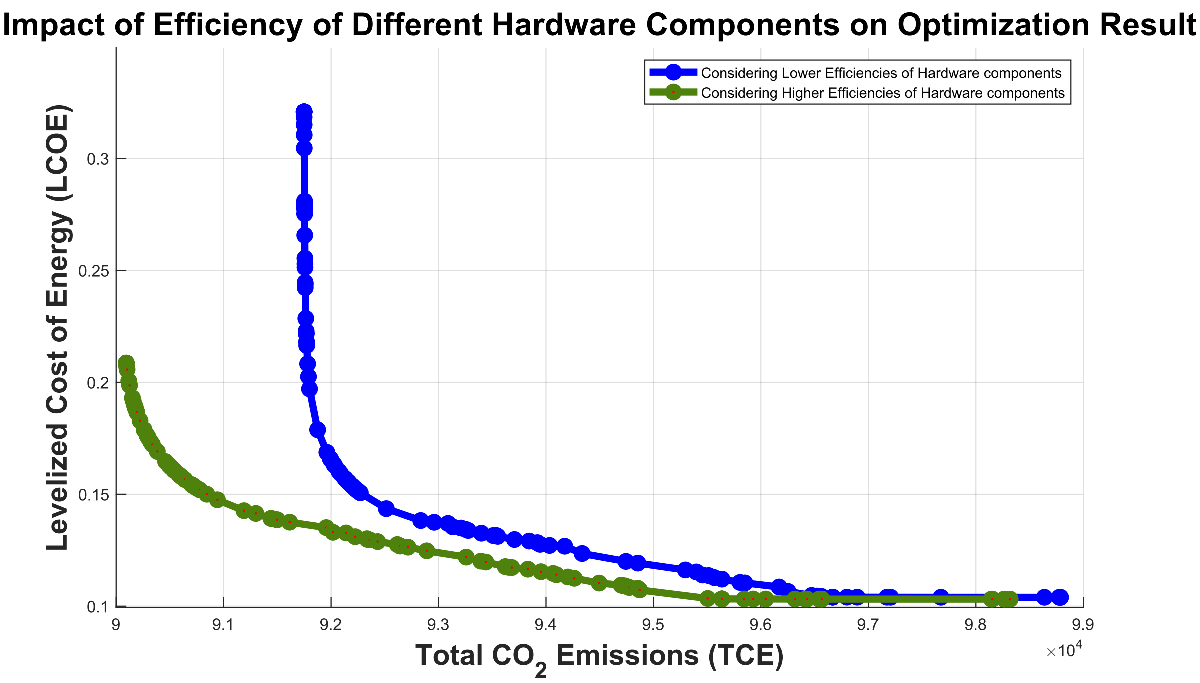

Fig. 17: Impact of Efficiency of Different Hardware Components on Optimization Result

Chapter 6

Demonstration of Outcome Based Education (OBE)

6.1 Introduction

Rapid evolution of engineering and technological disciplines demands a shift in educational methodologies such that the graduates are not only equipped with technical know-how but also with the practical skills and competencies to solve real-world problems. Outcome-Based Education (OBE) is a method of education that focuses on what is required of students by the time they graduate from their academic program. Rather than solely emphasizing theoretical instruction, OBE concentrates on measurable results such as critical thinking, effective communication, teamwork, ethical responsibility, and sustainable design.

In engineering education, OBE ensures that the students achieve the competencies to apply scientific principles in addressing societal problems, continue lifelong learning, and become effective contributors to national development. It aligns academic activities to program learning outcomes (PLOs), course outcomes (COs), and the vision and mission of the institution.

This chapter highlights how the present thesis project—designing a sustainable hybrid energy system incorporating solar, wind, gas turbine, and PEM fuel cell technologies—serves to achieve these outcomes. Students, by this project, have demonstrated that they are able to use multidisciplinary engineering knowledge, analyze complex energy systems, use modern tools and methodologies, and design systems that are environmentally and economically viable. The project is a practical example of how the OBE principles are incorporated into engineering education to produce graduates who are capable of meeting the demands of a dynamic and demanding profession.

