Integration of Fuel Cell with Renewable Energy Resources in a Microgrid Setup for an Off-Grid Community

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Supervisor: Dr. Majid Ali

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Nomenclature

BESS	Battery Energy Storage System
COE	Cost of Energy
CHP	Combined Heat and Power
FC	Fuel Cell
HRES	Hybrid Renewable Energy Sources
LCOE	Levelized Cost of energy
RER	Renewable Energy Resources
MGs	Microgrids
MPPT	Maximum Power Point Tracking
NPC	Net Present Cost
O&M	Operation and Maintenance
PMSG	Permanent Magnet Synchronous Generator
PV	Photovoltaic
P	Active Power
Q	Reactive Power
RES	Renewable Energy Sources
SMG	Smart Microgrid
SOC	State of Charge
SOFC	Solid-Oxide Fuel Cell
T&D	Transmission and Distribution

WT	Wind Turbine

Symbols

A	Area (m^2)
β	Wind blade pitch angle
E	East directions
F	Faraday’s Constant
∑	Total Summation
ὴ	Efficiency
λ	aerodynamic behavior of WT
P	Power
ρ	Air density
P_m	Mechanical power
R	Universal gas constant
T	Temperature

ABSTRACT

As the renewable energy is an increasing part of energy mix of many countries. Energy production accounts for a large portion of greenhouse gas emissions that contribute to climate change. Currently, energy production in many parts of the world still relies on fossil fuels. In order to prevent global warming, energy must shift from existing conventional sources to the Non-conventional sources. Renewable energy systems are safe, environmentally friendly and can meet our energy needs. The hybrid renewable energy situation demonstrates that various combinations of Non-conventional sources of energy could utilize simultaneously, providing energy in the form of grids supporting transport battery storage as backup systems. In this paper, the site location of Nooriabad was selected, and the average seasonal load demand, which is approximately (100-300) kW per month, was calculated. The technical and economic analysis was conducted using MATLAB/SIMULINK and Homer Pro software. This wind and solar modules, a fuel cell, BESS, a hydrogen tank, an electrolyzer, and an inverter based Microgrid system has 187 MWh power production in summer, and the total annual unmet load is 1945 kWh/yr. The presented system’s Total Net Present Cost and LCOE is approximately $2.9 million and $0.1518/kWh, respectively. Its Present Worth is $6,580, and its Annual worth saving is $253. Wind and Solar power considered as the main direct energy sources for transporting and charging the battery bank when there is a large number of generations. To evaluate the benefits of hybrid power plants, we analyze many important factors such as the combination of energy sources of the two technologies that make up hybrid power generation sysrems, the increase in electricity production due to limited capacity and the increase in energy consumption. During the design process of this electrical installation, simulations and optimizations were carried out based on electrical loads, weather data, electrical economics of electrical devices and other disadvantages that NPC had to consider to reduce options.

Keywords: Net Present Cost, Levelized Cost of Energy, Microgrid, Renewable Energy Resources, Battery Storage System.

CHAPTER 1 : INTRODUCTION

In the following chapter, major key points are related to production of electrification by various ways, use of energy resources in different forms is discussed. The problem statement and objective of research work is highlighted. Moreover, the challenges and advantages of usage of non-conventional resources in developing countries is discussed.

1.1 Background

It is estimated that the electricity installation capability of world may be doubled to obtain the needs of developing countries related to energy in next 40 years. According to the IEA report, more than 1.3 billion people in remote areas do not have access to public electricity due to different restrictions. More than 80% of people residing in isolated sites of emerging countries like Pakistan still rely on the usage of fire and wood to satisfy their daily electrical demands [1]. Therefore, rural electrification is the most compromising and challenging for any country to stabilize the consumption and demand of energy in these areas. Rural electrification is the topmost priority of many countries because it helps in the economic development of a country. There should be proper planning and optimization in load density, relative closed to the main grid, the accessibility of alternative energy supplies, and socioeconomic aspects that must be taken into consideration by any developing country [2].

Pakistan is a developing country and 85% of its energy imports of its consumed. It is accounted that around a worth of $14.4 billion cost of energy is imported by Pakistan as compared to a cost of $10.9 billion in the previous years. During April-July 2022, it is estimated that Pakistan’s total electricity generation capacity shift from 37261 MW increased by 11.5% and it reached 41,557 MW during the same period [3]. In the past, Pakistan is vulnerable in terms of issues like rising electricity demand, technological destitution, limited indigenous fuel reserves and climate change vulnerabilities. In addition, during the month of summer, most of those remote areas that have accessibility to grid experience the average power shortages for up to 18 hours per day. Stand-alone or islanded generation systems through indigenous resources could be helpful to alleviate electricity shortage, provide electricity to isolated sites, especially to those areas that are far away from national grid. These power shortages could cause huge damage to the economy of Pakistan and cause binding restrictions on the growth of national economy [4]. As power crisis is increasing and to overcome this issue, the usage of non-conventional energy in the power mix of country percentage also increased. Nowadays there are more encouragement facing by world to pursue the utilization of non-conventional energy resources especially those regions who have a huge potential of utilizing these resources mainly in remote areas [5]. But the rural electrification is not too easy to adopt because of many causes in terms of access, load density, revenue generation, low population density and adverse weather conditions. So the adjustments are required to tackle these demanding situations of adoption of renewable electricity in rural areas [6]. It is able to be achieved with the aid of getting access to the success and disasters of previous electrification projects in phrases of the technique in their implementation, renovation, development, and expansion, to degree the technical, financial, social, environmental and coverage-related alternatives for electrification projects [7].

Many new tendencies are emerging in Pakistan in renewable energy consumption zone, which can be also having an impact on its development and growth. Numerous new tendencies consist of specifically massive- scale renewable energy projects related to wind and solar farms, getting extra famous in Pakistan. After all, these initiatives, with capacities of ranges from ten's towards masses of megawatts are boosting the nation's potential for renewable power. One trend is extensively rising in Pakistan is integrating of renewable electricity sources into the present grid structure. Demand reaction structures, smart meters, and sophisticated manipulate systems with other grid and with-out grid integration technologies, justify effective control of non-conventional sources intake and deliver. Smart grid era helps the mixing of renewable strength assets, will increase grid protection, permits -manner communication and affords power performance. These new requirements show that renewable electricity area in Pakistan is developing. These parameters describe that the country's evolution is focusing on environmentally friendly energy options, technological development, and the transition to strong, green energy economy as shown in **Figure 1.1**. Adopting and supporting the development of these models can help Pakistan achieve its renewable energy goals and help the world combat climate change [8].

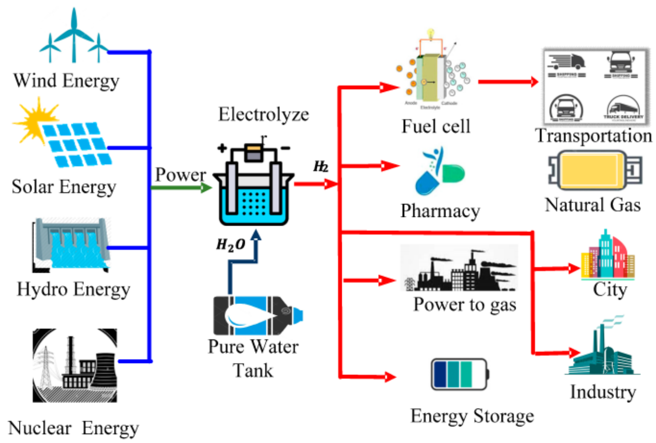

Figure 1.1: Non-conventional sources of energy [9]**.**

1.2 Problem Description

Pakistan offers top notch ability for the improvement of renewable power, but there are many barriers to overcome a good way to preclude this. The largest problem of Pakistan's renewable energy initiatives is the shortage of enough financing. The construction of the venture is hampered through the shortage of lengthy-time period loans, greater interests and need for collateral. Home participation with overseas buyers is restrained because of the lack of economic instruments and private automobile resources for renewable power production. Integrating renewable power can be tough if powered grid has capability of transmission and insufficient infrastructure. Effective integration of renewable strength with grid could be laid low with unstable strains and connections. The grid needs to be up to date and increased to house the ever-increasing use of renewable strength. Fixing these issues requires cooperation from policymakers, regulators, buyers and different stakeholders. to overcome these challenges and noted overall ability of non-conventional sources strength in Pakistan, studies with improvement must endorsed, security policies should be improved, implementation financing should be improved, the panel should be strong and knowledge should be increased [10].

A country like Pakistan faces worst energy crisis scenario as according to the recent survey, it has total electricity shortfall of 5000–7000 MW, that caused the 12 to 14-hours blackouts across the country and 67% of the country has access to electricity, which is 71% and 92% lower than South Asia and the East Asia [11]. The demand of electricity is rising day by day but this demand cannot be fulfilled by using the conventional resources of electricity production due to depletion of these resources day by day. Moreover, there is a lack of adequate planning and policies, political involvement, a lack of institutional ability, and rising economies and industries. Use-age of conventional sources such as Coal, Oil and Natural Gas etc. have greater impact on environment condition of a country, therefore a feasible solution for usage of renewable energy resources is needed [12]. The urban electrification rate is 92%, while rural electrification is 61% (the total electrification rate is 75%) [5]. About 46.3 million people as compared to 23% of the population, do not have an easy get entry to power in Pakistan and 108 million humans in comparison to 54% of world’s population lack safe and clean cooking environment in Pakistan. Pakistan has many feasible alternative power resources. However, the process is so sluggish in this way [13]. Urban electrification is more preferable in most parts of the world because of higher maintenance, capital and installation cost in rural areas due to transmission and distribution complexities. Excessive electricity is also big problem in most parts of the world in case of stand-alone system. Due to the long transmission, much effort is required to monitor electricity usage in space and compensate for the imbalance between generation and demand during peak times [14]. On average, many people are still use kerosene oil, wood and other sources for fulfilling their needs of energy consumption. There is the severe power shortages in Pakistan, with the average reported outages is for 2.5 per day for the total daily duration of 13.2 h on average. There is a lack of reliable electricity in Pakistan for more than 75% in terms of major constituent to its operation and growth [15].

As power generation investment in RER’s is a challenging case in a struggling country like Pakistan. There is a need to advance technology for increasing the role of usage of RER to assist the de-fossilization of economy. But, the current electrification system structure in a struggling country like Pakistan is not able to pursue the fundamental undertaking in development of a regulatory framework that actively helps the circulate in the direction of acceptable energy system [16]. In Pakistan's energy sector cost of production, generation and installation in terms of /kWh of the outdated power plants is significantly high. Fossil fuel consumption reached approx. 28.6 million tons of oil equivalent (MTOE) in 1990 as compared to 74 MTOE in present. According to recent survey, Pakistan energy production scenario indicates that electricity produced by using 41.2% by Natural Gas, Coal 6.9%, oil is 34.2%, Hydroelectricity 11.2 %, Renewable 4% Nuclear 1.5%, and others 1% as shown in **Figure 1.2**. But there is an increment in growth rate per year of usage renewable energy consumption which is almost 9.0% [17], [13], [18].

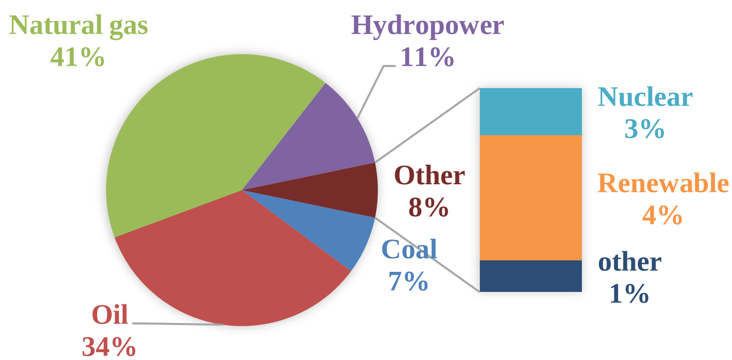

Figure 1.2: Pakistan's electricity production rate by various sources [17], [13], [18].

1.3 Potential of renewable sources in Pakistan

The potential of renewable sources of energy in Pakistan provides a ray of hope in achieving its energy security, environmental sustainability and socio-economic goals. By planning strategies, policies and partnerships, Pakistan can harness the power of renewable energy to create a better, cleaner and more sustainable energy future for its people. Pakistan has a vast potential to extract the clean and sustainable energy to achieve the national growing demand from renewable energy from many sources and handle energy security issues. Renewable resources such as wind, hydro, solar, geothermal and biomass have enormous potential in Pakistan [19].

