Energy, economic and environmental (3E) analyses of Solar Photovoltaic and Fuel Cell based hybrid energy system in Pakistan

By

Maham Fazal

Reg. No. 00000317972

Supervised by

Dr. Mustafa Anwar

US-Pakistan Centre for Advanced Studies in Energy (USPCAS-E)

National University of Sciences and Technology (NUST)

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US-Pakistan Centre for Advanced Studies in Energy (USPCAS-E)

National University of Sciences and Technology (NUST)

H-12 Islamabad 44000, Pakistan

August 2023

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by Ms. **Maham Fazal** (Registration No. **00000317972**), of U.S.-Pakistan Centre for Advanced Studies in Energy has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is within the similarity indices limit and accepted as partial fulfillment for the award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Signature: ____________________

Name of Supervisor: DR. MUSTAFA ANWAR

Date: 22/9/23

Signature (HoD ESE): ____________________

Date: 17/10/23

Signature (Dean/Principal): ____________________

Date: 18/10/2023

Certificate

This is to certify that work in this thesis has been carried out by **Maham Fazal** and completed under my supervision in, U.S.-Pakistan Center for Advance Studies in Energy, National University of Sciences and Technology, H-12, Islamabad, Pakistan.

Supervisor: ______________________

Dr. Mustafa Anwar

USPCAS-E

NUST, Islamabad

GEC member 1: ______________________

Dr. Muhammad Hassan

USPCAS-E

NUST, Islamabad

GEC member 2: ______________________

Dr. Sehar Shakir

USPCAS-E

NUST, Islamabad

GEC member 3: ______________________

Engr. Abdul Kashif Janjua

USPCAS-E

NUST, Islamabad

HOD-ESE: ______________________

Dr. Rabia Liaquat

USPCAS-E

NUST, Islamabad

Principal: ______________________

Prof. Dr. Adeel Waqas

USPCAS-E

NUST, Islamabad

Dedication

Dedicated to my beloved daughter, [Zainab Fatima], and my big brother, [Sohail Ahmed]. Throughout my academic journey and beyond, they have been an unwavering source of inspiration and guidance. Their constant encouragement, support, and belief in my abilities have propelled me forward, instilling in me the confidence to tackle challenges and pursue my passions.

ABSTRACT

The present study aims to check the feasibility of the PV-Fuel cell hybrid system in Pakistan (Developing Country). Previous studies on Hybrid systems (unreliability, environmentally unfriendly) have convinced the researchers to look for a better, reliable, efficient, and environmentally friendly combination with PV and fuel cell, because it possesses required properties. Additionally, energy, economic and environmental (3E) system analysis has been done to check economic and environmental feasibility. The evaluation tool used in the present study is System Advisor Model (SAM), while matrix laboratory (MATLAB) is used for energy load design. The environmental analysis via expressed equations is based on system consumptions and emissions. The upshots show that from an energy, economic and environmental perspective, the PV-fuel cell system is a step towards contributing to the Sustainable Development Goal 7, 11, 12 and 13. The PV-FC system exhibits the levelized cost of electricity as 7.36 (C/kWh), which is 0.073$/kWh, while the net present value of the system is $1.86 million. Systems' LCOE is less than the tariff rate of Pakistan i.e., according to IESCO (Islamabad Electric Supply Company), 0.078$/kWh for off-peak hours and 0.11$/kWh for on-peak hours. Environmental analysis showed that 1,927,200 kg/year of carbon dioxide emissions are being reduced due to Hybrid system. Results shows that PV-FC hybrid power production is cost-effective and environmentally beneficial. The research findings are imperative for stakeholders, policymakers, and investors to uphold low-carbon technologies.

Keywords: Solar PV; Fuel Cell; Hybrid Energy System; Feasibility Study.

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“Energy, economic and environmental (3E) analyses of Solar Photovoltaic and Fuel Cell based hybrid energy system in Pakistan” **(1st Revision Received)**

Chapter 1 Introduction

1.1. Global Status

Energy is the fundamental requirement of the nation for the expansion of its economy, the creation of new investment opportunities, and the growth of its nation. The reliance on fossil fuels for the world's energy supply has given birth to numerous primary concerns, the most prominent of which are pollution and climate change. About forty percent of the world's carbon dioxide emissions come from the combustion of fossil fuels to produce electricity. In addition, the use of fossil fuel comes with a number of drawbacks, including limited resources, challenging transportation, and inconsistent prices. These drawbacks motivate people all around the world to search for renewable and environmentally friendly alternatives to traditional sources of energy [1]. Biomass, hydropower, wind, fuel cell, and solar energy are all attracting a lot of attention as potential solutions to the problems caused by traditional resources. According to research by the International Energy Agency (IEA), approximately 26% of the world's electricity is generated from renewable energy resources. It is anticipated that this potential rate will reach 30% by the year 2024. Solar power accounted for around half of the total energy. The International Energy Agency (IEA) forecasts that solar power will soon become the dominant form of energy due to the rapid development of photovoltaic (PV) technology and falling prices [2]. Solar energy presents a promising option that is also environmentally benign for closing the demand-supply gap in the energy industry; nevertheless, solar energy also presents its own unique issues, such as unreliability and a discontinuous nature [3]. [4] Researchers claimed in their research that power production businesses in Japan have completely stopped investing in solar systems to avoid being influenced by variations in RE output. This was done in order to keep away from the influence of RE output changes.

Numerous studies address the difficulties associated with solar energy by employing one of three distinct strategies. Integration of several renewable energy resources, such as hydro or wind, is the first strategy [5][6]. The other strategy involves combining power from the grid with that generated by a PV system [7]. The last strategy involves combining a photovoltaic (PV) system with a storage device in order to maintain a constant supply of energy.

Researchers are looking into a variety of storage technologies that have a high potential for the generation of continuous power [8][9]. Batteries are one of the storage technologies that are typically paired with any renewable resource in stand-alone systems for electrification. However, batteries also have its limits, including the possibility of causing damage to the environment, a short life-cycle, and the requirement for periodic maintenance [10]. After suffering losses in the operation of independent solar systems, Japanese businesses developed the hybrid PV-SOFC system. According to the statements made by those companies, PV-FC-gas turbines might be a more effective alternative to using batteries. According to this study, this method has the potential to increase both the utilization of renewable energy sources and the efficiency of power generation by more than fifty percent [4].

The fuel cell is an alternative to batteries that is both more environmentally friendly and more modern [11]. Recent findings from a study on the PV-SOFC hybrid that was carried out by [11] indicated that this hybrid has the capacity to cover the shortfall in the demand for power. The overall conclusion of this study is that the PV-SOFC system is superior to the PV-Battery system in terms of both performance and feasibility. The development of fuel cells (FC) has shown promise as a realistic and dependable source of power generation that has a lower carbon footprint. According to [12], fuel cells, when combined with a variety of technological breakthroughs, have a tremendous potential to serve as a source of power in a variety of settings. Power modules have an advantage over conventional batteries since they may continue to generate electricity so long as they are supplied with a steady supply of hydrogen in addition to oxygen. As a result of the fact that power generation systems based on fuel cells may be utilized to provide capacity to company buildings, locations that are not connected to the grid, transportation, server farms, broadcast communications pinnacles, and hospital complexes, these systems are becoming increasingly popular. When the power generation from the system is in excess of the excessive amount of the energy mix that is delivered to the grid in order to increase the revenues.

1.2. National Status

Urbanization, population growth, an increase in energy consumption, a misconception of future energy demand, and a lack of planning in the energy sector are some of the factors that have contributed to Pakistan's power shortage problems during the past several decades. There is a lack of access to power for around 50 million people in Pakistan. According to a report by the World Bank, Pakistan is ranked 115th for its consistent electricity supply. The crisis that began in the power sector in 2005 is having an effect not only on the lives of individuals but also on the economy as a whole. This is because both domestic and international investments are suffering as a result of the increase in the cost of production. According to a report published by the World Bank in 2018, an increase in Pakistan's total energy supply will lead to a rise in annual household income of approximately $4.5 billion. According to [13] research, worldwide, the demand for energy is growing at a rate of up to 5% annually.

According to [14] research, the proportion of Pakistan's overall energy mix that comes from the generation of electricity using renewable resources is still under 2%. On the other hand, Pakistan is one of the luckiest countries in terms of having a great potential for energy generation from natural resources. This makes Pakistan one of the luckiest countries in the world. Wind energy, solar energy, hydropower, biomass, and other forms of renewable energy are abundant in Pakistan, making it an extremely energy-diverse country. The country will benefit from the use of available renewable resources when it comes to the electrification of rural areas and communities. The elimination of the supply-demand imbalance in the energy market will be significantly aided by research on hybrid systems.

1.3. Problem Statement

Considering the current surplus energy generation capacity, this study was conducted to examine how photovoltaic (PV) systems and fuel cells might best be utilized and integrated into Pakistan's energy landscape. Despite having surplus energy, the country faces challenges in effectively managing and storing this excess energy. This thesis investigates the viability of a hybrid energy system using PV and fuel cells. The paper examines the energy, economic, and environmental elements of this hybrid system to offer solutions to harness surplus energy and encourage sustainable and efficient renewable energy use. The research will improve Pakistan's energy resilience, reduce conventional fuel use, and promote a cleaner energy future. During the course of our investigation, I came across some limitations, including the fact that load data sheets and meteorological information covering the entire country are not now available.

1.4. Objectives

Objectives of the present study are:

- ➢ To perform Energy, economic and environmental (3E) analysis of the PV-Fuel Cell hybrid system.
- ➢ To enhance the reliability and resilience of energy systems by developing hybrid configurations that can operate efficiently.
- ➢ To minimize greenhouse gas emissions and contribution towards global movement of clean and green energy

1.5. Rationale of the study

Sustainability is needed due to climate change, fossil fuel depletion, and rising energy costs. Pakistan, like many developing nations, struggles with power shortages and fossil fuel dependence in spite of surplus energy generation capacity. Photovoltaic (PV) and fuel cell (FC) systems are being integrated into microgrids to address these concerns. This study will analyze PV-FC-based stand-alone and grid-connected systems in a Pakistani small housing society microgrid using 3E analysis.

This study will analyze PV-FC-based systems' performance, reliability, and energy generating potential. System energy production capacity can be calculated using PV panel and fuel cell energy output. Quantifying energy contributions and requirements allows the system's ability to meet tiny housing society demand in stand-alone and grid-connected modes. PV-FC-based systems will be assessed for financial viability and cost-effectiveness in the small housing society microgrid. PV panels, fuel cell units, and energy storage systems require upfront capital expenditure. The study will also assess fuel, system monitoring, and battery replacement expenses. Economic analysis can estimate payback period and cost competitiveness of these systems compared to conventional energy sources. The environmental analysis will evaluate PV-FC-based systems. This analysis will measure the greenhouse gas emissions decrease from switching to renewable electricity generation. PV-FC systems' carbon footprint and pollutant emissions can show the microgrid's environmental benefits.