6.2 Course Outcomes (COs) Addressed

The following table shows the COs addressed in EEE 4800 for Project and Thesis.

COs	CO Statement	POs	Put Tick (√)
CO1	Apply knowledge of electrical and electronic engineering to the solution of complex engineering problems.	PO1	√
CO2	Identify a contemporary real life problem related to electrical and electronic engineering by reviewing and analyzing existing research works.	PO2	√
CO3	Determine functional requirements of the problem considering feasibility and efficiency through analysis and synthesis of information.	PO4	√
CO4	Select a suitable solution and determine its method considering professional ethics, codes and standards.	PO8	√
CO5	Adopt modern engineering resources and tools for the solution of the problem.	PO5	√
CO6	Prepare management plan and budgetary implications for the solution of the problem.	PO11	√
CO7	Analyze the impact of the proposed solution on health, safety, culture and society.	PO6	√
CO8	Analyze the impact of the proposed solution on environment and sustainability.	PO7	√
CO9	Develop a viable solution considering health, safety, cultural, societal and environmental aspects.	PO3	√
CO10	Work effectively as an individual and as a team member for the accomplishment of the solution.	PO9	√
CO11	Prepare various technical reports, design documentation, and deliver effective presentations for demonstration of the solution.	PO10	√

CO12	Recognize the need for continuing education and participation in professional societies and meetings.	PO12	√

6.3 Aspects of Program Outcomes (POs) Addressed

The following table shows the aspects addressed for certain Program Outcomes (POs) addressed in EEE 4800 for Project and Thesis.

	Statement	Different Aspects	Put Tick (√)
PO3	**Design/development of solutions**: Design solutions for complex electrical and electronic engineering problems and design systems, components or processes that meet specified needs with appropriate consideration for public health and safety, cultural, societal, and environmental considerations.	Public health	√
		Safety	√
		Cultural	
		Societal	√
		Environmental	√
PO4	**Investigation:** Conduct investigations of complex electrical and electronic engineering problems using research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of information to provide valid conclusions.	Design of experiments	√
		Analysis and interpretation of data	√
		Synthesis of information	√
PO6	**The engineer and society:** Apply reasoning informed by contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to professional engineering practice and solutions to complex electrical and electronic engineering problems.	Societal	√
		Health	√
		Safety	√

		Legal	√
		Cultural	
PO7	**Environment and sustainability:** Understand and evaluate the sustainability and impact of professional engineering work in the solution of complex electrical and electronic engineering problems in societal and environmental contexts.	Societal	√
		Environmental	√
PO8	**Ethics:** Apply ethical principles embedded with religious values, professional ethics and responsibilities, and norms of electrical and electronic engineering practice.	Religious values	
		Professional ethics and responsibilities	√
		Norms	
PO10	**Communication:** Communicate effectively on complex engineering activities with the engineering community and with society at large, such as being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.	Comprehend and write effective reports	√
		Design documentation	√
		Make effective presentations	√
		Give and receive clear instructions	√
PO11	**Project management and finance:** Demonstrate knowledge and understanding of engineering management principles and economic decision-making and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.	Engineering management principles	√
		Economic decision-making	
		Manage projects	√
		Multidisciplinary environments	

6.4 Knowledge Profiles (K3 – K8) Addressed

The following table shows the Knowledge Profiles (K3 – K8) addressed in EEE 4800 for Project and Thesis.