1.3.1 PV energy potential

Due to its geographic location of Pakistan, it has significant high potential for solar energy as it is fortunately receiving a maximum of solar radiation, mainly in its western and southern regions. Both solar thermal systems and Solar (PV) are useful for cooling and heating system for generating electricity and can be able to make huge contributions to the mix of renewable resources. Now Pakistan has a few vast technological tendencies in renewable power include the manufacturing system, the efficiency of solar cells, and machine layout. As an end result, there is a sizable discount in solar panel expenses and strength results have multiplied. Because of those technological upgrades, Pakistan has faced the deployment of rooftop solar installations, off-grid projects powered by solar and utility-scale solar PV projects. Solar energy has become popular in recent years because it is available in different areas of the world that can be converted into heat and electricity. It is expected to finally replace coal by 2050. Therefore, solar energy may be best for the climate as it can deliver good results to meet the power needs of the future while creating jobs and increasing income for families, agriculture and small and medium-sized businesses. Green energy consumers tend to be ecologically conscious [20]. Pakistan has huge Solar Energy resource potential, especially in areas of Sindh and Baluchistan Provinces where the sun shines for about (7–8) hour/day or more about (2300–2700) hour/year [21] as shown in **Figure 1.3.** In Pakistan, a maximum yearly average of 2900GW of solar potential is estimated. In most of plain areas, where for more than 302 days per year sun shines with a maximum solar irradiance of around (1800–2200) kWh/m^2 at an annual average temperature, it would produce on average electricity of (5.5–6) kWh/m^2/day [22]. Meanwhile, first ever project of solar panels was established by Pakistan Engineering Council (PEC) in 2010 with capability of 178.08kW. Another project is the Solar Park (QSP) Bahawalpur, which has capability in the range of 1000 MW and is currently generating 400 MW**,** this shows that Pakistan has huge potential of producing power using Solar Energy [23].

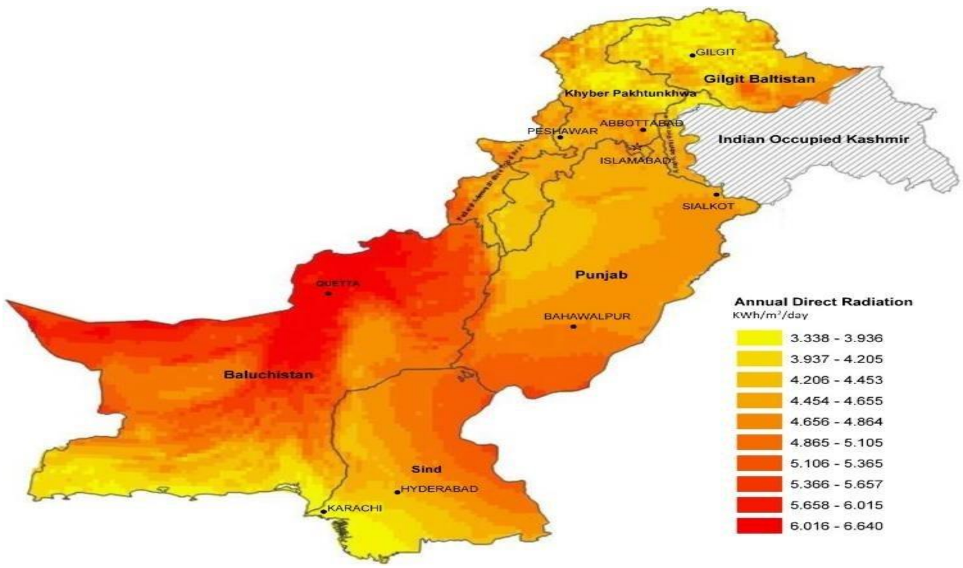

Figure 1.3: Solar irradiation in Pakistan [24]**.**

1.3.2 Wind energy potential

Pakistan's Sindh and Baluchistan provinces stretch for more than 1,000 miles along the Arabian Sea coast and have an excellent climate. Additionally, areas like Gharo, Kati Bandar and Jim Pir in Sindh and Gwadar in Baluchistan are known for their strong winds and consistent wind patterns. Wind speed on average in areas of land side can reach speeds of 6 to 7 (m/s) or higher, which is necessary for wind energy production. These regions experience constant storms, especially during certain seasons, and are therefore ideal for the installation of wind turbines. Many wind power plants are being built and put into operation, increasing the country's renewable energy potential. According to the latest data, Pakistan's installed power capacity exceeds 2,000 MW and many projects are under construction. These include grid integration issues, land acquisition issues and financial constraints. Overcoming these challenges and taking advantage of new opportunities such as renewable energy and external sources can further strengthen Pakistan's wind energy industry. Clean, sustainable and domestic energy sources would be helpful to obtain the energy needs of growing country, by reducing its dependence on fossil fuels. Continued investment, innovation and policy support are key to unlocking wind energy potential in Pakistan. Huge wind resources in Pakistan may be harnessed in coastal regions plus wide plain areas, making wind energy promising source of renewable energy [25]. Offshore and Onshore wind farms for renewable energy by harnessing its wind power may both greatly increase the capacity. At various locations of Pakistan, apprx.761 MW having 34% increasing rate of establishment of wind turbine has been evaluated which can be supplying electricity without delay to the country wide grid [26]. The provinces like Sindh and Baluchistan have the highest wind speed as in some of their regions the maximum power production can be attained in between (100- 500) MW [27]. Pakistan could produce around 320 GW power from Wind Energy Resources and has potential of wind energy of approximately 132 GW in total. The estimated production capacity of wind energy has reached 123 GW. In Sindh, the three regions Nooriabad, Jamshoro, and Thano Bulla Khan with their highest wind speeds at 10.6, 13.9, and 9.8 m/s, respectively, while their lowest wind speed were observed at 4.2, 5, and 2.7 m/s having annual production of approximately 4.2 MW [28]. Fauji Fertilizer Company Ltd. (FFC) first ever inaugurated wind power plant with an installed capacity of 50 MW in 2013 in Whimper, Sindh [23]. Moreover in a present study of a system, 14 MW of wind power plant is inaugurated in Gharo, Sindh [29] and many more projects are still in progress. The region of Pakistan with wind energy potential is illustrated in **Figure 1.4.**

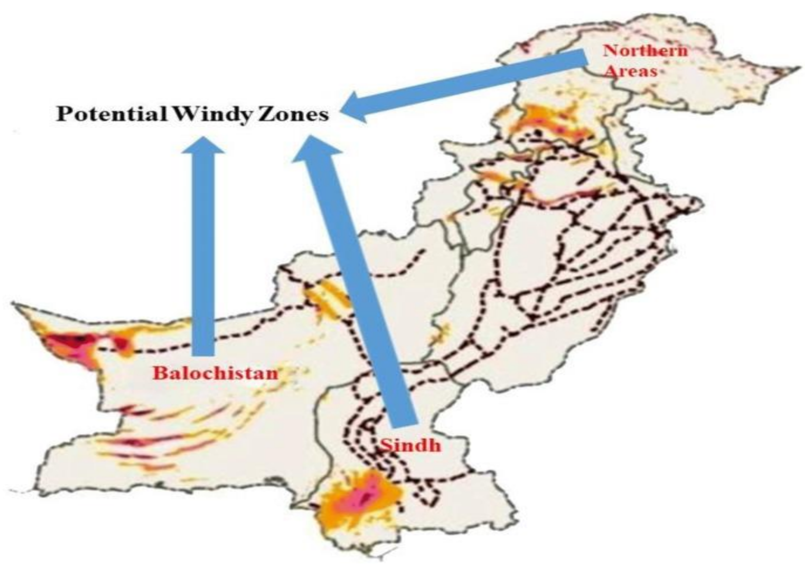

Figure 1.4: High wind speed potential areas in Pakistan [30].

1.4 Hydrogen as source of energy

Hydrogen is considered potential and attractive source of energy carrier that could help industries to eliminate global warming, in form of clean and green energy production, reduced cost in trade and transportation sector. A lot of people want to use low carbon emission based energy to produce hydrogen from the electrolysis process. Oddly, interaction of non-conventional sources of energy just like wind and solar makes energy production difficult to predict, making grids inconsistent. Therefore, hydrogen storage and production can provide a better solution by increasing flexibility of system. Hydrogen saved as a compressed fuel can be transformed into strength or used as food in manufacturing, home heating, and vehicle gasoline. Since, first internal combustion engine become powered by hydrogen and produced more than two hundred years ago, they have got come to be an essential a part of present day device and business automobile. Hydrogen is the best component for storing or transporting energy when produced from natural products. No gas has more energy per unit than hydrogen [31]. However, its volumetric energy content is lower due to its density at room temperature. Consequently, diverse production and storage technologies can be taken into consideration to gain extra power goals. In gasoline cells (FC), hydrogen also can be used to generate energy without developing pollution, especially if it's far made using renewable energy. The usage of hydrogen is useful, it can be useable in workplaces, public transportation and domestic heating. Hydrogen energy storage systems offer the opportunity to flexibly change and rework fixed energy systems, while also reducing overall energy costs, thanks to advances in integration and renewable energy [32]. Climate change, energy security and the health impacts of climate change are the drivers of the energy future.

1.5 Motivation

As a developing country like Pakistan has worst energy transition scenario. There would be a need to shift usage of energy resources from traditional to renewable resources. By monetizing and maintaining a paradigm of optimized usage of renewable energy resources, the emission problem can be controlled in a most suitable way. Pakistan has huge resources of renewable energy, so it should be utilized in a most efficient way to reduce the emissions and energy demand supply can also be reduced.

1.6 Objectives

This research work's objectives are summarized below,

- To develop a hybrid Microgrid model for energy resources.
- To integrate RER, BESS and Fuel Cell for off-grid community.
- Power of these energy resources is managed and supplied reliable power to the connected load in a hybrid MG.
- To evaluate the economic performance parameter for integrated hybrid Microgrid.

1.7 Thesis Organization

Thesis work is divided into 5 chapters. Chapter 1 presents the introduction of the research, problem definition, sustained energy, motivation and purpose. Chapter 2 is related to theoretical review. Section 3 presents the methodology of a whole proposed system. Section 4 includes the simulation, results, discussion, and financial analysis. Chapter 5 describes the research conducted.

CHAPTER 2 : LITERATURE REVIEW

In the following chapter, background of this work is highlighted. Microgrid set up for electrification for a small community is observed. The major new emerging trends, shifting towards renewable or clean energy with more beneficial future perspectives, problems related to electrifying rural areas are highlighted. The components used in a system is also described one by one. A brief introduction of Fuel cell in a Microgrid set up, its applications in power sector is discussed.

2.1 Rural Electrification

The electrification of rural areas may be defined in terms of provision of power up to areas with low demand and widely spread consumers. Power may be provided to such regions through small-scale self-technology, independent local networks, or significant regional or national grid. In this context, "rural electrification" commonly refers to significant grids due to the fact that most impact data are based on changes after the introduction of a relevant network. A distinction is made between the costs of auto-generation and the central grid, as they would vary. Additionally, the introduction of electricity to rural areas typically follows its use in urban areas and large towns. Therefore, investments in electricity generation and distribution are linked with future rural electrification, indicating that rural electrification is intertwined with electrification in general [33]. Electricity access in rural areas may lead to significant indirect impacts on economic progress, including its influence on social and public services, job creation, environmental enhancements, savings in foreign exchange, effects on migration, political stability, and the promotion of innovation and modernization. While these advantages may hold substantial significance in certain instances, alternative approaches may potentially prove more efficient in achieving these developmental objectives [34].

Infrastructure development in rural areas is often designed to empower local communities by providing them with access to resources and solving rural problems, thereby transforming rural areas as a whole and helping to achieve many societal goals and objectives. However, the lack of these activities has brought about serious economic problems for the local community, such as serious damage to health standards, low quality of life, increased health and education expenditures, slowing of growth economically and increment in unemployment rate. The main importance related to infrastructure projects in community life should be tailored to raise social development in isolated sites community development. The concept of sustainability has many characteristics when creating projects that strengthen a sustainable society in rural areas. One of the key points of economic-development is that infrastructure development in rural areas, such as the provision of transportation, promotes the growth of the regional economy. Public infrastructure can affect many social and situations related to economy, including GDP growth, quality of life, employment, quality of education, poverty, and health. [35].