This study will address, in addition to the 3E analysis, the socio-technical elements of integrating PV-FC-based systems into the small housing society microgrid. It will examine how renewable energy technology affect social acceptance, user happiness, and behavior. In addition, the study will determine the technical obstacles and hurdles that stand in the way of the implementation, such as concerns regarding grid connections, system dependability, and power quality considerations.

1.6. Significance of the study

This research will provide unique insights into the feasibility, benefits, and problems of integrating PV-FC-based systems into small housing society microgrids. These insights are extremely important for Pakistan's energy industry, which is why this research is of such major value. The findings of the study can serve as a guide for decision-makers in policymaking, energy planning, and investment when it comes to the adoption of renewable energy technology. In addition, the findings of the research will contribute to the current body of knowledge on the integration of renewable energy sources, particularly in the context of poor countries, and they can serve as a reference for future research and initiatives in settings that are analogous to these.

Summary

The purpose, background, and significance of the study are all laid forth in this chapter of the thesis. This chapter presents the concept of a hybrid energy system that combines solar photovoltaic (PV) and fuel cell technologies and provides background on the energy difficulties Pakistan is facing. This chapter lays the groundwork for the rest of the dissertation by defining the research questions and the scope of the investigation.

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Chapter 2 Literature Review

Transitionary evolution in the world's energy is happening as the fossil fuel-dependent economy shifts to a sustainable resource-based economy [1]. Moreover, green energy has rapidly been on a journey to a downtrend or pausing the massive global warming and climate change challenges. Furthermore, transitionary evolution seems to save the world from price and environmental shocks and decrease the energy supply-demand gap. Pakistan still needs these evolutionary renewable energy methods to overcome energy supply-demand gap that is rising critically. Pakistan also needs to over the carbon emissions that are coming from fossil fuel-based power plants and degrading the environment, evolutionary methods will not only fill the energy supply-demand gap but these methods will be environmentally friendly [2]. Pakistan contributes less than 2% of electricity generated from renewable resources. Fig. 2.1 is an illustration of the energy supply percentage in Pakistan. Every year, Pakistan imports fuel to fulfill its 1/3 of energy demand. Around $14.4 billion are used to import energy for Pakistan every year. This value is quite a lot compared to the previous year's import value, which was $10.9 billion. 75% of this increase in imports is due to price shocks [3]. In Pakistan, a South Asian country, conventional energy resource dominance greatly contributes to temperature levitation [4]. This kind of price and environmental shocks does not make the present energy supply percentage sustainable for Pakistan's environment and economy [5]. Pakistan's energy, economy, and environment seem to slow due to the aforementioned factors. According to World Bank Report, Pakistan is ranked 115th for reliable power. Total household income will increase by around $4.5 billion a year by increasing the electricity supply in Pakistan [6].

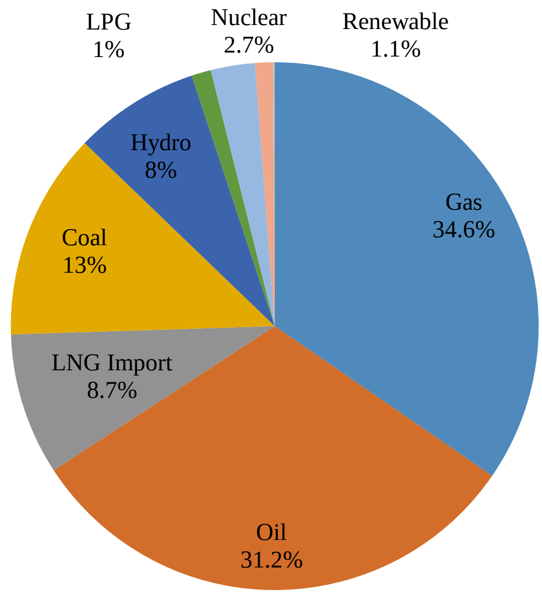

Figure 2.1: Pakistan's Energy Supply percentage [5].

Solar energy is a promising and environmentally friendly solution to fill the energy demand-supply gap due to its known advantages, i.e., clean energy, competitive cost, and free source. Around 50% of energy comes from solar. During 2020–21, PV was the best performing industry despite COVID 19 [7]. IEA presumes solar energy's significant domination due to the swift expansion of PV technology and dropping costs [8].

To prevent the depletion of fossil fuels, environmentally friendly alternatives to the generation of energy are required, and among all of these options, solar energy is the one that is most commonly employed and widely utilized [9]. According to Nelson and Grubesic's research from 2020, solar systems can be used on their own or integrated with other types of energy systems. Fuel cells, on the other hand, are a type of conversion technology that turn fuel into electricity while also producing heat energy and water as byproducts [10]. According to Peng et al.'s 2020 research, fuel cells offer efficient conversion in addition to low emissions and great reliability. According to Huang and Marefati's [11] research from 2020, technology such as solar systems and fuel cells are likely to be helpful in achieving sustainable development objective no. 7. In order to close the gap in energy supply, a number of academics came up with the idea of building hybrid systems [12]. The production of electricity by a hybrid system also results in the production of hydrogen fuel, as well as heating and cooling as a byproduct. According to [13] research from 2020, the system's overall performance and efficiency are improved as a result of these byproducts.

2.1 Hybrid Systems

Studies conducted on hybrid energy systems at international and national levels are given in 2.1.1 and 2.1.2.

2.1.1. International Level Studies

The techno-economic study of PV-SOFC and PV-Battery for hybrid systems was illustrated by [14]. During the course of this investigation, the researchers worked on two case studies that were centered on the photovoltaic with solid oxide fuel cell and photovoltaic battery system. The purpose of this project is to design a power unit that is independent from the grid by incorporating renewable energy resources that produce electrical power that does not emit any emissions. According to the findings of this research, the cost of PV-Battery is 0.16 dollars per kilowatt-hour, whereas the cost of PV-SOFC is 0.11 dollars per kilowatt-hour. This suggests that PV-SOFC is a more cost-effective and economic option. The stand-alone Fuel cell and PV hybrid system for the small community center in India was designed by [15]. The fuel cell, solar panels, hydrogen storage tank, and electrolyzer are the elements that make up the components of the system. The researchers were able to optimize and conduct analysis using the HOMER and ABC algorithms. The levelized cost of energy for stand-alone hybrid systems is going to be reduced to its absolute minimum as a primary focus of this investigation, along with the cost optimization of PV-fuel cell systems. The results that were achieved from using the technique were highly accurate and effective. The levelized cost of electricity generated by the hybrid system operating on its own is 0.228 dollars per kilowatt hour [15].

Solar photovoltaics, fuel cells, batteries and supercapacitors were some of the storage technologies that [16] worked on. They used diesel generators as backups. The purpose of the research was to determine whether or not this system has the capability of satisfying the major load. A study was carried out on behalf of the city of Khorkaffan in Sharjah. The optimization and simulation of the suggested system were performed with the HOMER Pro software, and the results demonstrated that the system has the capability to satisfy the principal load of the city. Mubaraak et al. (2020) applied a variety of tracking devices in the course of their investigation on grid-connected PV-FC hybrid systems. In this piece of writing, both technical and economic analysis was carried out, and the results revealed that vertical single-axis tracking provided the largest amount of PV. The findings of this study indicate that the PV-FC hybrid design with VSAT is the best configuration for the generation of power. [17] carried out a study on a PV-FC-wind hybrid in the city of Hurghada, which is located in Egypt. The system was developed for use during off-grid times. The PSO strategy was contrasted with various meta-heuristic approaches that were utilized. An economic analysis was carried out as part of this study, and the findings demonstrated that this system is economically viable with a levelized cost of energy (LCOE) of 0.0628 dollars per kilowatt hour, which is lower than the cost of power acquired from the grid in Egypt.

Vendoti et al. (2020) conducted research to identify the most effective strategy that may be used to electrify a community. In order to research the optimal hybridization strategies, the HOMER pro software is utilized. The levelized cost of energy (LCOE) as well as the net present cost were the primary focus of this research, and the researchers believe that a combination of photovoltaics, fuel cells, wind power, and biomass storage offers the best feasible option. The cost of COE is $0.214 per kWh [18]. Rezk et al. (2020) [19] carried out a study with the goal of discovering the optimal solution for NEOM CITY, which is intended to be the greenest city in the world. During the course of this study, a variety of different hybrid combinations were put to the test. The findings indicated that the hybrid of PV-FC-BS would be the most environmentally friendly option, as it would produce the fewest emissions of greenhouse gases and have the smallest impact on the rate at which the planet warms.

Odoi-Yorke and Woenagnon (2020) conducted research on PV-FC hybrid systems and evaluated the viability of installing such systems in telecom base stations in Ghana. The major objective of the study was to find ways to reduce the LCOE as well as greenhouse gas emissions. HOMER was the tool that was used for this analysis, and the findings revealed that areas with fewer wind and biomass resources should consider switching to PV-FC hybrid systems because they offer the most optimal and cost-effective solution in comparison to diesel-based ones. However, there would be significant up-front costs associated with this planned project [20]. Shaygan et al. (2019) proposed an idea for a hybrid system that combines PEM fuel cells and photovoltaics. The researchers gave an extensive examination of the suggested system's exergy, energy, and economic implications.

The purpose of this system was to generate both hydrogen and power from the system itself, meaning that the storage and utilization of energy were meant to take place at the same time [21].

The hybrid system that was shown by [22] included components such as photovoltaic cells, fuel cells, and batteries. The system is offered as a potential solution to the load uncertainty that exists inside the system. The plan was to construct a system that can get its electricity from a variety of different sources, and any excess energy that the system produced was supposed to be stored. Solar photovoltaic panels produce the most electricity throughout the day, while evening demand is at its highest. Therefore, the utilization of Fuel Cells and Batteries would not only boost the availability of the system but also the efficiency of the system. In addition, the utilization of Grid Power is taken into consideration within the system as a backup in case the proposed system is unable to keep up with the load demand [14] & [15] construct a stand-alone hybrid system, which has the potential to be the most effective option for the elimination of an electrical deficit. Because the system in this investigation is installed independently, there will be a blackout if it ever crashes or develops a technical problem; during this time, there will be no access to any sources of energy. This situation will persist until the system is fixed and can resume normal operation. If we disregard what was stated above, a grid-connected system would be a superior option. Failing that, any other alternative suggested solution will make these studies more realistic and practical.

Net Present Value is main variable to see the feasibility of the system and [20], [23] and [15] may overlook the calculation of this NPV to check the feasibility of the system. System feasibility check will make the research more authentic.