K	Knowledge Profile (Attribute)	Put Tick (√)
K3	A systematic, theory-based formulation of engineering fundamentals required in the engineering discipline	√
K4	Engineering specialist knowledge that provides theoretical frameworks and bodies of knowledge for the accepted practice areas in the engineering discipline; much is at the forefront of the discipline	√
K5	Knowledge that supports engineering design in a practice area	√
K6	Knowledge of engineering practice (technology) in the practice areas in the engineering discipline	√
K7	Comprehension of the role of engineering in society and identified issues in engineering practice in the discipline: ethics and the engineer's professional responsibility to public safety; the impacts of engineering activity; economic, social, cultural, environmental and sustainability	√
K8	Engagement with selected knowledge in the research literature of the discipline	√

The following table explains or justifies how the Knowledge Profiles (K3 – K8) have been addressed in EEE 4700/4800 (Project and Thesis).

K	Explanation/Justification
K3	This project uses fundamental electrical engineering knowledge, including circuit analysis, power flow, and energy conversion principles, to model and evaluate the performance of PV, wind, gas turbine, and fuel cell components. Theoretical backgrounds in these areas reflect a clear understanding of core renewable energy and power engineering fundamentals.

K4	The integration of advanced energy devices such as PEM fuel cells, electrolyzers, and hydrogen storage shows the requirement of advanced level of knowledge for the completion of this project.
K5	This project applies theoretical principles to design an actual hybrid energy system suitable for Bangladesh's resources and power demand. It involves system modeling, component sizing, and energy flow analysis, all of which reflect practical engineering design skills. Design-related knowledge, such as selecting suitable components, configuring system architecture, and optimizing energy distribution, has been utilized to implement and evaluate the overall system performance effectively.
K6	The project uses energy system modeling and efficiency calculations to show how engineering principles are applied to practical system design. MATLAB was used to simulate the hybrid PV–wind–hydrogen–fuel-cell system with gas-turbine backup, demonstrating how theoretical models can be translated into workable solutions that reflect real-world engineering practice.
K7	By providing renewable-based hybrid power systems, this project is meeting environmental sustainability and energy justice. It is meeting the economic benefits of reducing dependence on fossil fuels and the social advantages of creating reliable power in rural areas, pairing engineering activity with society's needs at large.
K8	The project is founded on a comprehensive review of recent literature and research on hybrid energy systems, fuel cell efficiency, and the optimization of renewable energy. Out of this interaction, the design is created from evidence-based research findings and current global best practices.

6.5 Use of Complex Engineering Problems

The work addresses the following complex engineering problem attributes:

P1:

The design and analysis of the hybrid PV–wind–hydrogen–gas turbine system required in-depth engineering knowledge. The work applied K3 through theory-based engineering fundamentals such as basic electrical circuits and electrical power systems. K4 was used to apply specialist knowledge of renewable and hybrid energy systems, and K5–K6 guided system design, simulation, and performance analysis using MATLAB. K8 was also addressed through the integration of recent research findings in hydrogen-based hybrid systems.

P2:

The project involves wide-ranging and often conflicting technical issues, such as managing the intermittency of solar and wind resources, ensuring power reliability, minimizing emissions, and maintaining cost-effectiveness. These challenges required balancing multiple performance indicators using an optimization framework.

P3:

The problem had no obvious solution and required originality in analysis. The system configuration, control logic, and optimization setup were formulated uniquely for the Gazipur region of Bangladesh, using multi-objective optimization to achieve reliability, efficiency, and sustainability.

6.6 Socio-Cultural, Environmental, And Ethical Impact

The resulting hybrid energy system solar, wind, gas turbines, and PEM fuel cells has some noteworthy socio-cultural, environmental, and ethical consequences:

Social Impact: Through decentralization of power generation using renewable energy, the system can provide reliable electricity to distant and rural areas of Bangladesh which lack it, improving the standard of living, promoting education, medicine, and local industry, and slowing down urban migration for lack of infrastructure.

Cultural Relevance: Energy autonomy encourages national resilience and allows communities to preserve their cultural practices dependent on secure living conditions, such as local agriculture, fishing, and crafts.

Environmental Impact: By reducing the consumption of fossil fuels and incorporating clean energy sources, the project decreases the emission of greenhouse gases, contributing to the mitigation of climate change, enhanced air quality, and healthier ecosystem.