In History, electrification was a major issue in most of the world. Efforts have been made by each country to characterize the extension of the central grid. These efforts have been significantly highlighted in many developments' literature, to achieve socioeconomic progress. However, it remained questioned in the context of the feasibility and sustainability of the strategies. Some research have been conducted by many scholars and diverse electricity-focused institutions to provide wide-scale approach to electricity, specifically in remote sides. However, the traditional grid extensions are still facing considerable economic and logistical obstacles, particularly in providing electricity services to remote populated areas [36]. Therefore, the microgrid system for remote areas is significantly proven as an optimize solution of electrification. Hybrid microgrid system which includes renewable energy resources has proven a cost-effective and efficient source of supplying electricity to off-grid communities. The use of renewable system in hybrid mode might reduce reliance on conventional or renewable systems [37].

Both urban and rural communities call for electricity as primary necessity of lifestyles, this means that, as compared to the traditional assets which were enforcing to offer them with grid power as the majority portion of people is enforced to live a conservative and difficult existence in near destiny. Inside the case of solar power, on the way to electrify all remote and distant homes must not take longer than ten years. IREA estimates that only 50% of the rural citizens of the nation are accessible to electrification that the imports of fossil fuel growing and gasoline and domestic oil manufacturing declines, nevertheless in villages out of total of approx. 125,000 from 30,000 people have not been accessible to electricity yet. This shows that still approx. 30 million people in a world are still live without electricity in major portion of distant areas [38].

2.2 Microgrid

A micro-grid is a section of the electricity distribution network that includes power generation sources, electrical storage facilities, and electrical loads. Micro-grids are present in residential and commercial settings and function as an active distribution network. Within micro-grids, production resources are broadly categorized as relying on either fossil fuels or renewable energies. These micro-grids can operate either independently or connected to the main grid. Smart grids are expected to continue playing a significant role in both current and future power system configurations [39]. Initially, microgrids setup were operated to fulfill local loads and local energy sources for a small-structured energy network, especially for the electrification of rural areas. Microgrids can be operated in diverse ways either in grid-connection mode or can be transitioned to remote operation mode during faults. But now, microgrids application has extended into more complex and various networks of distribution and have been applied extensively at levels of low voltage in industrial and residential sectors. This could increase the reliability, flexibility, efficiency and energy security demand for the national energy network. Nowadays, the microgrid framework includes renewable energy resources to provide electricity to the required area in a more effective way [40]. Many researchers have proposed the idea of a microgrid application using renewable energy resources either as a sole source of energy or in a Hybrid mode to provide electricity, especially for rural areas. This idea has been proven as the best solution to mitigate carbon footprint and shows a path towards a sustainable future [41].

Injecting an MG in the power sector framework offers numerous advantages over conventional system, including:

- Reduced carbon emissions
- Continuous and independent power supply to all micro-resources and loads in isolated mode
- Facilitation of operation of local grid in sustainable way, thereby enhancing the quality of overall power system.
- Play and Plug capabilities for seamlessly switching between grid-connected and isolated modes
- Operation as a source of backup power system in an event of a power shortages on the main grid.

2.3 Access to Sustainable energy

In this era, there is a need for sustainable energy solutions so Off-grid communities scattered across underserved and remote regions face a dual challenge of clean energy production and transmission. The pursuit of affordable electricity and a path towards environmentally friendly electricity generation. These communities like most rural areas of Pakistan distanced from traditional grid infrastructure, have long distances with the costly and environmentally detrimental infrastructure relying on diesel generators and fossil fuels. Such an energy dependency not only affects economic progress but also causes a global environmental crisis. In response to the problem of environmental degradation and costly energy production, an innovative and clean energy paradigm emerges at the intersection with non-conventional energy resources (wind, solar) with fuel cell technology in a microgrid system that would be a transformative solution for off-grid communities [42]. In comparison of traditional energy sources, renewable energy resources usage increases day by day. The one major reason for shifting towards RE is because of its environmental and economic benefits [43]. The technology is still advancing as now the hydrogen hybridization is taking place in most part of the world because of its contributions for rectifying the energy instability between availability and demand formed by interaction of wind and solar resources. The hydrogen hybridization also contributes in storing and delivering the hydrogen based energy to the end consumers [44].

2.4 Potential of introducing Off-grid renewable energy resources

The shift to reliable and practical hybrid renewable power structures worldwide is commonly driven with the aid of elements, the techno-economical potential benefits in different combinations in hybrid mode and fast reduction of conventional strength resources. In Pakistan, many remote areas lack access to energy. Therefore, diesel generators (DG) are applied to obtain the demanded load for those regions. The working price of diesel generators is excessive due to fluctuations in conventional fuel charges and generator composition and installation. Therefore, opportunity power sources like photovoltaic and wind, at the side of their diverse combinations in a hybrid way, offer suitable options for energy production in remote/isolated regions. Wind and PV renewable energy have emerged as substantial non-conventional technology alternatives in this period of ever-growing demand.

The study explores the technical and economic stability of solar PV energy production and wind power generation, a significant driver of global industrial advancement and economic growth. As energy is a crucial component of global progress, with fossil, nuclear, and other renewable energy resources. Governments face challenges such as rising fossil fuel costs, escalating energy demand, supply unpredictability (especially for natural gas and oil) due to geopolitical issues, and environmental impacts such as climate change. Renewable energies offer sustainable development objectives and energy security, and an examination of existing literature emphasizes the important use-age of non-conventional energy sources in advancing sustainable growth and reducing greenhouse gas emissions [45].

Introducing the feasibility of non-conventional electricity assets off-grid through standalone renewable hybrid electricity structures is magnificent. Nowadays, with charge versions of fossil fuels, to the increasing need to reduce CO_2 emissions and increase the efficiency and affordability of new technologies, all groups or centers that were previously excluded from the grid can now receive electricity at low cost through these systems. Approximately 1.3 billion people, or almost one in seven people worldwide, are now expected to be without electricity. There are many reasons why the traditional grid is not enough, low distance to meet the needs of customers, natural constraints and lack of interest of energy companies in investments. Lack of electricity in isolated groups or developing countries is an obstacle to economic and social development. [46]. Stand-alone power systems in many of available systems includes diesel generators based system that cause several issues related to uncertainties and fluctuations in fuel price of generators, inefficiency, CO_2 emissions, diesel generators purchasing costs, maintenance and other operations related costs, lack of modern age facilities, transportation cost of diesel and lack of investments, penalties related to gaseous emissions and many more. Renewable systems in hybrid mode are being considered more and more advantageous and will grow of the positive benefits (free of charge of renewable resource facilities, CO_2 emissions reductions, other subsidies, etc.) and helpful in dealing with insufficiencies (diversity of renewable resources availability and purchasing cost, etc.) through the system design control and optimization [47].

2.5 Hybrid Renewable Energy Systems

Reliability of electricity is a necessity in the business world, and the delivery system of these electrical services is being re-prepared to adapt to the increase in electricity production. Given current scenarios evaluate the climate change impact of associated with the of fossil fuel use-age, frequent transition towards renewable energy production is an important strategy that must be implemented to overcome the worst effects related to climate change. With this in mind, much research has been done to convert electricity into 100% renewable energy production (primarily wind and solar photovoltaic). Many energy sector de-carbonization plans call for 80% of future electricity to come from solar and wind energy. However, the extent to which solar and wind energy can be combined will be limited over time, by the difference between solar and wind products, the time and location of electricity demand, and other aspects of energy (e.g. transmission), dispatch-able power, additional services and reliability [48].

It’s necessary to emphasize that renewables such as PV, wind own inherent intermittency that could fulfill required demanding electricity situations by keeping a regular energy supply. To overcome the scenario, it is encouraged to have renewable power operations with steady power supply system, like battery storage system. The integration of RE with storage components like batteries or diesel generator is popularly called Hybrid Energy System (HES). HES can function in grid related mode or in standalone mode. Those structures have been increasingly more identified for its extensive technical, economic, and environmental benefits. Many of the direct advantages consist of discounts in electricity bills, stepped forward strength security, stronger resiliency, and reduced emissions.

Hybrid Renewable Energy Systems (HRES) include two or more energy generating resources with at least one of them is non-conventional and integrated with power controlled equipment and backup system (optional) that can be served as a backup system. Hybrid electrical systems could use existing electrical component
and add equipment to reduce costs, environmental effects and downtime. The purpose of planning the hybrid energy market is economic rather than technological. The most important thing is to choose the best energy sources that meet end user's needs in the most reliable way. At least one fuel source that provides renewable energy. Such systems aim to make sure the accessibility (availability) of renewable energy by providing utility with a non-renewable energy source or making it more efficient by providing energy storage for electronic devices [49].

2.5.1 Hybrid energy system in off-grid mode

Off grid hybrid energy systems includes integration of several generation systems, with at least one renewable source of energy. Off-grid systems are usually placed in remote locations or rural areas because they don't have access to the main electricity grid. Stand-alone or islanded mode is used when an off grid system is connected to the grid. Stand-alone usage is restricted within the research community, while off-grid usage is preferred for a more broad audience. A single source renewable energy system is widely used in many cases. But the recent studies shows that the world is shifting towards a Hybrid source renewable energy system rapidly, because of its vast applications and advantages in power sector. SSRES comprises of any single non-conventional energy technology, such as wind, solar, or biomass as the energy generating system, an energy backup device, control unit, and an inverter in case of an alternating current load. Renewable energy systems generation from single-source has widely adopted in case of both emerging and developing nations. Many single sources renewable energy system installation are explored here. In a recent research, hybrid photovoltaic hybrid systems and photovoltaic-wind based hybrid systems use different methods in different fields to evaluate the efficiency of the system to meet the load demand to achieve various objectives such as optimum sizing and configuration of components of system in hybrid mode. Improve the performance management system. Increase battery efficiency [50]. Turkey has developed its solar energy potential in the region, which receives an estimated total of 2741 hours of sunlight per year (7.5 hours in total per day) and the total solar energy increased by 1527 kWh per square meter[51]. Pakistan's 14 different promising cities are selected and installation of Solar power based projects potential is studied related to its environmental, economic, social, climate benefits and location [52]. In the city of Saudi Arabia Al-Qurrayyat, 1MW turbine produces 2357MWh of electricity per year at a cost of $0.092/kWh and a payback period of 8.1 years and emission reduction of 1124.15 tons/year [53]. Ras Benas station in Egypt installed, there are 20 commercial wind turbines in the 30 MW wind power plant. The wind speed at an altitude of 100 m is 9.8 m/s per year. The estimated power of the wind farm is 130GWh/year. [54]. In Canada's remote areas, $4.7 million average $Cdn, Canadian projects likely to be installed. It could be expected to make wind energy projects over a 10 year period of approx. 14.5 MW [55]. One of the most underdeveloped state of India, installed total photovoltaic capacity of 2289 MW solar power based project in Rajasthan. In the Jaisalmer district of Rajasthan , the Dhirubhai Ambani Solar Park at Dhursar village is installed providing 40MW photovoltaic power station since 2012 [56]. A 3900MWh Solar based project in one city of Iran is taken under consideration with the nominal power of approx. 20,000KW and about 0.94KWh per day are the PV losses and 0.12KWh per day is average system losses with annual array efficiency is about 14.18% [57]. A rural electrification in the north east of Thailand has a load of 542Wh and is electrified utilizing a single source remote PV system rather than a PV system in mode of grid connection [58].