2.1.2. National studies

Shahzad et al. (2017) construct an optimal and cost-effective combination of biomass and photovoltaics for use in an agricultural farm and a residential community in Layyah, Pakistan [24]. After HOMER had been used for designing and conducting a techno-economic study, the results were subjected to sensitive analysis so that they might be refined further. The price of biomass as well as its potential, load changes, and the amount of solar radiation were selected as the sensitive analysis's sensitivity parameters. The findings of this analysis indicated that the system was viable when considering the cost of energy as well as the net present cost. [25] & [26] have each conducted study on the techno-economic analysis of an off-grid photovoltaic (PV) system in their respective regions of Punjab and Sindh. According to these findings, the provision of power in rural parts of Punjab and Sindh may be possible through the installation of PV systems.

A group from COMSATS LAHORE that did research on fuel cells, published their findings [27]. They examined all of the researches on fuel cells that had been carried out in Pakistan and made recommendations for various hybrids that may be formed using fuel cells. However, there was not a single mention of a PV-FC hybrid anywhere in this article. This review study suggests that fuel cells would be a better option than other potential solutions for solving Pakistan's electrical problems. [28] conducted research in Pakistan regarding hybrid systems. Energy from wind and biomass were used to power the system. On the modeling and optimization front, HOMER was the tool of choice. The chosen location could receive uninterrupted power supply from the system that was proposed at all times. [4] carried out their study in Gilgit-Baltistan, which is located in Pakistan. The 1.8 million residents of Gilgit-Baltistan were supposed to benefit from the hybrid system that the researchers were trying to establish. The results of the study were gathered with the help of HOMER. In the context of this study, hybrid refers to both wind-hydro and battery backup.

An analysis of the relevant published material shown in table 1 reveals that there is significant potential for the combination of PV and fuel cells. Numerous studies on this subject are carried out each and every year. However, in Pakistan, a variety of hybrid systems, such as photovoltaic biomass, wind-hydro, wind-biomass, and so on, were the subject of research and study. PV and fuel cells have each been the subject of their own research, but there has been no investigation into a hybrid PV-FC system as of yet. Because Pakistan is still a developing country, there is a significant disparity between the country's energy demand and its energy supply. The current research will be helpful for the country in the creation of electricity with very few negative effects on the environment. The SAM simulation model of a grid connected system is utilized for the purpose of research and the design of hybrid photovoltaic fuel cell systems. SAM is a software that is simple to use and is utilized in the creation of both stand-alone and grid-connected systems. SAM also optimizes the way different problems are solved by using a straightforward approach.

Table 1.1 Study of Hybrid Systems Conducted in Pakistan and developing countries.

Load Type	Hybrid System	City/Countries	Comments	Ref.
Village (Residential Load)	PV-Battery-Diesel Generator	DI khan	Environmental emissions have been significantly reduced	[4]
Industrial Load	PV-Biomass-Wind-Battery-Diesel Generator	Faisalabad	Carbon dioxide emissions have been reduced by 68%	[29]
Village (Residential Load)	Hydro-Solar	Muzaffargarh	Carbon dioxide emissions have been lowered	[30]
Customer Control Overload Appliances	PV-Wind	Pakistan	Measures have resulted in a lowering of carbon emissions	[31]
Remote Industries	Solar-Wind-Diesel	Swabi	There's been a cutback in carbon dioxide emissions	[32]
Residential Load	Solar-Hydro-Biomass-Battery	Rural area	The level of carbon dioxide emissions has been brought down	[32]
Residential Load	Solar-Hydro	Rural area	Carbon dioxide emissions have experienced a decrease	[33]
Domestic Load	Wind-Solar System	Lahore	There's been a decline in the release of carbon dioxide	[34]
Community and Commercial	Hydro-Solar-Biomass	Murshakhel KPK	Carbon dioxide emissions reduced	[35]
Remote area	PV-Fuel Cell hybrid	Egypt	_	
Village area	PV-Fuel Cell	India	Carbon dioxide emissions have been reduced by 68%	[18]

Northeast India, Rural area	PV-Fuel Cell	India	Carbon dioxide emissions have been lowered	[36]
Rural area	PV-Fuel Cell	-	Measures have resulted in a lowering of carbon emissions	[37]
Rural area	PV-Fuel Cell	California, Mexico	There's been a cutback in carbon dioxide emissions	[38]

2.2. Contribution of Present Study

Contribution and significance of present study are as follows:

- Being the first research in the country to introduce the concept of a PV-fuel cell hybrid system. The research on PV-FC hybrids is more significant in terms of their use in real life.
- A comparison of photovoltaic batteries and photovoltaic fuel cells.
- The majority of the country's resources are not considered to be reliable. Nevertheless, the combination of a stable source, such as a fuel cell, with a photovoltaic system is a significant gift to the country. This study will help the country to eliminate the energy supply-demand gap and will help in stop deteriorating natural resources.
- The proposed project will have better economics and less emissions.

Summary

This chapter provides a summary of the essential research and literature that pertains to the technologies of photovoltaic solar cells and fuel cells, as well as the incorporation of these technologies into hybrid energy systems. It provides an examination of the research that has already been conducted on the energy, economic, and environmental aspects of hybrid systems that are comparable and have been implemented in various countries. The literature evaluation contributes to the process of locating knowledge gaps and provides a foundation for the approach and analysis that will be presented in subsequent chapters.

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Chapter 3 Methodology

3.1. Site selection, Software, and Load Assessment

Lahore is the provincial capital of Punjab and Pakistan's second-largest metropolis [1]. Lahore is chosen as the selected site for the proposed study. One of the necessities of energy system designing is calculating the selected site's energy demand. Raw data of the PRECON data set is used as a load [2]. Load is evaluated w.r.t connected load in use for a single house and then multiplied by the number of houses having similar circumstances for the total load demand of the community area [3]. A residential community of Lahore, with an average highest and lowest temperature of 41oC and 8oC respectively, consisting of 100 houses, is considered for the current study. The daily temperature detail of the selected site for one year has been put under consideration for research purposes [4].

3.2. Solar Irradiance (Hourly)

The availability of solar energy resources and knowledge regarding this resource is a pre-determined factor. To design an efficient solar system at finest condition, it is necessary to know about the solar resource availability at the selected site. Insufficient solar energy resources can affect the performance of the solar photovoltaic system [5]. Pakistan is a rich country for solar energy utilization due to its weather conditions as it has the large solar energy potential shown in Fig. 3.1.

The hourly beam irradiance, measured at the surface perpendicular to the sun and obtained at the selected site, is shown in Fig. 3.1. Horizontal axis of Fig. 3.1 shows the months of the year, and the vertical axis shows the beam irradiance (W/m2). The months of July and August have a low value of direct solar irradiance. Low solar irradiance is measured due to the monsoon season in Islamabad-Pakistan [5]. The maximum value of direct radiation found in the month of March due to the maximum clearness index is very useful for the solar concentrators' technology in the future as the clearness index predicts the clearness of the atmosphere [6].

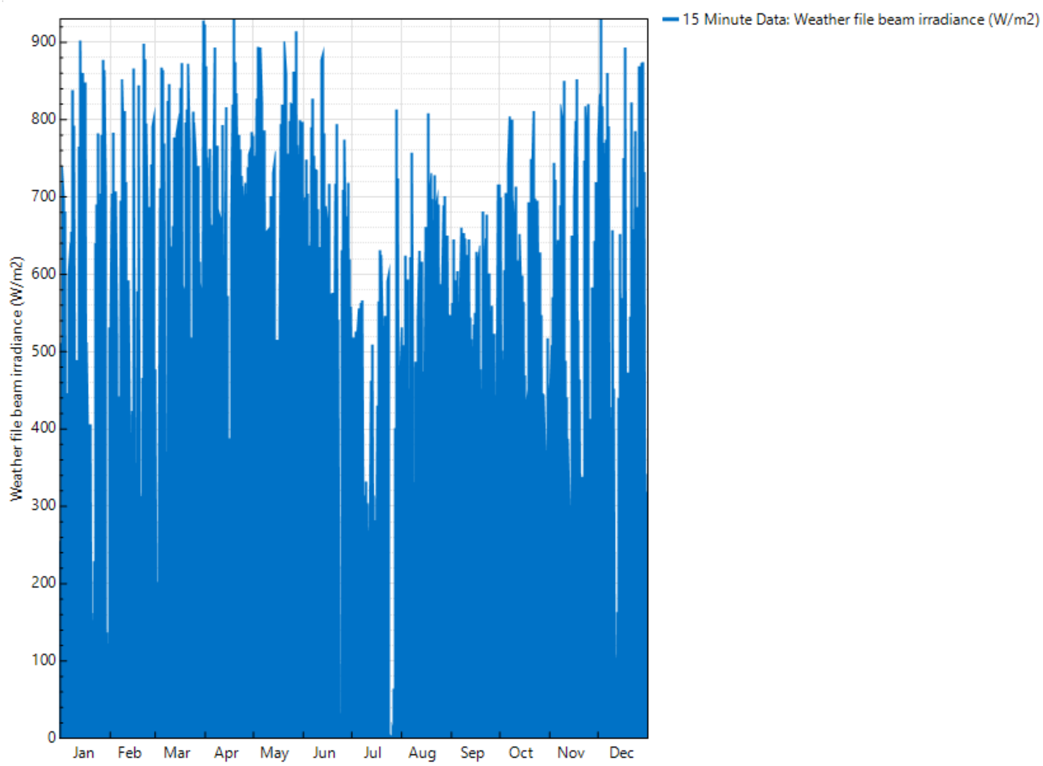

Figure 3.1: Hourly Beam Irradiance.

3.3. MATLAB

Load is designed using MATLAB. This problem-solving software is used for technical analysis, where mathematical notations express the solution. MATLAB works on visualization, exploration and data analysis by prototyping, simulation, and modeling. MATLAB permits the implementation of algorithms, matrix manipulations, functions, and data plotting. The connected electrical load is designed by using the matrix manipulation method in MATLAB. The raw load data was extracted from the PRECON DATA SET made available by Energy Informatics Group [2], and a cluster of 100 homes was formed for electrical load. The load is managed in MATLAB and converted into 8760 values for SAM software as an input.

3.4. SAM

System Advisor Model, user-friendly software that gives detailed and self-explanatory results, is used for obtaining the optimum size of the hybrid system. Both technical and economic analyses are performed on SAM alone. Integration of PV-Fuel cell combination has been done for the selected site. In SAM, in-built residential sheets of fuel cell and PV and weather files are utilized. Electrical load is calculated by using MATLAB. Calculated values were put into SAM to get the results of the present study. SAM software is used for energy and economic analysis. Viability and evaluation have also been performed on the same software.

U.S. Department of Energy's National Renewable Energy Laboratory's (NREL) System Advisor Model (SAM) software is an effective resource for performing economic and energy analysis of renewable energy projects. In addition to solar, wind, geothermal, biomass, and concentrated solar power (CSP), SAM can also be used to represent various types of renewable energy systems. Here's a rundown of how SAM does its energy and economic analyses:

Input of Data

In order to conduct its analysis, SAM needs a wide range of information to work with. Location, system capacity, funding details, and more are all included in this data set that is unique to this project. Access to a database of meteorological data or the ability to submit one's own weather data files is provided by SAM, which is crucial for projects using renewable energy.