Ethical Views: The system promotes equitable access to energy and addresses intergenerational fairness through investment in non-consumptive technology for the future that does not deplete resources. The system also complies with the virtues of ethical engineering through reducing harm to the environment and promoting social welfare.

6.7 Attributes of Ranges of Complex Engineering Problem Solving (P1 – P7) Addressed

The following table shows the attributes of ranges of Complex Engineering Problem Solving (P1 – P7) addressed in EEE 4800 for Project and Thesis.

P	Range of Complex Engineering Problem Solving	Put Tick
Attribute	Complex Engineering Problems have characteristic P1 and some or all of P2 to P7:	**(√)**
Depth of knowledge required	**P1:** Cannot be resolved without in-depth engineering knowledge at the level of one or more of K3, K4, K5, K6 or K8 which allows a fundamentals-based, first principles analytical approach	√
Range of conflicting requirements	**P2:** Involve wide-ranging or conflicting technical, engineering and other issues	√
Depth of analysis required	**P3:** Have no obvious solution and require abstract thinking, originality in analysis to formulate suitable models	√
Familiarity of issues	**P4:** Involve infrequently encountered issues	
Extent of applicable codes	**P5:** Are outside problems encompassed by standards and codes of practice for professional engineering	
Extent of stakeholder involvement and conflicting requirements	**P6:** Involve diverse groups of stakeholders with widely varying needs	
Interdependence	**P7:** Are high level problems including many component parts or sub-problems	√

The following table explains or justifies how the attributes of ranges of Complex Engineering Problem Solving (P1 – P7) have been addressed in EEE 4800 (Project and Thesis).

P	Explanation/Justification
P1	This project entails modeling and integration of renewable and conventional energy components like solar PV, wind turbines, gas turbines, PEM fuel cells, and hydrogen storage. For designing, analyzing, and optimizing this system, in-depth engineering

	expertise is needed in thermodynamics, fluid mechanics, electrical systems, and renewable energy technologies. It also entails the use of first-principle equations and system efficiency calculations. K3 is applied to understand fundamental principles of thermodynamics and energy conversion. K4 is needed for modeling and simulation of electrical and mechanical systems. K5 is used to evaluate and compare system performance through analytical methods. K6 supports the application of advanced techniques for optimization and system efficiency analysis.
P2	The project involves wide-ranging systems like PV, wind, hydrogen fuel cell, and gas turbine. Each has different technical requirements and behaviors, creating conflicting engineering issues that must be balanced for efficient operation.
P3	The project has no direct or ready-made solution. It needs original thinking to design models and use optimization methods like NSGA-II and MOPSO to find the best system performance.
P4	
P5	
P6	
P7	The problem is multi-disciplinary and consists of several interdependent subsystems—each with its own components and performance dependencies (e.g., solar energy depends on irradiance, wind energy depends on velocity, hydrogen storage depends on electrolyzer output, etc.). Fixing one part of the system (e.g., energy surplus management) impacts others (e.g., hydrogen production and gas turbine use), so it is an interdependent problem.

6.8 Attributes of Ranges of Complex Engineering Activities (A1 – A5) Addressed

The following table shows the attributes of ranges of Complex Engineering Activities (A1 – A5) addressed in EEE 4800 for Project and Thesis.

A	**Range of Complex Engineering Activities**	**Put Tick (√)**
Attribute	Complex activities means (engineering) activities or projects that have some or all of the following characteristics:	
Range of resources	**A1:** Involve the use of diverse resources (and for this purpose resources include people, money, equipment, materials, information and technologies)	
Level of interaction	**A2:** Require resolution of significant problems arising from interactions between wide-ranging or conflicting technical, engineering or other issues	√

Innovation	**A3:** Involve creative use of engineering principles and research-based knowledge in novel ways	√
Consequences for society and the environment	**A4:** Have significant consequences in a range of contexts, characterized by difficulty of prediction and mitigation	√
Familiarity	**A5:** Can extend beyond previous experiences by applying principles-based approaches	

The following table explains or justifies how the attributes of ranges of Complex Engineering Activities (A1 – A5) have been addressed in EEE 4700/4800 (Project and Thesis).