2.5.2 Hybrid Energy Systems (HES)

Renewable energy system in hybrid mode is becoming popular as compared to single source Renewable energy system. As the HRESS is more cost effective and efficient system. It includes a combination of renewable energy sources in two or more ways that combine to generate power with increment reliability, sustainability and efficiency. In recent studies, most of the research is mainly focused on systems that are in hybrid form for remote side electrification. A case study related to hybrid renewable energy resources system in South Cameroon remote area is held , 170,095 kWh/yr. is total electricity generation with the COE of 0.443$/kWh [59]. In a recent case study of Jubail, an industrial city, HRESS designed for apartment comprised 3 bedrooms with a load demand of 12,160, 3289 and 4532 kWh/day and peak load of 688, 270 and 467 kW. This system has 0.183, 0.224 and 0.244 US$/kWh COE and the average total NPC of three apartments are 9.9, 5.6, and 3.9 million US$, respectively. The system is designed to reduce the carbon footprint as a result it saves 2800 tons of carbon-dioxide emissions/year [60]. In terms of economic and technological study, wind potential is quite low in comparison to great solar potential at two separate sites, one in Nice, France and the other in Nicosia, Cyprus [61]. The optimized case study is observed in rural area of Iran with the hydro/Solar/battery/diesel hybrid system having $113201 net present cost, considered as most economical solution of electrification [62]. A hybrid solar/battery/diesel system for application on remote side in an isolated community in case of Bangladesh having 360kWh per day load demand with a peak load demand of 75.34kW is studied by using major battery technologies such as Lead Acid and Lithium-ion batteries [63]. For Dongola, Sudan, hybrid renewable energy isolated from the grid is intended for the use of electricity in agriculture and hydropower. The system has a total current cost ($24.16 million) and level energy cost ($0.387/kWh) and also has a good return on investment of 39.94%.[64]. A techno-economic analysis of a hybrid power system for an off-grid mining company in Ghana was conducted. The system consists of solar photo-voltaic, fuel cell system, 600 batteries and a 20 MW diesel generator, producing 152.99GWh per year, with an optimal cost of $0.25/kW and a minimum cost of $0.22/kW [65]. Hybrid wind/hydrogen with battery system's economic analysis is conducted in Tehran, Iran with the average daily electricity consumption of 18kWh per day with the peak load demand is almost 1.5kW, this system has total current cost of $63,190 with the levelized cost of energy is $0.783 per kWh [66]. A grid connected case study held in Bangladesh for the local community for electrification. Its average daily load is maximum1739.74 kWh and maximum demand load is 366.53kW. For 16.86 years of payback period, it offers approx. 32% cheaper cost of energy than its present rate which is $0.0442 per kWh cost of energy [67].

2.5.3 Hybrid Microgrid system based on RER

A Microgrid system include assessment, sizing, and social management. By keeping these things into consideration, a case study conducted in Peru where interviews held with people of the country to suggest Microgrid based designs. Proposed a system of Microgrid in hybrid which is comprised of 6kW PV system and 2 of 3 kW of wind turbines, each supplying daily demand on average of 23kWh at steady power of almost 1–1.2 kW, this project has 20 years lifetime with $36,000 cost of energy [68]. In a case study related to off grid mode of Koh Jik location, the best optimized system is selected to provide electricity at their lowest cost of LCOE in combination with the highest renewable fraction and it is as low as of €0.220 per kWh obtained with the payback is also as low as 6.4 years and 15.28% is the internal rate of return of this project [69]. In the region of Gabel El-Zeit, which is located in the coastal side of the Red Sea, Egypt. This conducted study consist of a large scale grid connected hybrid solar with wind system. The proposed system in hybrid mode is proposed on basis of 200 MW wind project and 250MW solar farm and its modeling and simulation have been performed using MATLAB/Simulink software. The results of this simulations summarized as 1509.85GWh per year is the total power generation annually from the proposed system of hybrid renewable based energy system with 1391.7GWh per year (92.17%) obtain from the wind farm and 118.15GWh per year (7.83 %) generates by using solar station [70]. The author suggest 21 different working system configurations in total having 6 home based energy systems and diverse 15 number of microgrid for country side community in the region of Philippine by considering both remote and grid connected hybrid systems. At the local homes, author suggest hybrid photovoltaic and wind systems (17–40)% impact with BESS is lower in contrast to the stand-alone installations per kWh [71]. Around 22 million people in Latin America do not have electricity and governments in many developing countries struggling to deal with rural electrification programs. In this context, according to technical, environmental, socio-economic and institutional measurements of sustainability, different thirteen projects in microgrid system in North Western Venezuela are presented. The evaluation of these Microgrid is based on some ad hoc criteria and assessed by means of semi-structured interviews, technical visits, and 106 surveys of technical beneficiaries with operations and evaluated results elaborate that hybrid Microgrids could be helpful in obtaining the power needs of people [72]. Another case study presented by Indian authors describes the optimization of energy use in rural areas of Uttarakhand, India. This study shows how to use gray wolf optimization to reduce cost related to energy (COE), current cost (NPC), and emissions. Four other models were evaluated and taking their comparison that is based on economic and environmental considerations. In accordance with latest estimate, LCOE of the best configuration is $0.203/kWh, with renewable energy at 92% [73].

2.6 Fuel Cell (FC)

Fuel cell is the fourth type generation of electricity generator. Its thermal efficiency does not limited by carnot cycle and its two to three times more as compared to the internal generator. It converts the chemical energy of fuel into electrical energy without the need for combustion processes or motion [74]. In 1839, the first basic demonstration of Fuel cell was given by William Groove. Fuel cell is an electrochemical device that by combining hydrogen and oxygen produces electricity without combustion to produce water and heat. It was widely used in marine, Submarine and for transportation system [75]. But now, Fuel Cell has many vast applications as it can be used in large-scale power distribution and generation system. Many different types of Fuel Cell are available now-a-days. Some of those can be used as a backup power system and can replace the batteries in terms of energy storage and conversion [76].

Moreover, FC is considered environmental-friendly system more in contrast to other non-renewable energy resource systems. It can generate electricity by using Green Hydrogen which is significantly an environmentally friendly process with least CO_2 emissions. Through the interaction of hydrogen and oxygen as an electrochemical reaction, the fuel cell converts by product hydrogen or hydrogen based other fuels into electricity directly with liberating heat [77]. The use of FC is increasing rapidly in many applications especially in power sectors in order to develop a clean energy system [78].

The research on FC integration with different renewable energy resources is still carried out in most part of the world but Pakistan still lack in the technology to adapt this system. Fuel cell integrated with renewable energy resources will be sustainable and cost effective recommendation for the problem related to electrification of isolated sides. There are following different types of fuel cell applications as shown in **Table 2.1.**

Table 2.1: Applications of types of fuel cell

S#:	**FC Types**	**Capacity (We)**	**Application**
1	PAFC	(50k-1M)	Distribution generation
2	SOFC	(10-200)k	Large distribution generation, Auxiliary power
3	AFC	(5k-3M)	Submarine, Military
4	DAFC	(100m-1k)	Laptop/Mobile devices

CHAPTER 3 : METHODOLOGY

In this chapter, the site and load profile of selected area, the total load demand requirements, solar irradiance data and wind speed data is analyzed. The methodology used in developing a proposed system on basis of technical and economic analysis is discussed. Each component's cost is estimated and calculated according to mathematical formula.

3.1 Site and Load Profile of study area

An integration of the HRES system with Fuel Cells is developed for the targeted location name Nooriabad, Sindh, having site elevation at 180 m with **25.17°N**, **67.8°E** latitude and longitude above the mean sea level [79]. The usage of electricity is less in country side areas in contrast to populated sides. Because population in the remote areas use non-traditional materials wood burning for cooking and other purposes. In the schools of rural areas, clean water facilities for drinking purposes, toilets, and electricity are

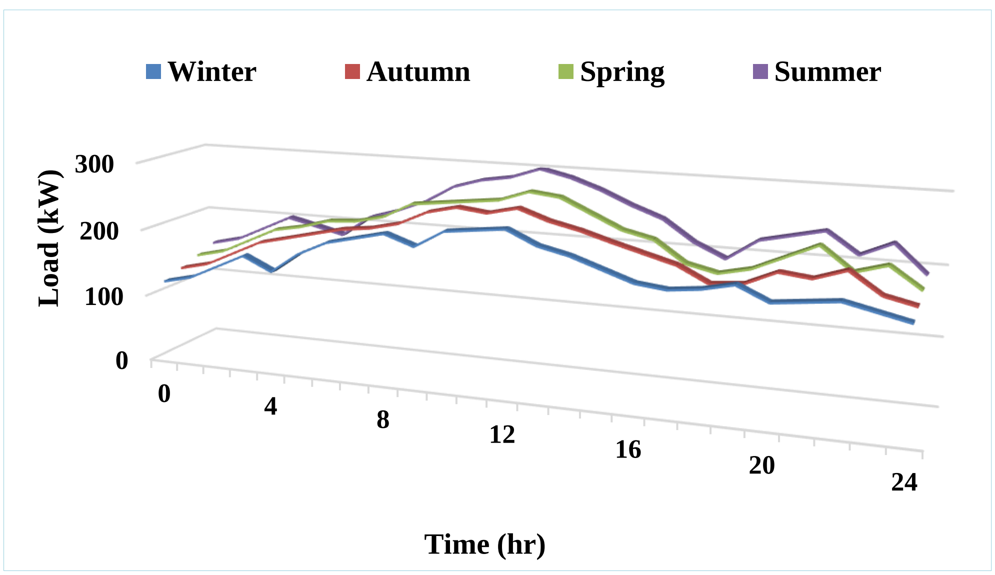

Figure 3.1: Electrical demand for Nooriabad [82].

considered as the only basic facilities for children. Many of people in rural sites lack access to electricity [80]. The proposed site location of Nooriabad has a huge potential for electricity production by using wind and solar energy resources to make these areas electrified [81]. There are almost 5-10 family member reside in each house in rural site and the total number of houses in the village is about 100-150. The power load on average is assumed to 2000 kWh per day for the selected community with 281 kW considered as peak load in summer. The scaled load of (130-300) kW on average is illustrated in **Figure 3.1.** There are 8760 hours in the simulation year. A full-year analysis is not necessary; thus an average seasonal simulation with set points of 8760 takes approximately ninety times longer than an analysis with 96 set points. Additionally, the sensitivity analysis performed in this study requires running the simulation more than once. Therefore, the hourly demand for each month is represented by only 24 data points, so 96 set points including 4 seasons 1 day per month 24 hours per date are used for the simulation instead of 8760 data points [82]. So the daily demand profile presented by 24 data points.

3.2 Microgrid Components

3.2.1 Fuel Cell

The fuel cell used to generate electricity by conversion of produced hydrogen using an electrolyzer which is stored in hydrogen storage tank into electricity obtained from the chemical reaction. Fuel cell used in this model is SOFC (Solid-oxide Fuel cell). It has greater efficiency and can be operated for a long period as compared to other fuel cell technologies and its specifications are illustrated in **Table 3.1** [83]. The excessive electricity produced by wind turbine and PV panel would be used in the production of hydrogen by using an electrolyzer that is stored in hydrogen tank. In the proposed model, its rated power generation capacity is 200kW. Fuel Cell has estimated capital cost as $850 per kW, its replacement cost is taken as 0, and operating and maintenance cost is $13/kW. The estimated lifetime of fuel cell will be 30,000 h in total [84] as shown in **Table 3.5.**

$$E = E_0 + \frac{RT}{2F} ln\left(\frac{P_{H_2} * P_{O_2}^{0.5}}{P_{H2O}}\right) \tag{3.1}$$

Where E is the total potential, E_o shows the potential at standard value, here R is called as universal gas constant with the operating temperature of the Fuel Cell represented as T measured in kelvins, and F shows Faraday constant, $P_{H_2}, P_{O_2}^{0.5}, P_{H2O}$ represents the Hydrogen, Oxygen, and Water partial pressure.

Table 3.1: Fuel Cell specifications

Fuel Cell type	**SOFC**
Efficiency (%)	88
Temperature (°C)	600-1000

3.2.2 Electrolyzer and Hydrogen Storage Tank

In this proposed model a generic electrolyzer model is being used. Breaking down of water into hydrogen and oxygen molecules is a process that occurs in an electrolyzer. This process of breaking water molecules is called an Electrolysis. Hydrogen that is being produced during the process of electrolysis is used for the generation of electricity [85]. capital cost of an electrolyzer is considered as $600 per kW while replacement cost will be $400 per kW and the maintainance and operation cost is taken as $12 per kW [86]. The electrolyzer has a lifetime of 15 years and it is considered 85% efficient. In this system, the electrolyzer has a nominal capacity of 300kW. Hydrogen storage tank connected with electrolyzer is used for capturing hydrogen. The stored hydrogen is utilized by fuel cell to generate electricity [87]. Capital cost of this hydrogen stored tank is assumed as $350 per kg. The replacement cost is $120 per kg and the operating costs taken as $6/year [88]. Hydrogen tank size is used from 1 to 200 kg. The estimated lifetime of this hydrogen stored tank is 25 years as shown in **Table 3.5.** The estimated hydrogen can be produced by using Eq.(3.1).