Assembly of Components

Users set the parameters for the model of their chosen renewable energy system. Renewable energy generators (such as photovoltaic panels and fuel cells stacks) as well as storage systems and other components must have their types and capacities detailed. Single- and multi-technology setups are both supported by SAM.

Simulation of Energy Generation:

For a given time period (usually hourly or sub-hourly), SAM simulates the renewable energy system's energy production using the provided system setup and meteorological data.

Models of energy production are based on physical and engineering principles and are unique to each renewable energy technology. To reliably predict energy output, SAM uses elaborate models.

Budgetary Simulation

To determine the project's financial feasibility, SAM use financial modeling. It computes a wide range of financial measures, like as

- Over the course of a system's lifespan, the cost of electricity per unit is referred to as the levelized cost of energy (LCOE).
- The NPV of a project is the sum total of all future cash flows less the initial investment.
- The discount rate that results in a negative net present value for a project is known as the internal rate of return (IRR).
- The time it takes to get a return on an investment made in a project is known as its payback period.
- Financial criteria like as financing terms, incentives, tax rates, and O&M costs can be entered by users of SAM.

3.5. Electric Load Estimation

The connected electrical load is computed by using the equation given in [6]:

$$E_{Load} = Prating * Q_{ty} \qquad (1)$$

Where,

E_{Load} = Estimated electrical load (kW).

P_{rating} = Power Rating (W) for appliances

Q_{ty} = Represents Total Quantity of Appliances/Equipment,

Fig. 3.2 shows the load data of the selected site. The X-axis shows months of the year, and the Y-axis shows load (kW) concerning the hours of the day. The Electric load determined how much power was drawn from the power system [7]. Load assessment is the most important factor for the modeling of a hybrid energy system to avoid the excess production that can affect the economic parameters like higher cost, low Net present value and high simple payback period of the energy project and under production could not meet the load demand [8]. Fig. 3.3 shows the peak demand of load from June 15-22. Fig. 3.3 also illustrates that the proposed system meets the load demand.

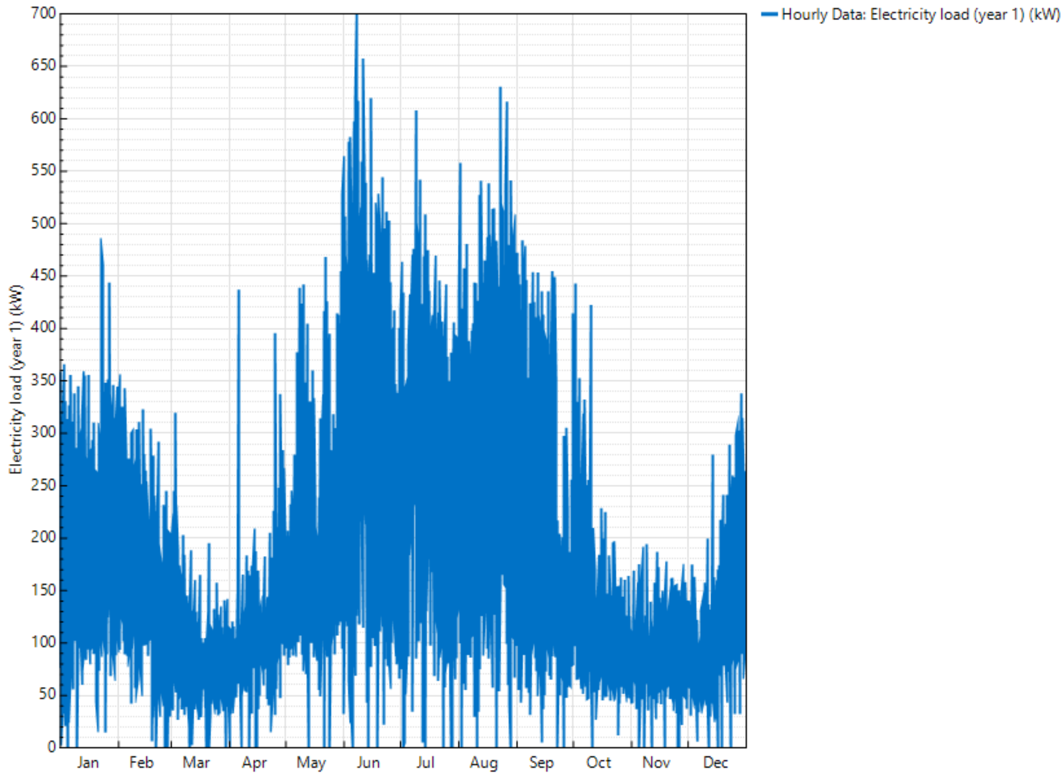

Figure 3.2 Electric Load Data of the Selected Site.

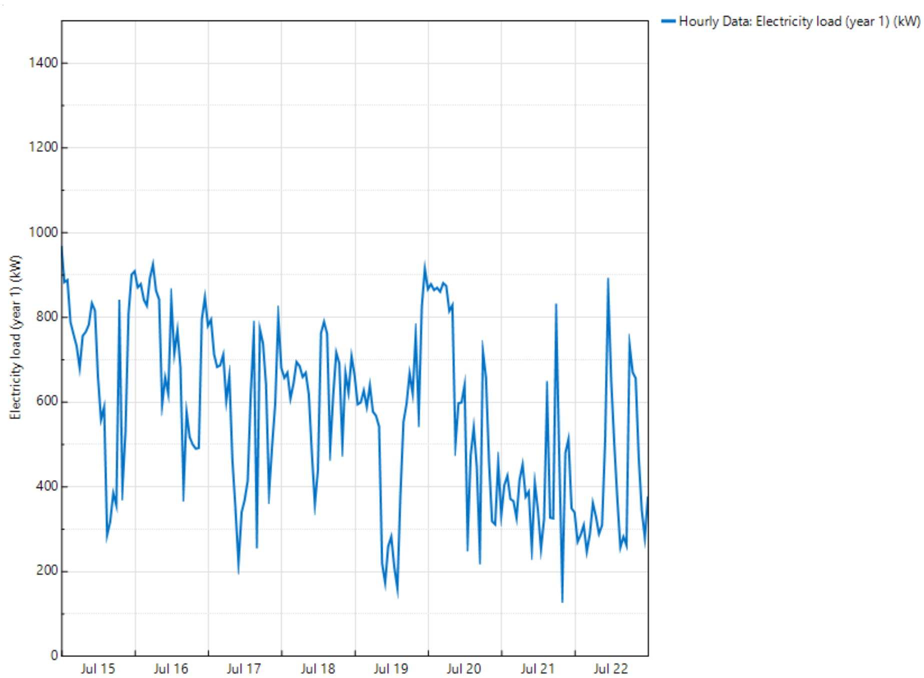

Figure 3.3 Electric load of specific days near peak demand.

In this paper, the load of a residential community is considered for designing and analyzing a hybrid energy system. The peak demand for electric load is calculated as 700 kW in June, shown in Fig. 3.2b, due to the summer season in Islamabad-Pakistan. Electricity usage is high from May to September due to the use of heavy load (kW) electric appliances. When the entire system and all connected loads are fully operational, the peak demand (700 kW) occurs. The major electricity distribution is among fans, LED lights, smart TV, laptop, refrigerator, motor, and other electronic appliances. The month of June's load is considered a peak load. The selected site's energy demand varies from season to season and day to night. This variation comes due to ambient temperature differences in different seasons and loads consumption at different times of the day/night. The connected estimated load is given in Table.3.5.

3.6. Technical Parameters

Technical parameters studied in present research are as follows:

3.6.1. Capacity factor

The total amount of energy a plant produces during a specific time to the amount of energy a plant could produce at full capacity [9].

3.6.2. Energy yield

Part of the watts of sunlight (Irradiance, Watt/m2) that are converted to the DC power by the module determines how efficiently the system is near its peak values over the year [10].

3.6.3. Levelized cost of electricity (LCOE)

LCOE is the total average cost or net present cost of electricity generation for the energy system during the project's life [11]. The annualized cost of the system (ACS) consists of the annual capital cost (ACC), annual replacement cost, salvage value and maintenance cost [12].

Table 3.5 Electrical Load Distribution of Selected Site

S. no.	**Load Description**	**Power rating (W)**	**Quantity**	**Total (W)**
1	Ceiling Fan	80	04	320
2	Exhaust Fan	60	04	240
3	Smart TV	80	01	80
4	Refrigerator	180	01	180
5	LED Light	10	07	70
6	Fluorescent Tube	50	05	250
7	Washing Machine	900	01	900
8	Charging Device	05	04	20
9	Laptop	40	03	120
10	Water Pump	750	01	750
11	Electric Iron	1000	01	1000
12	Water Purifier	1600	01	1600
13	Microwave Oven	1200	01	1200
14	Outdoor Spotlight	50	03	150
16	Bracket Fan	60	02	120
Total Peak Load of 01x House (W)				7,000
Total Peak Load of 01x House (kW)				7
Total no. of Houses				100
Total Peak Load				700

3.6.4. Payback time-period

It is the time in which initial investment bear on the project is recovered, and investment achieves the break-even point.

3.6.5. Net present value (NPV)

It is used to analyze the feasibility and profitability of a proposed project. NPV is the present value of cash inflows minus the present value of cash outflows over the analyzed period of the project [13].

3.7. Environmental Parameters

As the system generates less or no carbon dioxide emissions, it is a more environmentally friendly system. CO_2 savings on a yearly basis and CO_2 potential emissions are calculated in the proposed study. The following equations are used to understand the costs related to the CO_2 emissions of the designed hybrid system. This study's unit damage cost (U_{CO2}) is estimated at 0.024$/Kg [14]. Using equation (4), the emission-saving potential of CO_2 for the current study is calculated [15]. Herein, $\alpha_{co2(ref)}$ is the CO_2 emission of a conventional thermal power plant, which is coal-fired. The $\alpha_{co2(ref)}$ is used for the estimation of the CO_2 mission potential ($\alpha_{co2(potential)}$)) of the proposed system [15]. Environmental damage cost (D_{CO_2}) estimated using the unit damage cost (U_{CO2}) value for the environmental modeling. The impact of environmental benefit (B_{env}) can be estimated by using the following expression of equation (6).

$$D_{CO_2} = P_{CO_2} \times U_{CO_2} \quad (4)$$

$$\alpha_{CO_{2(Potential)}} = \alpha_{CO_{2(ref)}} \times \alpha_{CO_{2(sys)}} \quad (5)$$

$$B_{eny} = D_{CO_2} \times \alpha_{CO_{2(potential)}} \quad (6)$$

Where;

D_{CO_2} = Environment damage cost

P_{CO_2} = Potential emission of CO_2

U_{CO_2} = Unit damage cost

$\alpha_{CO_{2(ref)}}$ = Standard coal fired power plant's CO_2 emission

B_{env} = Environmental benefit

3.8. Characteristics of PV-FC hybrid system

Solar irradiance is measured by using SAM software. In-built weather files of software were used to calculate the data of the selected site. Fig. 3.3 shows that the selected site has solar resources in abundance.