A	**Explanation/Justification**
A1	
A2	The project deals with integrating PV, wind, hydrogen fuel cell, and gas turbine systems which have different operating behaviors. Balancing their performance, cost, and reliability creates conflicting technical issues. These problems need careful optimization and control to make the system work smoothly together.
A3	The project makes use of novel integration of renewable energy systems solar PV, wind turbines, and fuel cells with hydrogen storage and gas turbines. The project uses research-based knowledge in a new arrangement to develop an efficient and clean hybrid energy solution suitable for Bangladesh's energy needs. The new concept helps to balance intermittent renewable resources with conventional sources.
A4	The intended system addresses critical environmental and social problems in Bangladesh, including carbon emission mitigation, fossil fuel dependency, and improvement of energy access in rural or disadvantaged areas. Its adoption can bring long-term returns to society and minimize environmental degradation, but the expectation and avoidance of effects (e.g., cost, scalability) must be adequately planned.
A5	

Chapter 7

Conclusion and Future Work

This study presented the modeling, optimization, and performance evaluation of a hybrid renewable energy system (HRES) with photovoltaic (PV) arrays, wind turbines, electrolyzers, hydrogen storage, fuel cells, and a gas turbine for stable and sustainable power generation. The system was optimized using two advanced multi-objective optimization techniques—Non-dominated Sorting Genetic Algorithm II (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO)—for reducing the Levelized Cost of Energy (LCOE) and Total CO_2 Emissions (TCE).

The Pareto front analysis revealed the trade-off between cost and emissions, and three representative solutions were derived for decision-making. The cost-optimal design achieved the lowest LCOE of 0.1126 \$/kWh (NSGA-II) and 0.1134 \$/kWh (MOPSO) but with higher emissions of approximately 97,054 tons CO_2. Conversely, the emission-optimal configuration cut TCE to 91,769 tons CO_2 with corresponding LCOE of 0.2119 \$/kWh (NSGA-II) and 0.2291 \$/kWh (MOPSO), which is the cost of deep decarbonization. The balanced configuration demonstrated the most favorable trade-off, achieving 93,325 tons CO_2 and 0.1404 \$/kWh under NSGA-II, and 93,092 tons CO_2 and 0.1451 \$/kWh under MOPSO.

Comparative study of the two algorithms revealed that NSGA-II yielded lower cost solutions, particularly at the cost-optimal and balanced points, while MOPSO demonstrated quicker convergence and a more uniform Pareto front. Thus, NSGA-II excelled at cost accuracy, while MOPSO offered more diversity and exploration capabilities.

Sensitivity analyses also highlighted the influence of economic and environmental parameters on system performance. A lower discount rate (5%) decreased the LCOE by approximately 25% compared to a 10% rate, illustrating high financial sensitivity. Similarly, lower up-front investment costs and higher component efficiencies significantly improved both cost and emission outcomes. In contrast, lower Global Horizontal Irradiance (GHI) or poor ambient conditions raised both LCOE and TCE, illustrating the climatic sensitivity of system performance.

In conclusion, the optimized hybrid system demonstrates the potential for substantial cost reduction and emission mitigation in the Bangladesh power sector. The inclusion of hydrogen-based storage greatly adds flexibility, reduces curtailment, and improves energy reliability.

For further extension of this study, several extensions are proposed. First, the inclusion of battery storage systems coupled with hydrogen can improve short-term energy balancing as well as system responsiveness. Second, the model extension to include other renewables such as biomass or geothermal energy can enhance resource diversification. Third, uncertainty and probabilistic analysis in various weather and economic scenarios would add robustness and real-world applicability. Finally, real-time control and dispatch approaches based on regional data and dynamic pricing schemes will facilitate real-world implementation and policy compliance for a low-carbon energy future.

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