3.2.3 PV Panel

A general photovoltaic flat-plate panel is processed in this proposed model and its specifications are described in **Table 3.2**. General PV module is almost 20% effective with their lifetime is supposed to be around 25 years in total. PV system has nominal capability of 250 kW power and the maximum power production capacity is attained in summer due to maximum solar irradiance observed in summer [89]. Initial capital cost of PV system is estimated as $1100 per kW with replacement cost of $900 per kilowatt and operating cost of $15 per year is considered [90] as shown **Table 3.5**. Derating factor of PV system is approx. 89%.

Table 3.2: PV panel specifications

PV Panel Model	Generic
Panel Type	Flat Plate
Derating factor (%)	80
Temperature Coefficient	-0.46
Operating Temperature (ºC)	25
Efficiency (%)	18.7

Solar energy production is evaluated by taking area of the photovoltaic panel, solar radiation and average temperature. All energy is obtained from solar photovoltaic panels is calculated using equation (3.2).

$$P_{PV}(t) = \left(\frac{R_P}{1000}\right) * P_{PV,rated} * \eta_{PV,MPPT} \quad (3.2)$$

Where P_{pv} denotes total power generated by using PV arrays, Rp represents solar irradiation in (W/m^2) at surface which is perpendicular surface, $\eta_{PV,MPPT}$ represents the estimated efficiency of this system at maximum power point tracking (MPPT).

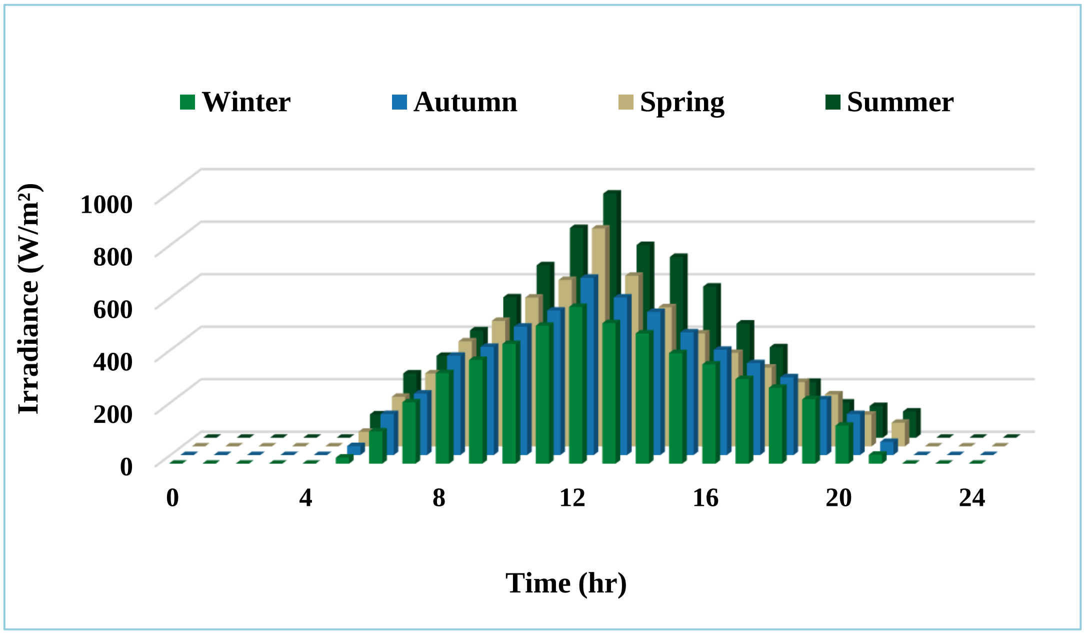

Figure 3.2: Average solar irradiance across four seasons [89].

3.2.4 PMSG-type Wind Turbine

The PMSG type wind turbine is used in the presented system and it has estimated efficiency of about 59.2% including all type of losses and its precise estimated specifications are described in **Table 3.3**. PMSG type wind turbine is feasible due to economical availability and cost-effective.

Table 3.3: Wind turbine specifications

Wind Turbine Model	PMSG-type
Hub heights (m)	30,50
Cut in speed (m/s)	3
Cut out speed (m/s)	25
Wind class (IEC)	IA

Rotor diameter (m)	76.5

PMSG based wind turbine is suitable for small scale energy capacity purposes which is best suited for almost 10-15 m/s wind speed [91] as shown in **Figure 3.3**. This type of wind turbine has capital cost of $2500 per kW, the replacement cost is $2000/kW and operation and maintenance costs are set at $20 [92]. Power is calculated by using Eq. (3.3) [93] and the capacity of PMSG type wind turbine in this proposed system is about 300kW. The estimated lifetime of the PMSG type wind turbine is about 25 years total on average as shown in **Table 3.5.**

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta) v^3 \qquad (3.3)$$

Where P_m represents the total power attained by wind sources, ρ shows the density of an air, A denotes the area of a blade of turbine, v denotes its wind speed, here Cp represents the ratio between the speed of the tips of the wind turbine blades and wind speed, β shows blade pitch angle and λ shows aerodynamic behavior of wind turbine.

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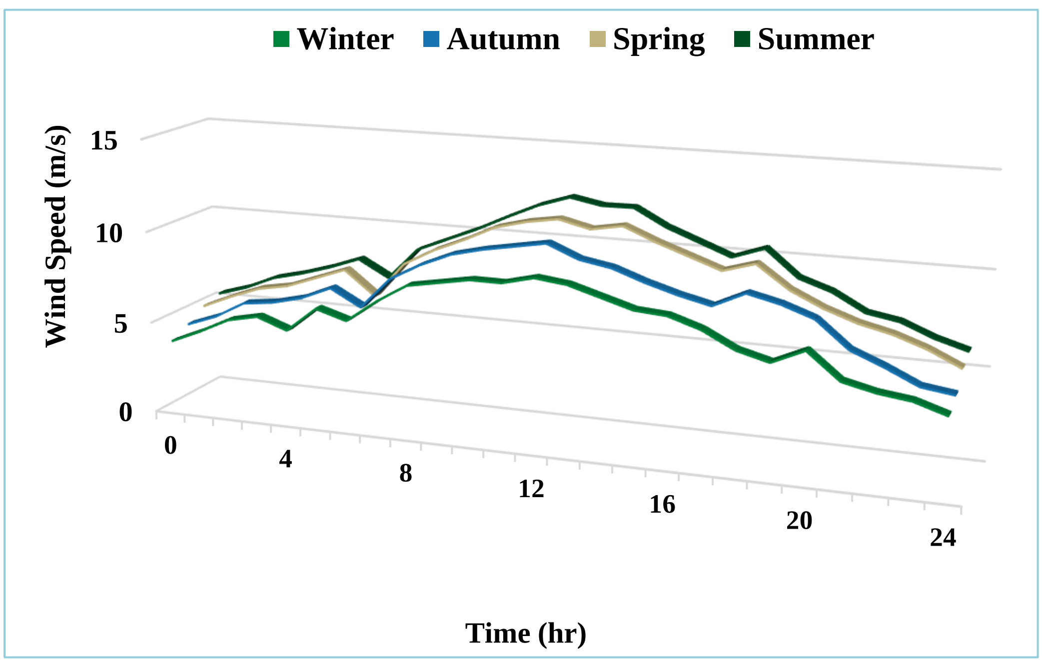


Figure 3.3: Seasonal Average Wind Speed data per day [91].

3.2.5 BESS

Wind and solar energy based on weather conditions and fuel cell based on hydrogen production and conversion so in case of power shortfall or decreased in electricity from these resources, there is a need of backup power, so with the help of batteries the required load demand can be obtained as an asset of auxiliary system. BESS is used and managed according to regulating its DOD (Depth of Discharge) and SOC (State of Charge). Where depth of discharge is defined as fully charged battery discharge capacity divided by the rated capacity of the battery and a battery's state of charge (SOC) represent its current capacity as a function of its rated capacity and its capacity requirements are shown in **Table 3.4**. When accessed power is produced using RER's and fuel cell the battery starts to charge and when insufficient power is produced to meet the desire demand, at this point battery discharged and used as a backup power system [94],[95]. BESS is suitably used for backup system in most of power generation and utilization system. Capital cost for battery is $1500 per kW, the replacement cost is $1000/kW and operation and maintenance costs are taken as $14/kW [42]. Energy generation capacity is about 200 kW. The average estimated lifetime of the BESS is about 15 years total as shown in **Table 3.5**. The nominal power capacity of BESS in the proposed model is 30000kWh with an average minimum SOC of BESS is 20% and average maximum SOC is 80%. The maximum utilization of battery is in summer during load shedding hours, and its total power can be determined by using Eq. (3.4).

Table 3.4: BESS specifications

Battery storage type	**Generic Li-Ion**
Nominal voltage (V)	6
Nominal Capacity (Ah)	167
Round trip efficiency (%)	90
Initial State of Charge (SoC)	100 %

Minimum State of Charge (SoC)	20%

The BESS is comprised of energy that is electrical in nature by formation of chemicals and supplied as electricity. The system's BESS capacity is observed by the electric demand and supply of energy hours per day. The capacity of battery bank (kWh) is evaluated using the equations [96]:

$$P_{batt} = P_{Load} - (P_{FC} + P_{PV} + P_{wind}) \tag{3.4}$$

$$P_{batt_{ch}} = P_{ch}(t) \begin{cases} P_{gen} > P_{load} \\ C_{source}(t) = \min\left(C_{source}(t)\right) \\ E_e = 0 \end{cases} \tag{3.5}$$

$$P_{batt_{ch}} = P_{ch}(t) \begin{cases} P_{gen} > P_{load} \\ C_{source}(t) = \min\left(C_{source}(t)\right) \\ E_e = 0 \end{cases} \tag{3.6}$$

$$SOC_{min} < SOC < SOC_{max} \tag{3.7}$$

$\boldsymbol{P_{batt_{ch}}}$and $\boldsymbol{P_{batt_{dis}}}$ represent battery state of charge and discharge, respectively. P_{gen} indicates the generation of power in total of the presented system, whereas P_{load} indicates desired load for system in total. SOC indicates charging state of battery that would be calculated from the battery by equation (3.7).

3.3 Architecture of Microgrid

A Microgrid structure of Nooriabad, Pakistan operating at 5kV is formed in MATLAB/Simulink as illustrated in **Figure 3.4** with fuel cell, RER (solar and wind), BESS and load modelling. The MG would not work stably without battery which serve as a backup power because ERs are naturally intermittent. As additional power likely to be store in BESS to attain desire electrical demand and it would be discharged as per system requirements [97]–[101].

All components total power must be greater or equal to load demand. Each component connect to 5kV AC bus-bar. Wind turbine produced AC so it is directly connected to AC bus-bar then with load but BESS, solar and fuel cell connected to inverter to convert its DC power to AC. Fuel cell and solar is connected to same voltage controlled source inverter. There is boost converter attached to both solar and fuel cell to boost up voltage and to reach up to same level of 5kV.

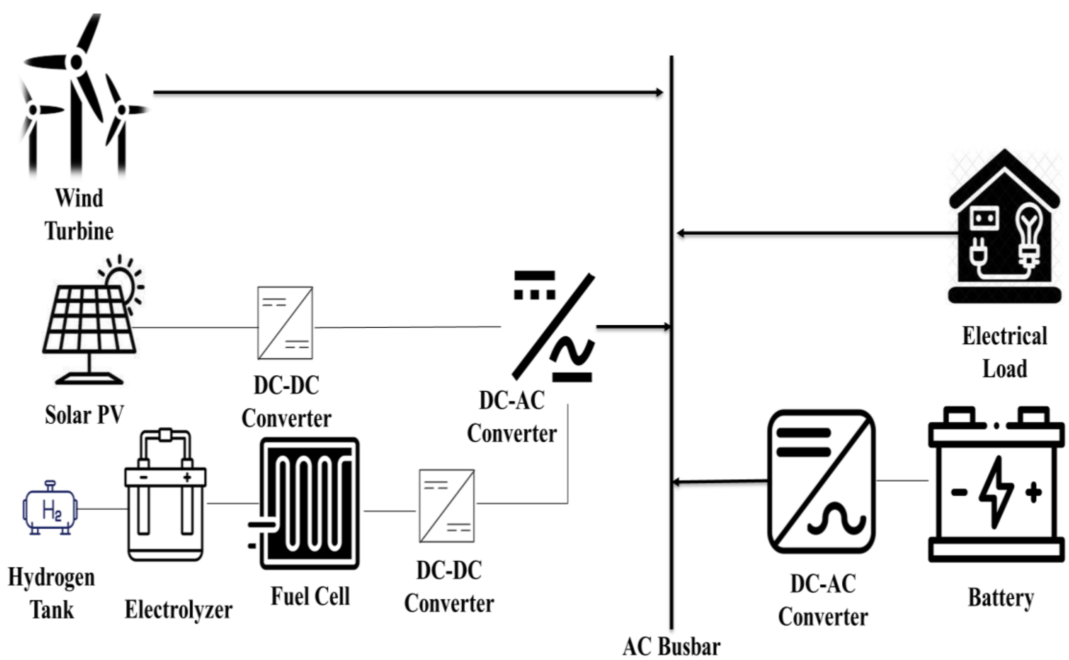


Figure 3.4: System architect of a proposed model [97]–[101].