Keeping the economic and technical parameters in mind, a solar system of 500kW is installed in the residential community. Details of several variables of the solar system are given in Table.3. A solar system has a capacity of 500kW is installed at maximum power point tracking to get maximum output. The LCOE and total cost of the system have been increased by increasing the installed capacity of the solar system. The system performs best at a power rating of 500 kilowatts. The system generates direct current, due to which a converter is installed to convert the DC into AC. After the conversion of the current, it supplies into a residential community. The rated inverter size was selected to meet the DC/AC ratio near unity for minimum power loss.

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Chapter 4 Results and Discussion

Herein, the study of hybrid system examined regarding different input variables using SAM software. By changing different input variables the performance of the hybrid system and its components are scrutinized and analyzed with respect to energy, economic and environmental parameters and then proposed the optimal values of that parameters. The proposed hybrid system on SAM software in specific circumstances (in Pakistan) is not studied before although solar PV and fuel cell are seperatly studied in Pakistan. Most of the input variables that are used for this study are also new and does not use in the previous literature. Energy, economic and environmental (3E) analysis of PV-fuel Cell hybrid system with a power rating of 800kW is considered in the present study. Variables that are put under consideration for economic analysis are:

- Levelized Cost of Electricity (LCOE)
- Net Present Value (NPV)
- Payback period

Some other variables are:

- Capacity Factor
- Energy yield

Firstly, electrical load is calculated. Then the system is designed, and the study of the hybrid system is examined regarding different input variables using SAM software. By changing different input variables, the performance of the hybrid system and its components are analyzed for financial and environmental parameters, then the best values of those parameters are proposed.

4.1. Energy analysis

In the proposed study PV and Fuel Cell hybrid system is designed to meet the electrical energy requirements with peak of 700 kW across residential society in Lahore. To evaluate and rank the potential of renewable energy in the chosen city, the load profile was assumed to be constant. The System Advisor Model was used to pull Lahore's weather information (solar radiation). Fig 4.1 shows the heat graph of Annual AC energy per year. Fig4.1b shows that fuel cells are being used as primary system for electricity generation because FC produces energy if fuel is being given to the system. PV system is used as secondary source of electricity. PV system is working at almost 96% efficiency while fuel cell gives minimum 62% of nameplate.

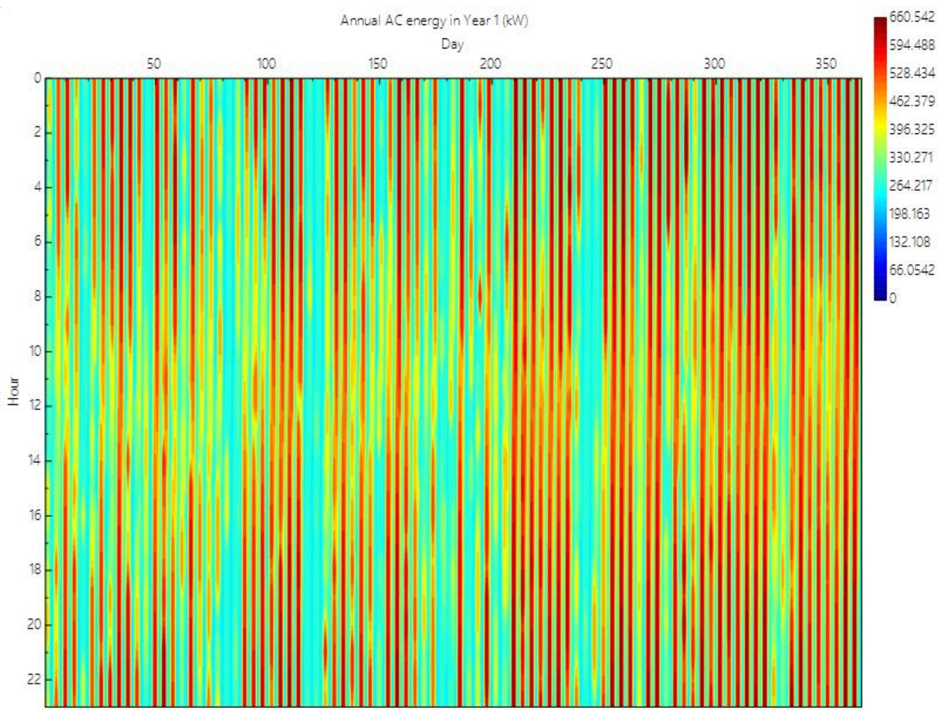

Figure 4.1 Annual energy per year

4.2. Technical Analysis

Technical analysis has been done by using SAM. Capacity factor and energy yield are the two variables that were particularly considered for the technical analysis. By changing Inflation Rate. Capacity factor and energy yield have been evaluated, and results showed that the inflation rate does not affect technical parameters. Capacity and energy yield are non-correlated to this factor; therefore, no relation is established. Fig. 4.2 and Fig. 4.3 interpret capacity factor and energy yield behavior, respectively. By changing the inflation rate, the value of the capacity factor and energy yield are identical because the power system was working on its natural capacity usage rate. Unquestionably, the capacity factor and energy yield remain constant by increasing the inflation rate, because, these two factors are independent of inflation rate.

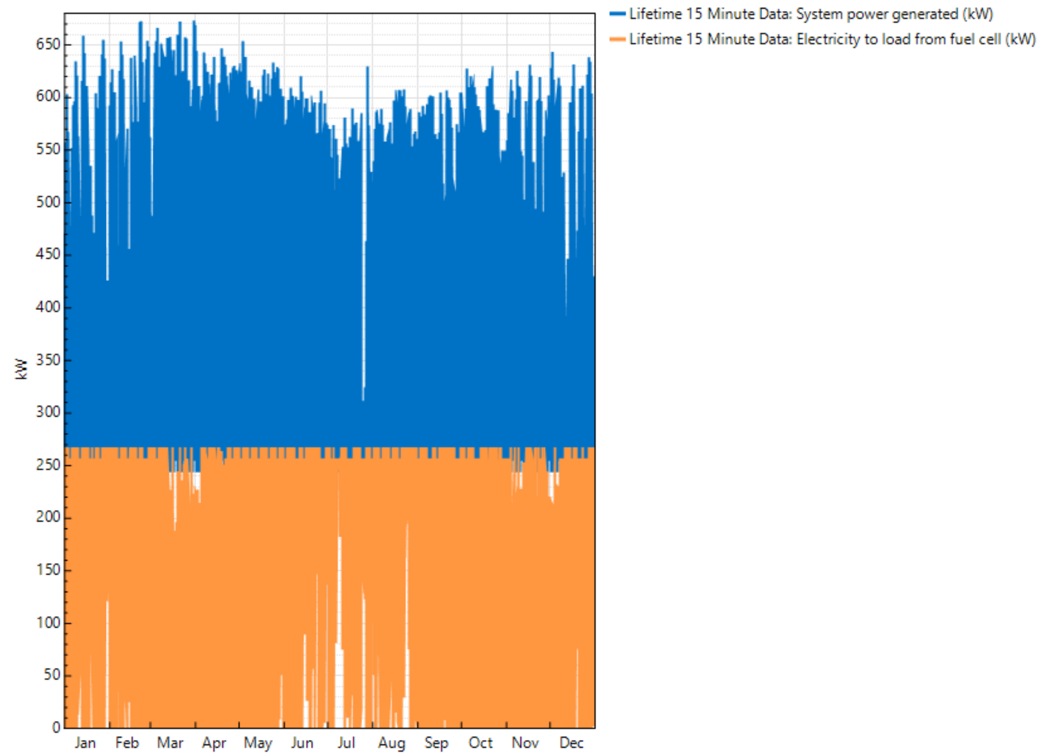

Figure 4.2 System Power Generated

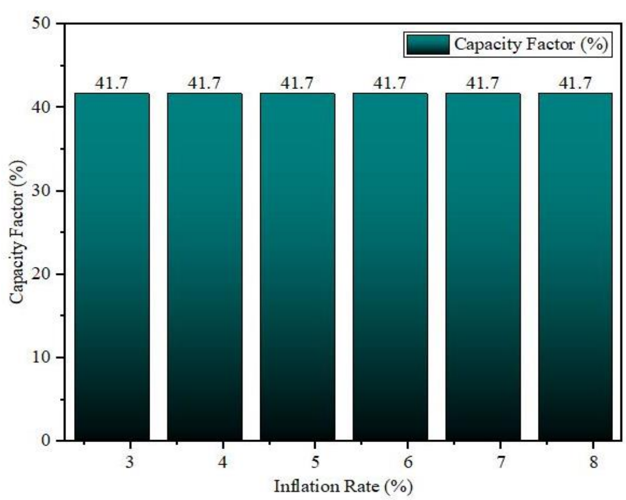

Figure 4.3 Relation between inflation rate and capacity factor

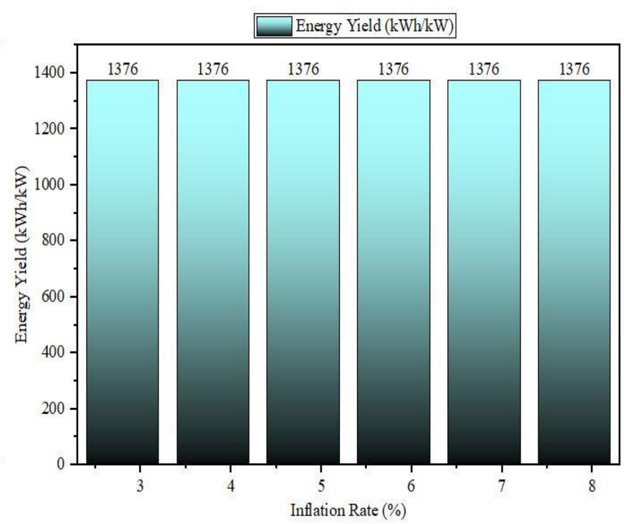

Figure 4.4 Relation between inflation rate and energy yield

4.3. Economic Analysis

Economic analysis of the proposed system was conducted by putting the three main parameters under consideration, i.e., Levelized Cost of Electricity (LCOE), Net Present Values (NPV) and Payback Period, because of their importance in checking the feasibility of the project in economic perspective. Herein, by changing different input variables the affect of these variables are examined on the technical and financial parameters by using SAM software. In the present study, most of the presented parameters are new and do not examined in the previous research for the study of PV-Fuel cell hybrid system like Net present value (NPV), Simple payback period and capacity factor. These parameters of present study make this research most important in the scenario of Pakistan and give the better proposed system to the energy sector of the country. The performance of hybrid PV-Fuel cell system is checked in different circumstances and then proposed the optimized hybrid energy system, which is efficient in energy and economical prospective and better than the PV-battery storage system in terms of technical and financial parameters.