3.4 Cost analysis based on per year economy

Presented system's analysis based on finance is carried with evaluation of FC, renewable energy (Solar, Wind) with battery, installation projects in accordance with measuring its budgeting and financially optimizing parameters calculations that are performed by taking estimations to evaluate the investment feasibility of project. In the present study, financial analysis of a system is measured using Homer Pro software. NPC, LCOE, total annualized cost and each component total cost is calculated using Homer Pro.

Table 3.5: Illustration of cost of components.

Components	Capital Cost ($/kW)	Replacement Cost ($/kW)	O&M Cost ($/kW)	Lifetime (/year)
BESS	1500	1000	14	20
Fuel Cell	850	0	13	3.43
Electrolyzer	600	400	12	15
Hydrogen Tank	350	120	6	25
Wind Turbine	2500	2000	20	25
PV Panel	1100	900	15	25
Inverter	200	150	8	15

Moreover, unmet electrical load, total electrical power served in average with annual savings and capital investment are also estimated. In this presented system, the total capital cost, replacement cost, O&M cost of each component used in a microgrid is estimated and total estimated lifetime is as shown in **Table 3.5**.

3.4.1 Net Present Cost (NPC)

The system's net present cost in hybrid mode in a Microgrid calculated by calculating the sum of the capital, replacement, operation, and maintenance costs of the system as described in the Eq.(3.8). Homer Pro software is being used to calculate the NPC of each component by using formula,

$$NPC = \sum(C^{Capital} + C^{Replacement} + C^{O\&M}) \qquad (3.8)$$

where $C^{capital}$ is an Initial Cost, $C^{Replacement}$ is Replacement Cost, $C^{O\&M}$ is the Operation and Maintenance Cost of the system [102].

3.4.2 Levelized Cost of Energy (LCOE)

LCOE of an asset can be presented as an average cost per unit in total to build and operate the asset at all capacities. Levelized energy cost measures cost of living and highlighted the opportunities to develop different scale of projects for long-term values for facility, community, or for commercial purposes. It can be calculated by using Eq. (3.9) [103].

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \qquad (3.9)$$

Where $C_{ann,tot}$ = Total Annualized Cost of the system ($/year), E_{served} = Total Annualized Load Served (kWh/year).

3.4.3 Levelized Cost of Hydrogen (LCOH)

It is an assessment of initial capital, manufacturing, maintainance and operating costs of the processed hydrogen based on different types of hydrogen. Levelized Cost of Hydrogen should be calculated by taking difference between total annual value and price of electricity required annually and dividing it by total annual hydrogen production, as shown in the following Eq.(3.10) [104].

$$LCOH = \frac{C_{Annualized} - C_{Electricity}}{M_{Hydrogen}} \quad (3.10)$$

Where total current cost of system denoted as $C_{Annualized}$, in a Year ($/year), the revenue generated from annual electricity sale represented by $C_{Electricity}$ in ($/year), and $M_{Hydrogen}$ shows production of hydrogen in a year (kg/year). This system is considered as an Off-Grid system, so there would be no sale of electricity to grid.

3.4.4 Total Annualized Cost

The Annualized Cost's total value is calculated using a formula that is presented through NPC and then processed by CRF multiplying factor using Homer Pro software. It is expressed as the annual value of all current liabilities.

CHAPTER 4 : RESULTS AND DISCUSSION

In the following chapter, simulations attained by using Homer Pro and MATLAB/SIMULINK software is discussed. Homer Pro software was used for analyzing financial calculation and MATLAB/SIMULINK software was used for technical evaluation. System LCOE, NPC, total annual cost and other costs include Homer Pro. The daily average electricity consumption and utilization is estimated by using MATLAB/SIMULINK. The results of each of the four seasons are compared one by one. The simulation runtime is 24 Hours.

The simulation is done according to the average monthly production of power by each component in a day. This study covers the 4 months of season winter that are January, February, November, and December for the season spring, cover 2 months March and April, for the season summer, cover four months of May, June, July, and August and for season autumn which cover two months such as September and October. Moreover average monthly contribution of each resource used in this proposed case is calculated by using Homer pro software.

Average seasonal data is calculated by taking Average of four months in a season then the month which has almost more sun irradiance and wind speed data is taken for evaluation using MATLAB/Simulink software. Rather than, evaluating 8760 points which is data for one year, we divide it into 24 set points. So the simulation will be smooth and not much time taking by dividing it into 24 points.

4.1 MATLAB/ Simulink model

A Microgrid structure of Nooriabad, Pakistan operating at 5kV is developed in MATLAB/Simulink with Fuel Cell, RER (Solar and Wind), BESS and Load modelling as shown in **Figure 4.1**.

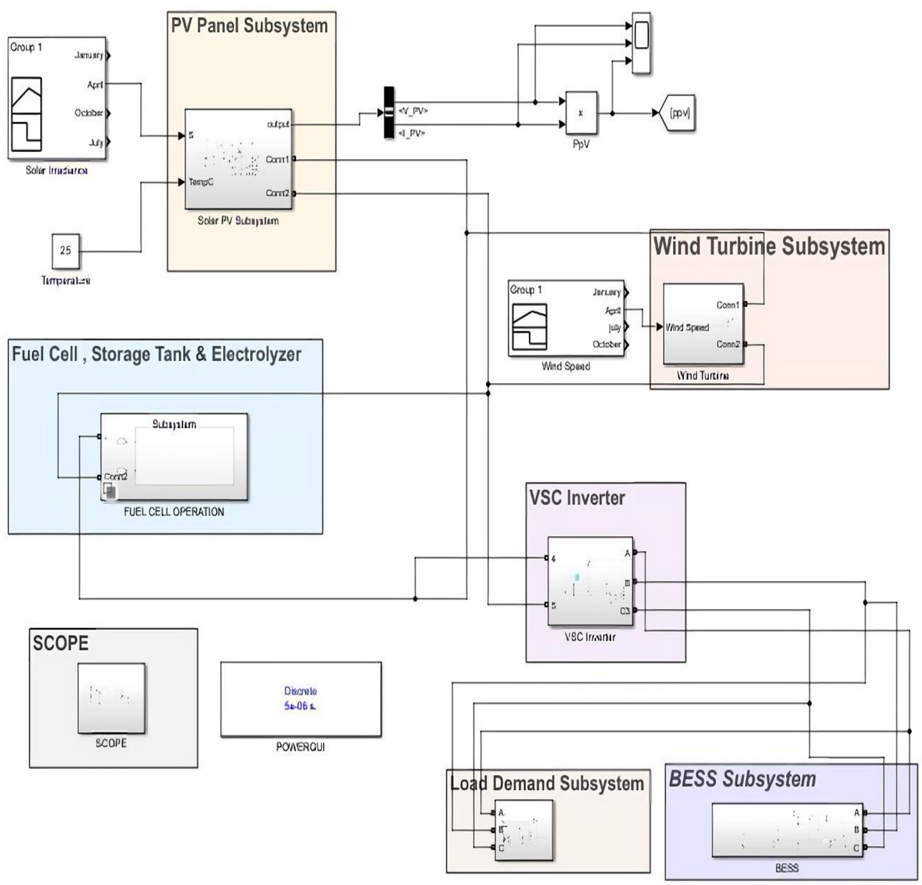
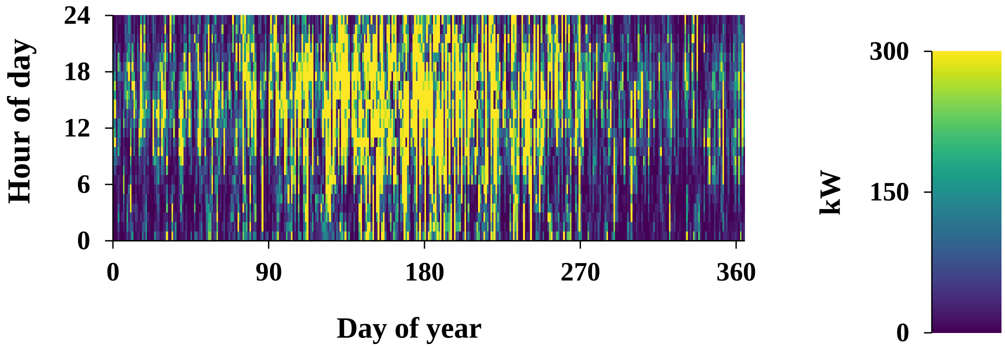
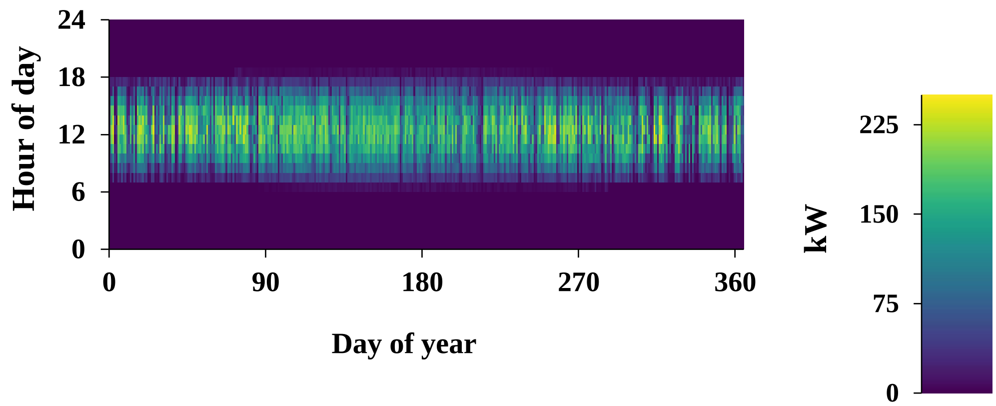


Figure 4.1: MATLAB/Simulink proposed case with integrated FC, wind, and solar with battery

4.2 Evaluation of power produced in a year

The average yearly data of each component used in presented case is composed using Homer pro software, according to which estimated annual production with respect to hour of day per 365 days is represented in **Figure 4.2**. The following figures present the total estimated electricity generation per year from wind turbine, fuel cell and solar PV. Annually, total electricity generated by Fuel cell is 295,054.56kWh/year, solar panel produce 573,717.2kWh/year and wind turbine produce 819,596kWh/year. The annual estimated calculation is done by using Homer Pro software. Homer pro calculated monthly as well as yearly power production while MATLAB/Simulink software is being used to calculate average season data and peak month with monthly peak power calculations is also performed using both software's.





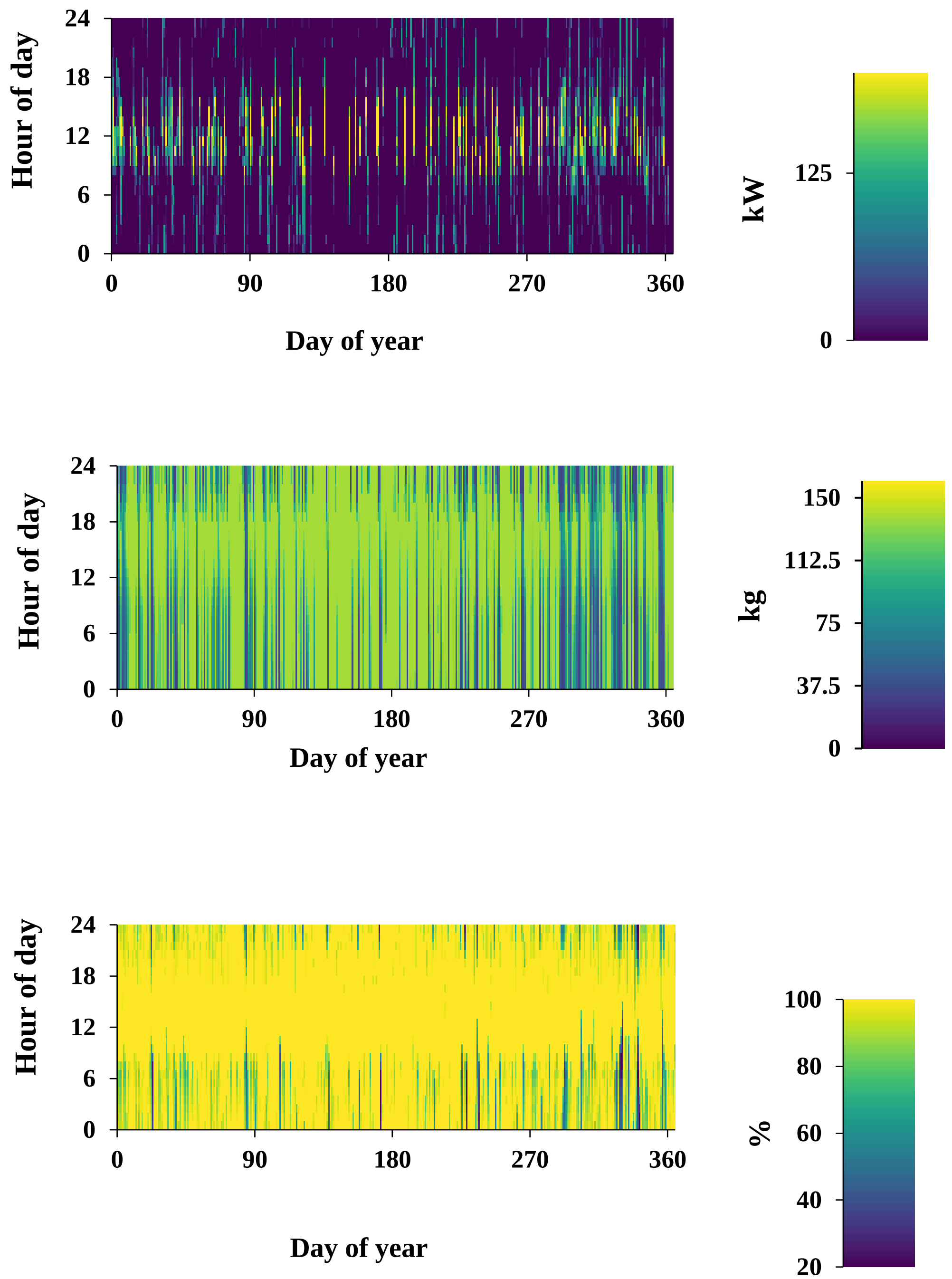


Figure 4.2: Average annual power production by (a) Wind (b) Solar PV (c) Fuel cell (d) Hydrogen tank (e) BESS

4.3 Technical Assessment

The average seasonal power generation simulation is performed using MATLAB/Simulink software. In this software 24 hour time per day is set to obtain results according to average per month data. A simulation with 8760 set points take about 90 instances longer than an analysis with ninety six set points. As a result, the hourly demand of each month is explained by way of 24 sets, resulting in a simulation the use of ninety six set points (four seasons 1 day per month 24 h per day) instead of 8760 set points. Daily demand profile set with 24 data points. Moreover, average monthly power generation data is also obtained using Homer pro software. The seasonal load profile with average power production results of MATLAB/Simulink software are summarized below and discussed one by one.

4.3.1 Winter Season

During the winter season, wind energy resources produce a maximum of 237kW and the maximum power produced by solar energy is 190kW. While Fuel Cell produce approximately 95kW. At the time 00 to 3:00, BESS starts to charge because the excessive power is produced by RER's and Fuel Cell as compared to load demand. From 9:00 to 15:00, BESS discharged and provided 90kW to meet the required load demand. Excessive power is also needed for hydrogen production and storage in hydrogen tank by running an electrolyzer. The Hydrogen utilization is from 120 to 48kg/day in winter season as illustrated in **Figure 4.3**.

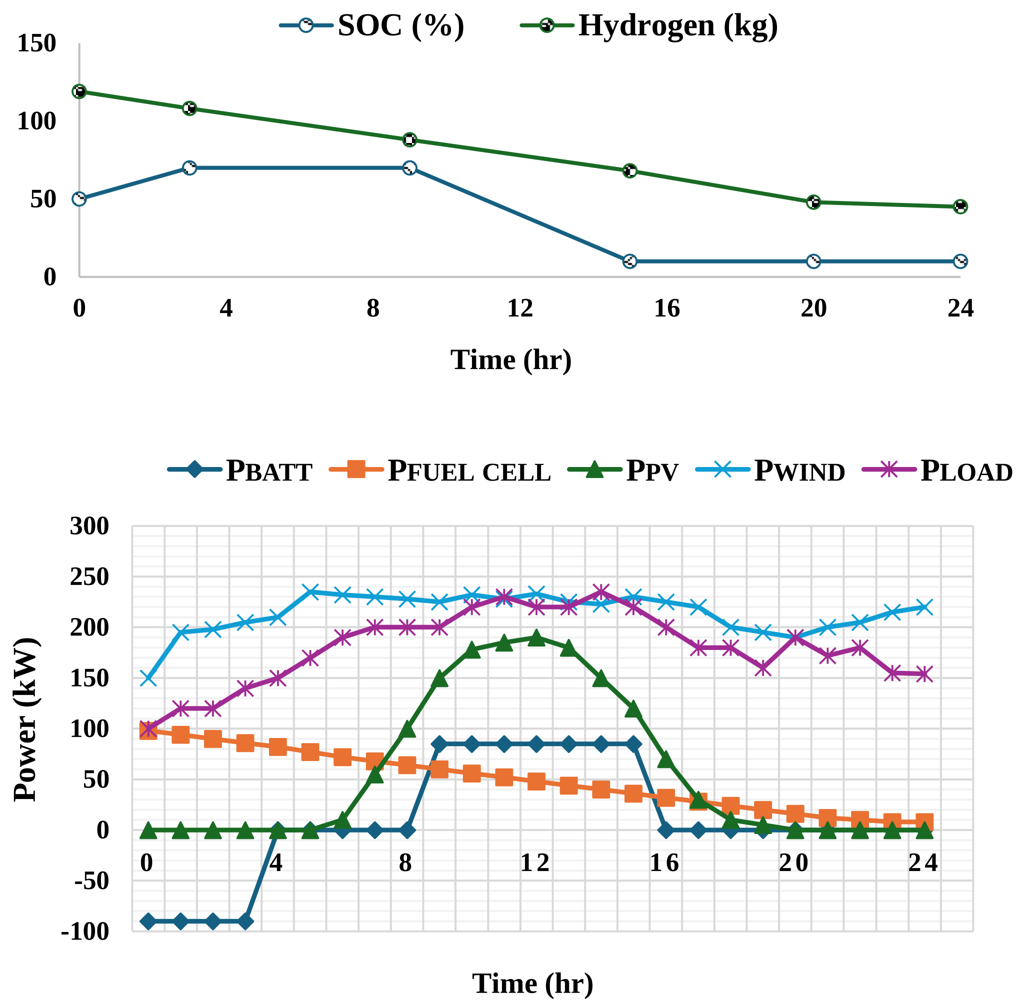
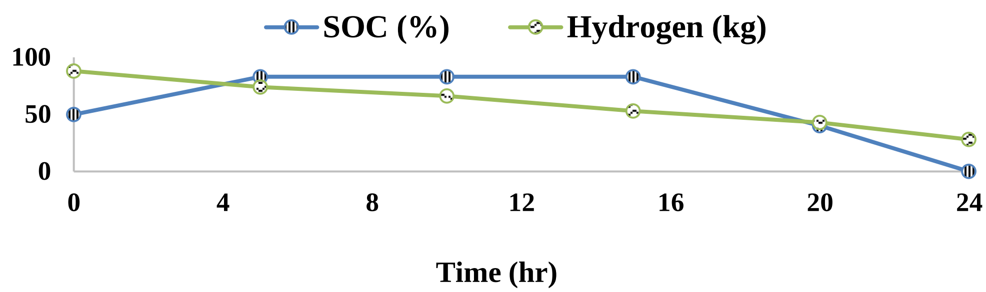


Figure 4.3: Winter season MATLAB/Simulink results (a) Hydrogen & SOC (b) Power

4.3.2 Autumn Season

During the autumn season, wind energy resources produce a maximum of 248kW and the maximum power produced by solar energy is 198.5kW. While Fuel Cell produces approximately 83kW which decreases over time due to a reduction in Hydrogen production capacity. At the time 00 to 5:00, BESS starts to charge because the excessive power is produced by RER's and Fuel Cell as compared to load demand. From 15:00 to 24:00, BESS discharged and provided 55kW to obtain the required load demand. Hydrogen utilization is from 96 to 37 kg/day in autumn season as illustrated in **Figure 4.4**.



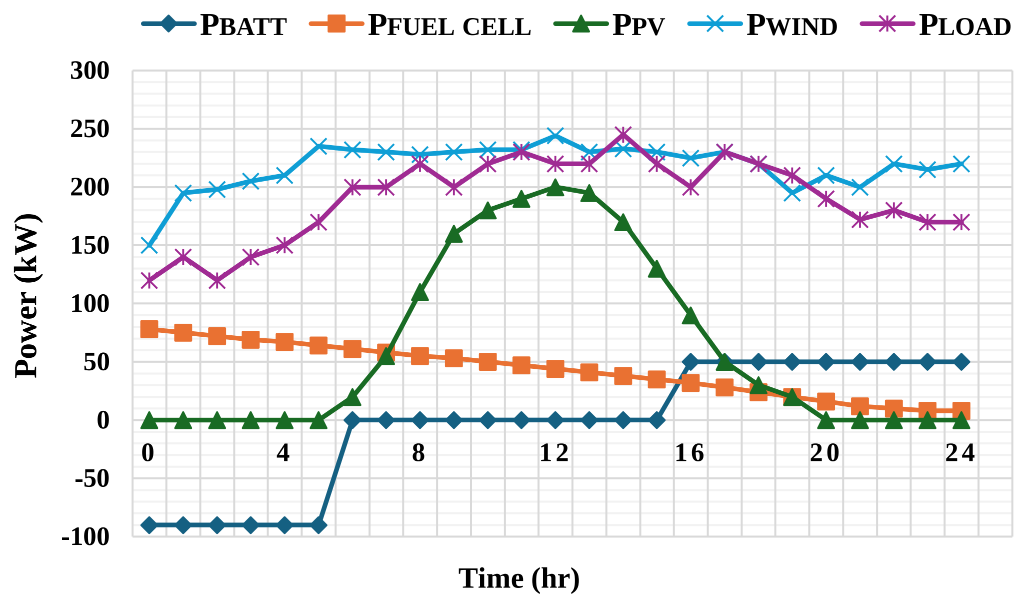


Figure 4.4: Autumn season MATLAB/Simulink results (a) SOC & Hydrogen (b) Power

4.3.3 Spring Season

During the spring season, wind energy resources produce a maximum of 265kW and the maximum power produced by solar energy is 213kW. While Fuel Cell produce approximately 115kW. At the time 00 to 6:00, BESS starts to charge because the excessive power is provided by RER's and Fuel Cell as compared to load demand. From 18:00 to 24:00, BESS discharged and provided 87kW to attain the required load demand. Hydrogen utilization is from 127 to 53 kg/day in spring season as illustrated in **Figure 4.5**.