NPV is more important in terms of the feasibility of any project. The positive value of NPV shows that the system is viable, the negative value shows that the project cannot be possibly installed, while zero NPV shows that the project is not a loss or profit. All the chosen variables affect the NPV of the project. Fig. 4.4 shows the NPV and payback period trend by varying inflation rate, type of fuel cell, tracking technology and fuel cell dispatch rate option. The simple payback time is decreasing by increasing the inflation rate. Simple payback measures the time in which initial investment recovers. By achieving a break-even point, the profitability of the project starts. Increasing the inflation rate increases the NPV of the hybrid energy system. As the inflation rate increases, the value of cash inflows increases. NPV is directly related to the cash inflows, so the value of NPV also increases. By increasing cash inflows, the energy project recovers its initial investment very early and achieves its payback in a short time.

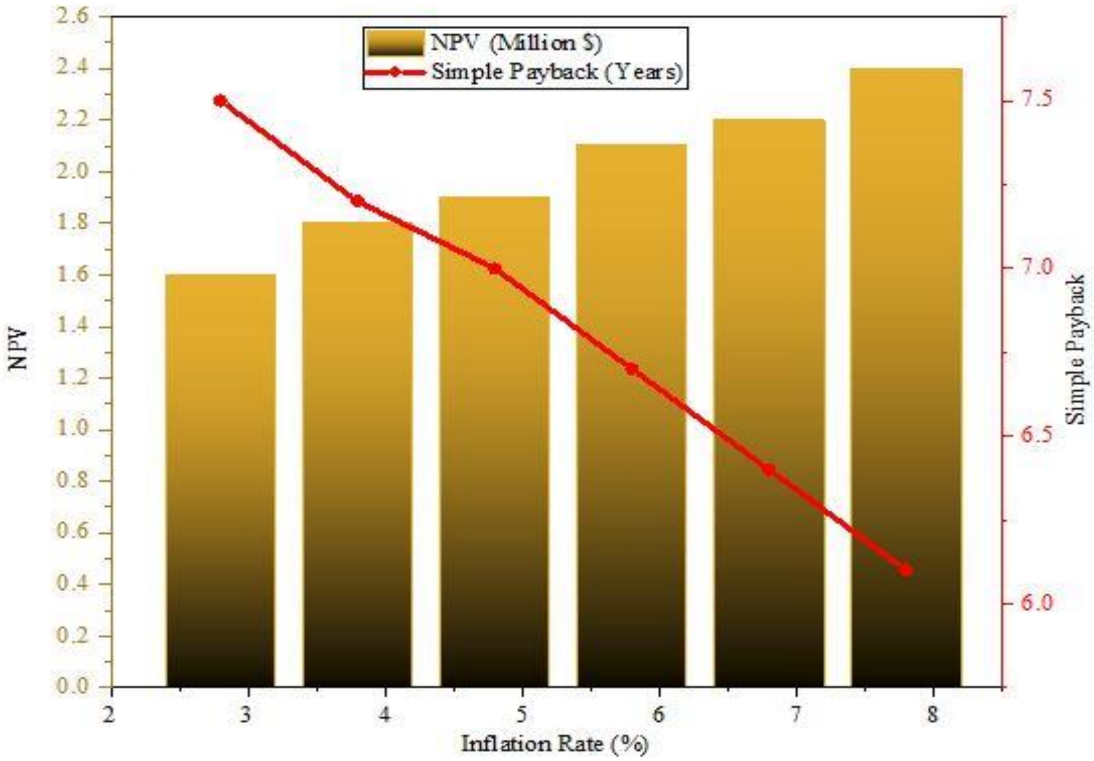

Figure 4.5 Relation of inflation rate with NPV and Simple payback period

As NPV shows the practical feasibility of any project over a specific period, it should be positive to start a project. NPV of the current study is $1.86 Million, which makes the project viable. The net present value of the project, which comes in at $1.86 million, and its original cost, which comes in at $3.02 million, both point to the fact that the project has potential from a financial point of view. Even if the initial expenditure is somewhat large, the fact that the NPV is positive suggests that it is anticipated that the project will create cash flows that will justify this expense over the course of its operating life. However, in order to verify that the project's financial viability is strong in a variety of different scenarios and market conditions, it is vital to conduct a full study, which should include sensitivity analysis and evaluation of other financial indicators.

LCOE is the relative measure of the cost of energy. LCOE seems to increase or decrease by changing the inflation rate, fuel cell type, tracking technology and fuel cell dispatch, as shown in Fig. 4.5 which shows the trend of LCOE with respect to selected input variables. The optimum fuel cell type with reference to LCOE is the solid oxide fuel cell because of its heat recovery percentage. By increasing the inflation rate, LCOE decreases for this study because the return ($)

of the system increased, which has reduced the system's operating cost and increased the cash inflows. But inflation rate could not be increased from its standard limit because it can disturb the economical parameters of the energy system.

The LCOE for the current study is determined as 7.36 C/kWh; converting into dollars becomes 0.073 $/kWh. This value makes the system feasible because when comparing the LCOE of this project with previous studies conducted at the national and international levels, results showed that 7.36 C/kWh is viable. The PV/hydro/DG system is studied by [1], Gilgit Baltistan region and seen that LCOE of the project ranges from 0.0582-0.172 $/kWh. In this same study, another PV/hydro/battery system has an estimated LCOE of 0.059-0.185 $/kWh. Another study on hybrid systems was conducted in the DI khan region of Pakistan by [1], combination used for the hybrid system consists of PV-DG-battery. Findings of this research showed that if system is grid-connected, then LCOE would be -(0.072$/kWh and 0.078$/kWh) and for a stand-alone system, the LCOE will increase from (0.145$/kWh to 0.167$/kWh) [1]. Table 4.1 has few hybrid systems (previously studied) with their LCOE.

The battery system's components cost is higher than the fuel cell, which plays an important role in the determination of LCOE. As the power generation of a battery-based system over time is also low, LCOE for a battery-based system is high [2]. LCOE of the current study is lower than other studies conducted at the national level because all the combinations formed in the literature are very complex and costly. Herein, natural gas is used as fuel for the fuel cell. Natural gas has low cost and less emissions, making the PV-Fuel cell hybrid system more economically viable.

Studies conducted on PV-Fuel Cell at the international level also have LCOE higher than the current study's LCOE. A study conducted by [2] on a PV-Battery and PV-Fuel Cell hybrid has capacity of 42.5kW with the LCOE of 0.16$/kWh and 0.11$/kWh. [4] also researched the PV-Fuel cell hybrid system with a capacity of 160 kWh, and findings show that the project has LCOE of 0.222 $/kWh. Another study on the PV-FC hybrid is conducted by [5] and the system has an LCOE of 0.22$/kWh. The proposed project's LCOE is lesser than the previous literature because of complex combinations (Battery, Diesel Generator) and fuel opted for the fuel cell.

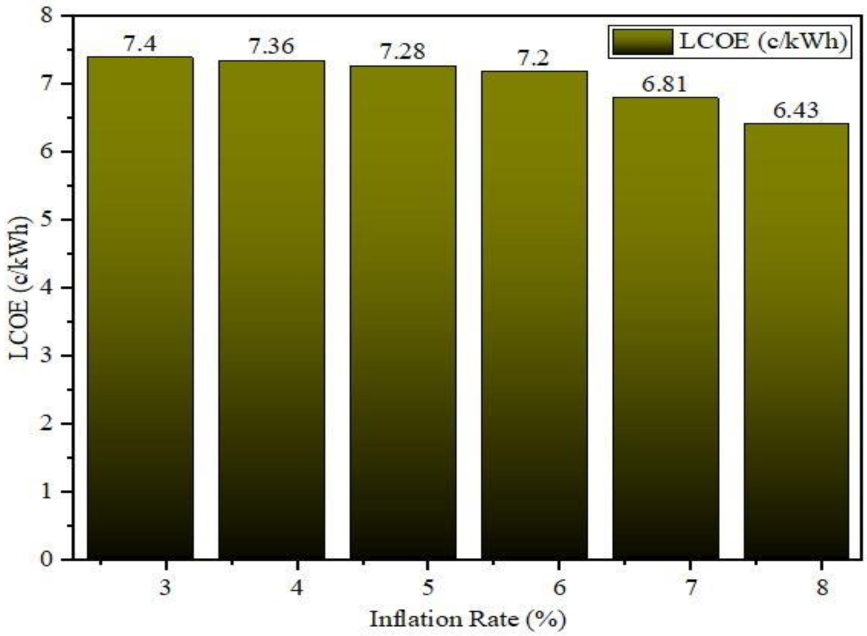

Figure 4.6 Relation between inflation rate and LCOE

Table 4.1 Hybrid system with LCOE.

Hybrid system	LCOE	References
PV/hydro/DG	0.0582-0.172 $/kWh	[1]
PV/hydro/battery	0.059-0.185 $/kWh	[1]
PV-DG-battery (on-grid)	0.072$/kWh-0.078$/kWh	[3]
PV-Fuel hybrid	0.222 $/kWh	[4]
PV-FC hybrid	0.22$/kWh	[5]
PV-DG-battery (off-grid)	0.145$/kWh-0.167$/kWh	[3]
PV-Fuel Cell	0.11$/kWh	[2]
PV-FC hybrid system	0.0728$/kWh	Proposed Study

The hybrid system studied in the current study has LCOE less or almost equal to previous studies mentioned above because the system is efficient using SAM of 800 kW total capacity in Pakistan. If a system with increased or decreased capacity is installed, LCOE will also be increased or decreased accordingly, but there will be a huge difference in the capital cost seen in Fig. 4.6 and 4.7. By rising the system's total capacity, the net present value (NPV) increased because by generating more power, cash inflow increased, which tends to increase the NPV of the system. But the capital cost is higher due to the addition of more components, which makes the hybrid system costly, expensive, and less economical. By decreasing the total capacity of the hybrid system from the optimized value, the NPV of the system decreases because the system produces less power. Due to that, cash inflows cut which tends to decrease the NPV. Although LCOE and capital costs are low, , system with low total capacity couldn't meet the load demand for the selected site. NPV and LCOE of this proposed project prove that the PV-FC hybrid is an economically feasible and better solution for energy generation. The country's current scenario suggests that energy generation is required for the un-electrifying areas of Pakistan, making it an energy-secure country. Suppose market analysts (Al-Khori et al., 2021) paper mention that fuel cell prices will drop soon because of material improvements, bulk production and new regulations. So, in the future, the proposed system will not only generate electricity without harmful emissions but will also provide electricity at minimal rates.

4.4. Significance of Hybrid System

Fig. 4.8 shows that the capital cost of the PV-Battery system is low due to less equipment costs. The cost of PV modules and battery components of PV-Battery system is low compared to the cost of fuel cell alone and PV-Fuel cell hybrid system. The operational cost, maintenance cost, lifetime cost and replacement cost of the PV-Battery system are higher. The lifetime of the battery bank is short, and replacement of the battery is required after every fixed interval. During the analysis of 25 years, the battery bank is replaced approximately every five years. Due to sulfation and stratification, the operation and maintenance cost of the PV-Battery system has increased, and with the passage of time, the power generation of the battery base system is also low. For all those reasons, the LCOE of PV-Battery systems is higher than Fuel cell alone and PV-Fuel cell hybrid systems. The high LCOE of PV-Battery system compared to PV-Fuel cell is also reported in previous studies i.e. [2].

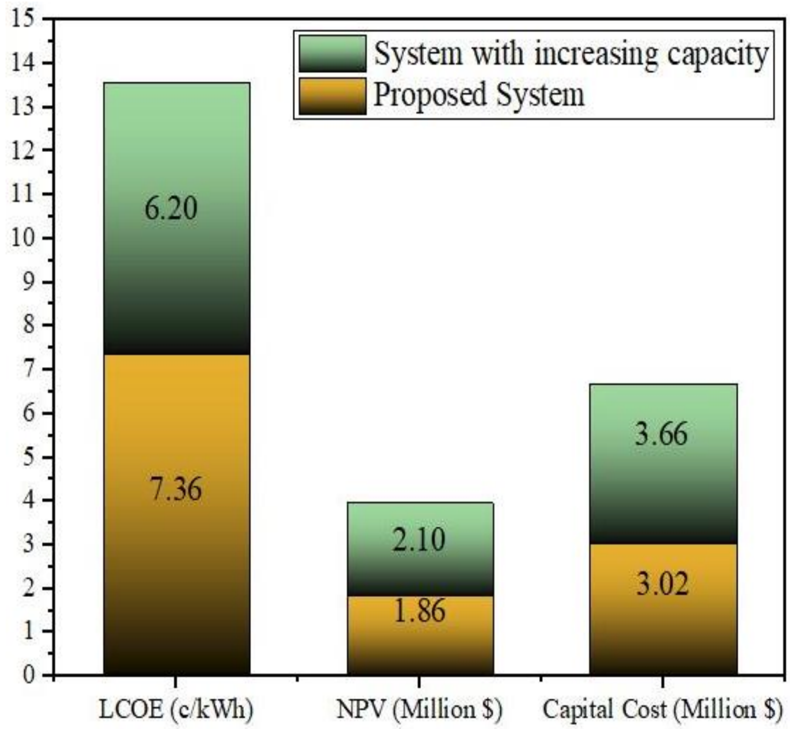

Figure 4.7 : By increasing the system capacity.

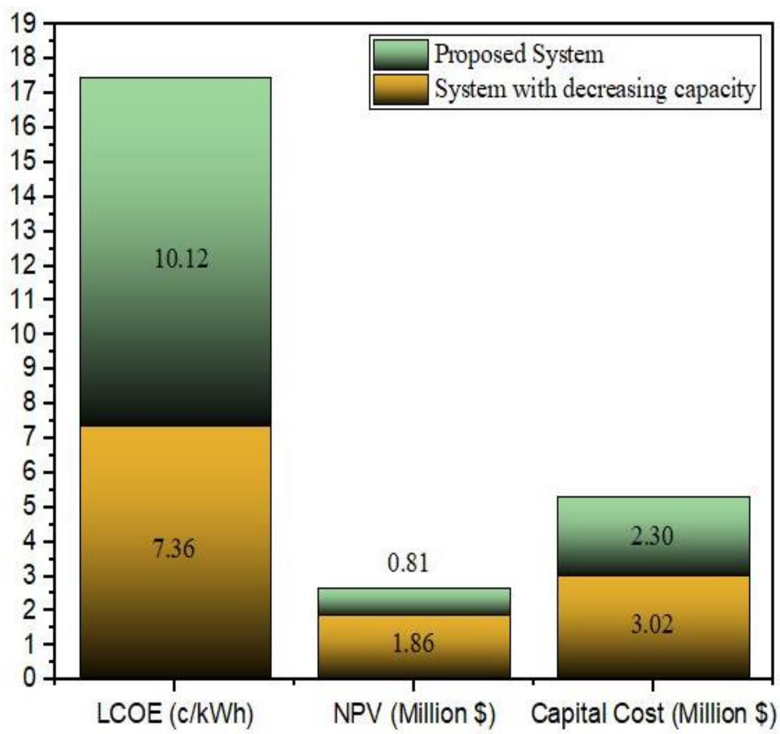

Figure 4.8 : By decreasing the system capacity

The operation and maintenance cost of the fuel cell is lower, and no fuel cell replacement is required like a battery due to the low LCOE of the PV-Fuel cell system. The LCOE of a fuel cell-alone system is higher than a PV-Fuel cell hybrid system because the cost of producing electricity on a large scale by a fuel cell system alone is less economical.

The system with greater NPV is the more economically reliable and profitable project. If two or more alternatives are present for the decision of project feasibility, then select the alternative with numerically higher NPV [6]. Herein, the PV-Fuel cell hybrid system has a greater value of NPV than the PV-Battery system. PV-Fuel cell system is economically more feasible and profitable. The return ($) of the PV-Fuel cell system is higher, which tends to increase the cash inflows. That is the reason the value of NPV for PV-Fuel cell hybrid system is greater. Although the NPV of Fuel cell alone system is greater, its capital cost is much higher than PV-Battery and PV-Fuel cell systems. So, it's an expensive option to choose, which is economically not viable.

During dark times, the PV system would shut down the power supply to the load. During this time battery bank used its already saved energy. When the battery bank reaches its depth of discharge, the load will face a blackout. Although fuel cell provides a continuous supply of energy, their capital cost is very high, and the difference between LCOE and hybrid system is moderate. Admittedly, that is the biggest drawback of the PV-Battery system. To resolve this problem in the present study, fuel cell is used with PV for the continuous energy supply.

4.5. Environmental Analysis

Environmental assessment has also been done for the proposed system. As suggested by [7] that PV-Fuel cell hybrid produce zero carbon dioxide emissions. The proposed system also produces zero carbon dioxide emissions. Environmental analysis of the proposed system is based on how much CO2 has been saved by the hybrid system on yearly basis. PV and Fuel cell don't emit any GHG [8] by fuel cell produce heat as a by-product [9]. Around 12kWt heat is being produced by the system every 15 minutes as seen in fig. 4.10 around 2kg Coal or 0.3 galloons of crude oil is used to produce this much heat generation. If this produces heat will be used for purposefully then around 70080kg coal and 1,925,000 kg CO2 emissions can be saved on yearly basis by this hybrid system. Fig 4.10 shows fuel savings, if the produced heat will be used instead of using other fuels for generating heat.

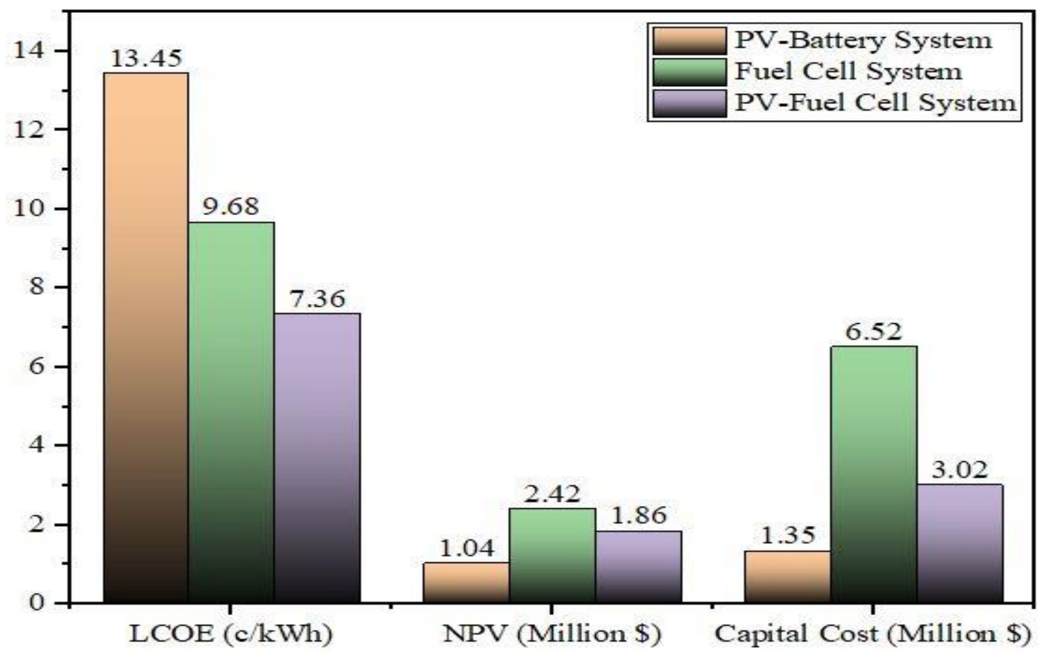

Figure 4.9 : Stand-alone Systems vs. Hybrid System.

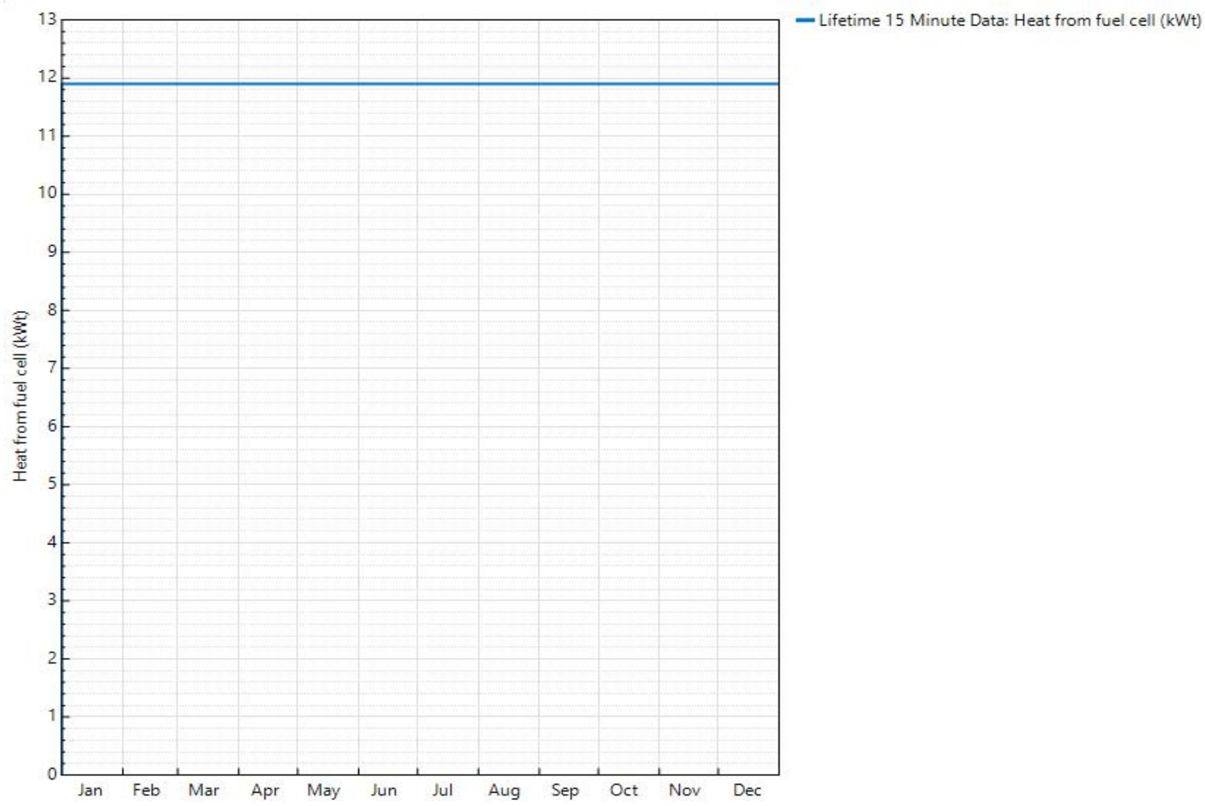

Figure 4.10 : Heat from fuel cell

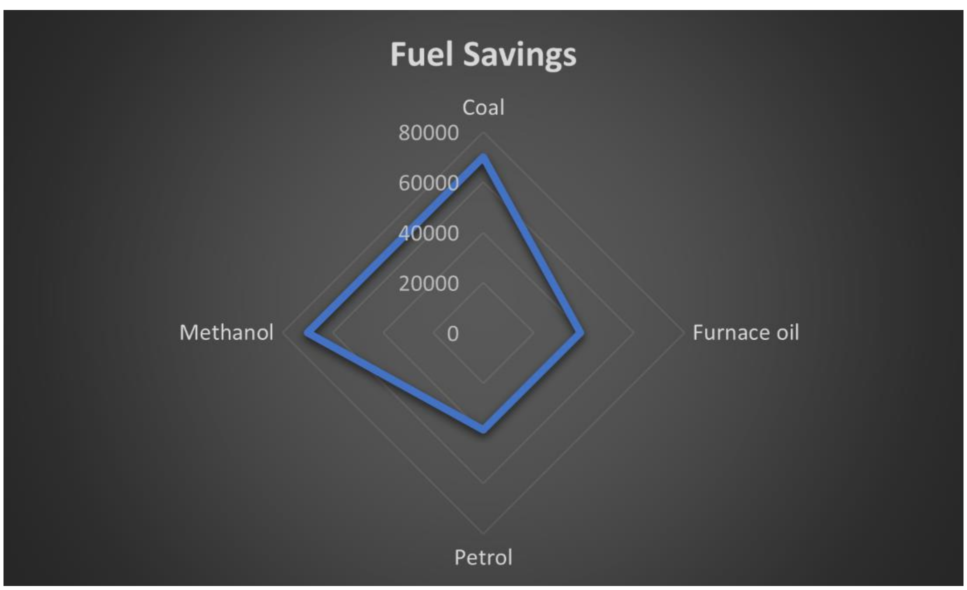

Figure 4.11 : Fuel Savings to produce 12kWt Heat

Carbon dioxide emissions potential is also calculated in environmental analysis of the proposed system. Environmental impacts triggered by coal-based power plants and proposed projects have been compared. According to a 2019 study (Mallapragada et al., 2018), coal-based plants emit around 1.236 kg CO_2 per kWh, and a 2014 study (Mittal et al., 2014) suggested that the CO_2 emission range of coal-based power plants ranges from 0.91-0.95 kg CO_2 per kWh. In the study of [10], 1.18 kg CO_2/kWh was estimated. As a reference by [11], it is assumed that coal-based plants emit almost 1.18kg CO_2 per kWh. The emission rate of the proposed hybrid system for carbon dioxide emission is 0.307 kg/KWh, which is calculated using the emission factor values for grid consumption and natural gas. The emission factor for grid consumption and natural gas is 0.573 kg/kWh and 0.207 kg/kWh, respectively [12], which is quite lower than coal-based plants. The value of CO_2 emission potential (α_{CO_2}(potential)) is calculated by using the CO_2 emission from a coal power plant and CO_2 emission of the proposed system from equation (5) and environmental benefits from equation (6). The calculated CO_2 emission potential for this study is 0.853 Kg/kWh. In the proposed hybrid system, the fuel that is used for a fuel cell is natural gas. The CO_2 emission of natural gas is much lower than other conventional resources. Consequently, fuel cells hold momentous importance than other storage systems to form a hybrid with Solar PV. Therefore, the emission of the PV-Fuel cell hybrid system is lesser than a coal-based power plant. This hybrid system is most significant in improving the country's environmental conditions.

4.5.1. Climate Change Mitigation

Reducing Greenhouse Gas Emissions to Help Mitigate Climate Change PV-fuel cell hybrid systems have the potential to help mitigate climate change by reducing emissions of greenhouse gases. PV systems generate power without directly producing any emissions because they use semiconductor materials to convert sunlight into electricity. On the other hand, fuel cells generate electricity while emitting just trace amounts of pollution since they run on hydrogen that was created using renewable energy. PV-fuel cell hybrid systems are beneficial because they assist reduce reliance on fossil fuels and overall carbon emissions. These benefits are achieved with renewable energy sources.

The above explanation proves that:

- The proposed system is environmentally friendly.
- The proposed system is contributing to achieving the 7th sustainable development goal.
- The proposed system produces green and clean energy as it has less emission during its power production than other conventional power production units.
- The proposed system will be helpful in saving carbon dioxide up to 1927200 kg/year.

Summary

Energy efficiency analysis of the solar PV and fuel cell hybrid system is covered in this chapter. The simulation results assess the energy conversion efficiency of individual components and the hybrid system. The chapter addresses system performance under different operating situations and energy efficiency improvements. The Pakistani solar PV and fuel cell hybrid system's economic viability is examined. The research shows hybrid system setup, operational, and revenue costs. A cost-benefit analysis evaluates the technology's financial viability and appeal, taking into account economic variables, government incentives, and financing possibilities. This chapter also analyzes the environmental impact of hybrid energy system adoption. It measures the environmental benefits of renewable energy integration, including greenhouse gas emissions and carbon footprint reduction. The chapter also examines hybrid system component manufacture, operation, and disposal environmental implications. It promotes sustainable methods and strategies to boost the system's environmental impact. The energy, economic, and environmental evaluations of Pakistan's solar PV and fuel cell hybrid system are summarized in the concluding chapter. The research findings and their impact on Pakistan's energy sector are discussed. The chapter advises policymakers, energy planners, and stakeholders to adopt and integrate renewable energy technology for a sustainable and resilient energy future in Pakistan.

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Chapter 5 Conclusions and Recommendations

The current study explored the potential of PV-Fuel Cell for the first time in Pakistan. This paper demonstrates a cleaner and more efficient energy production solution by integrating a PV system with a fuel cell. Electric load data is collected according to the nature of appliances used by the consumers and processed using MATLAB to find the electrical load demand. Benefits of system i.e. continuous availability, cost-effectiveness, enhanced reliability and high efficiency, the system can contribute to Sustainable Development Goal 7 and the global movement of clean and green energy. The levelized cost of PV-Fuel Cell system electricity is 7.36 C/kWh (0.0736 $/kWh), which is less than the tariff rate of IESCO i.e. 0.078$/kWh for off-peak hours and 0.11$/kWh for on-peak hours [66]. Furthermore, the positive NPV of PV-Fuel cell is $1.86 million, which makes this system practically viable. Noteworthy outcomes of the present research are concise as follows:

- Overall, hybrid system availability makes this system the best solution for removing the energy supply-demand gap.
- The grid-connected hybrid system makes this system more authentic as if the system got any technical issue, and the grid will meet the load.
- The calculated CO_2 emission potential for the present study is 0.853 kg/kWh. While the CO_2 emissions savings in the proposed study is 1.9 million kg per year.

As this is the first PV-Fuel cell system study conducted in Pakistan. Further study is required for more understanding of this hybrid system. Pakistan is facing a huge energy supply-demand gap, and some areas i.e. Rakhni, Baluchistan of Pakistan, have access to electricity for only 3-4 hours/day. Practical and further studies will be helpful in the complete eradication of the supply-demand gap in Pakistan. Some other recommendations are as follows:

- A study should be conducted on different fuel cell types, hybrid with a PV system.
- A study should be conducted on those areas of Pakistan whose weather files are not available in software by calculating real-time data.
- A comparative study on PV-Fuel hybrid and other hybrid systems should be conducted.

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Appendix 1 – publications

Energy, economic and environmental (3E) analyses of Solar Photovoltaic and Fuel Cell based hybrid energy system in Pakistan

Maham Fazal[a], Mustafa Anwar[a], Abdul Kashif Janjua[a]

Abstract

The present study aims to check the feasibility of the PV-Fuel cell hybrid system in Pakistan (Developing Country). Previous studies on Hybrid systems (unreliability, environmentally unfriendly) have convinced the researchers to look for a better, reliable, efficient, and environmentally friendly combination with PV and fuel cell, because it possesses required properties. Additionally, energy, economic and environmental (3E) system analysis has been done to check economic and environmental feasibility. The evaluation tool used in the present study is System Advisor Model (SAM), while matrix laboratory (MATLAB) is used for energy load design. The environmental analysis via expressed equations is based on system consumptions and emissions. The upshots show that from an energy, economic and environmental perspective, the PV-fuel cell system is a step towards contributing to the Sustainable Development Goal 7. The PV-FC system exhibits the levelized cost of electricity as 7.36 (C/kWh), which is 0.073$/kWh, while the net present value of the system is $1.86 million. Systems' LCOE is less than the tariff rate of Pakistan i.e., according to IESCO (Islamabad Electric Supply Company), 0.078$/kWh for off-peak hours and 0.11$/kWh for on-peak hours. Environmental analysis showed that 1,927,200 kg/year of carbon dioxide emissions are being reduced due to Hybrid system. Results shows that PV-FC hybrid power production is cost-effective and environmentally beneficial. The research findings are imperative for stakeholders, policymakers, and investors to uphold low-carbon technologies.

Keywords: Solar PV; Fuel Cell; Hybrid Energy System; Feasibility Study

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