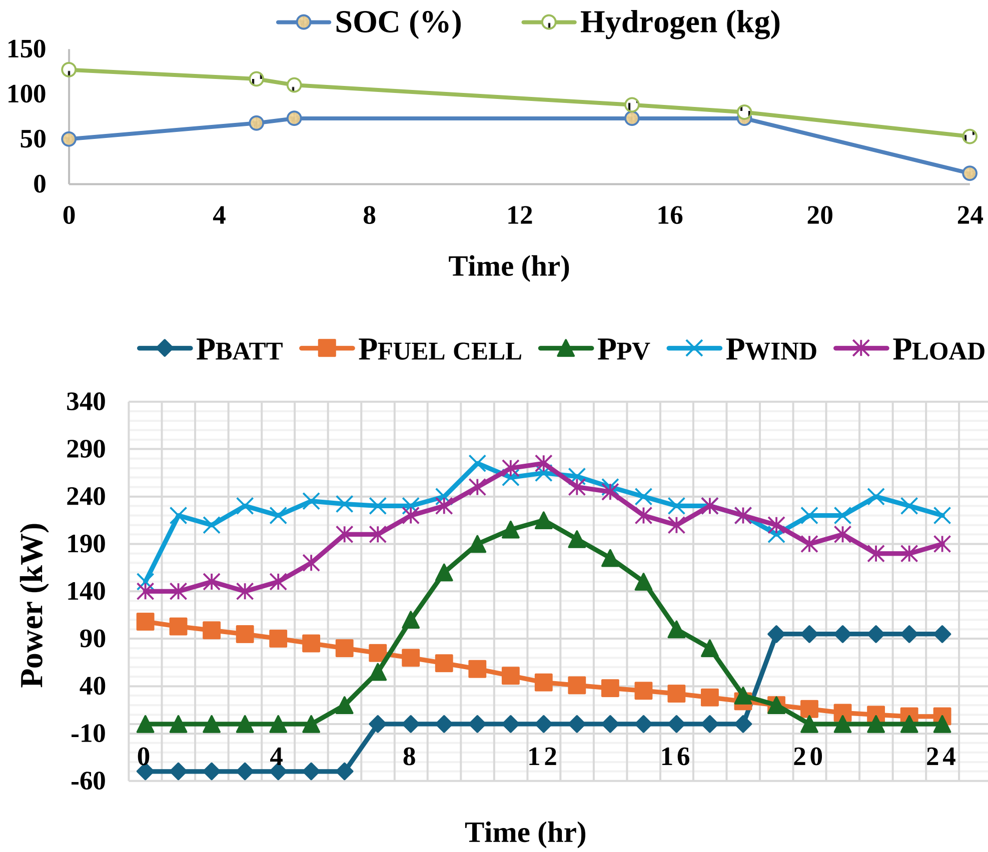


Figure 4.5: Spring season MATLAB/Simulink results (a) Hydrogen & SOC (b) Power

4.3.4 Summer Season

During the summer season, wind energy resources produce a maximum of 277kW and the maximum power produced by solar energy is 226kW. While Fuel Cell produce approximately 129kW. At the time 00 to 4:00, BESS starts to charge because the excessive power is produced by RERs and Fuel Cell as compared to load demand. From 12:00 to 19:00, BESS discharged and provided 96kW to fulfill the required load demand. Hydrogen utilization is from 138 to 55 kg/day in the summer season as illustrated in **Figure 4.6**.

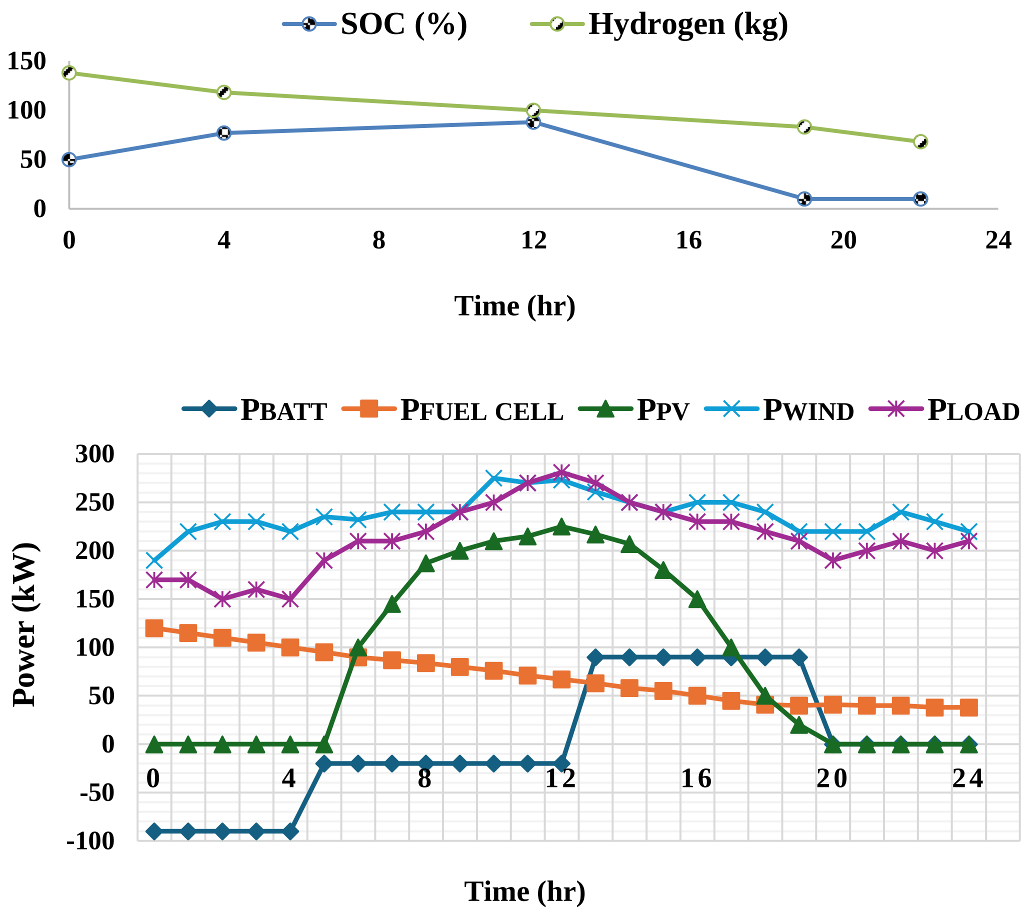


Figure 4.6: Summer season MATLAB/Simulink results (a) Hydrogen & SOC (b) Power

4.4 Economical Assessment

The economical assessment of proposed case is evaluated using Homer Pro software, its total initial capital, replacement, and O&M costs of each component used in a proposed Microgrid setup is estimated. The obtained results present that wind turbine has the highest Cost in comparison to other components because of the major contribution of wind turbine in electricity production in the following system. As wind energy resources have greater potential for electricity production in Sindh, it has a major contribution to this system. This proposed system has approximately $1.47 million capital cost, approx. $0.73 million replacement cost and approx. $1.06 million O&M cost as shown in **Table 4.1** and cost of each energy resource used in the proposed system is shown in **Figure 4.7**.

Table 4.1: Evaluation of each component's cost.

Components	Capital Cost ($)	Replacement Cost ($)	O&M Cost ($)	Total Cost ($)
BESS	150,000	78,278.56	101,618.56	329,897.12
Fuel Cell	225,000	0	258,345.64	474,498.54
Electrolyzer	240,000	142,650.42	195,420.31	469,136.80
Hydrogen Tank	140,702	28,530	54,000	201,445.92
Wind Turbine	360,000	237,750	281,405.24	697,599.40
PV Panel	300,000	198,125.59	170,280	527,108.67
Inverter	54,349.89	47,271.43	84,968.53	186,589.81
Total	**1,469,349.86**	**732,606.79**	**1,061,069.75**	**2,886,276.27**

This system's estimated lifetime is 30 years with a Nominal Discount Rate is 8% and Real Interest Rate is 0.9%. Moreover, Homer pro calculated system's total Net Present Cost and LCOE using Eq.(3.8) and Eq.(3.9) which is approx. $2.9M and 0.1518$/kWh, its Present Worth is $6,580, Annual worth savings $253. LCOE of wind energy and solar energy is 0.0253$/kWh and 0.0452$/kWh, respectively. Total un-met electric load demand is 1945kWh per yr. which is around 0.266% and excess electricity produced in a system is approx. 112,345kWh/yr. which is around 4.3%.

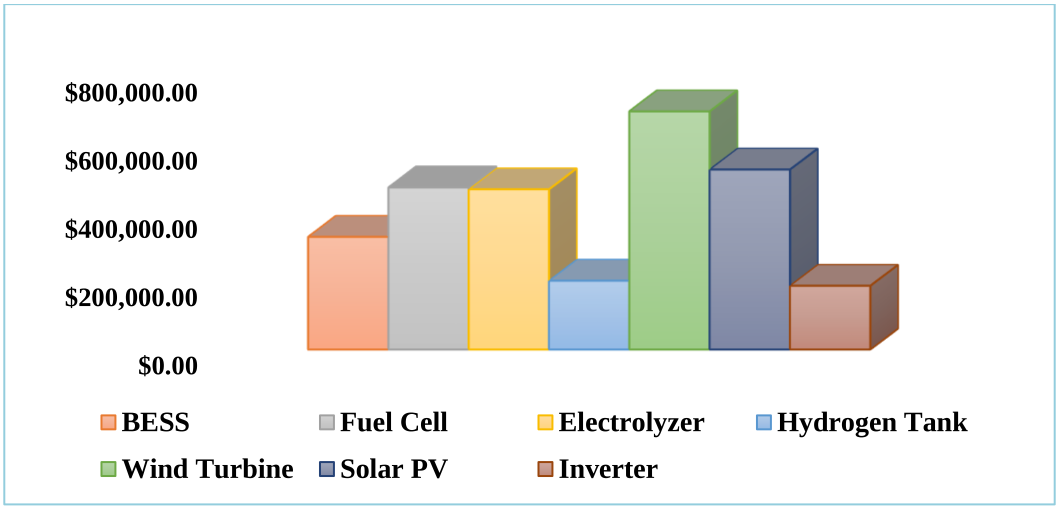


Figure 4.7: Total estimated cost of components.

4.5 Cumulative Cash flow

The cumulative cash flow over a project lifetime for 30 years is illustrated in **Figure 4.8.** This figure illustrate that it will help stakeholders to invest more and more in adapting renewable energy resources in near future for better solution to reduce rural electrification problem. If a project is based on reduction of the carbon footprint, then there will be increment in providing more funds for developing the Renewable energy resources-based projects.

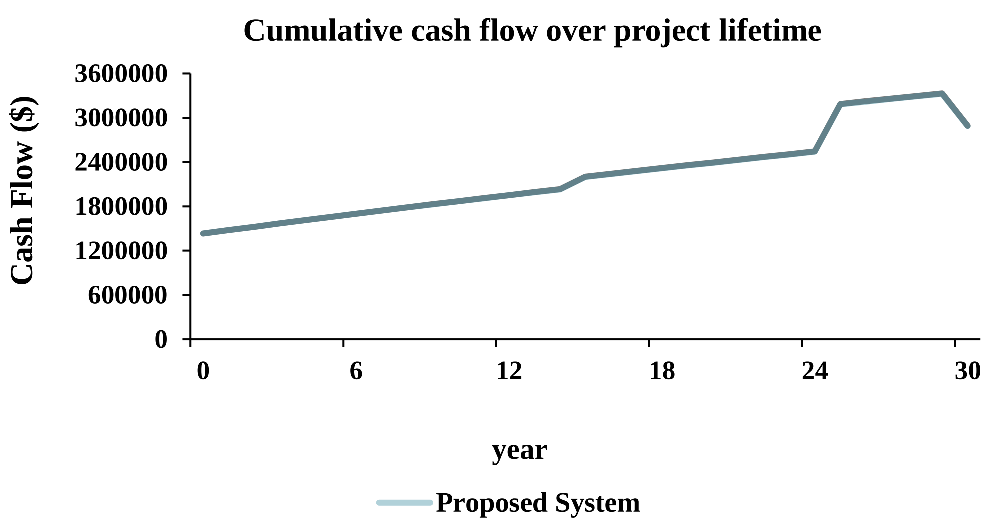


Figure 4.8: Cumulative cash flow of project over lifetime

4.6 Estimation of total Power production per month

There is huge potential of wind energy production in areas of Sindh, Pakistan. Therefore, in this project wind resource has more contribution because of average wind speed site area of Nooriabad, Sindh is high as compared to many other areas of Sindh. It also depend on availability of different sources in particular areas as well as weather of selected location also matters. The Fuel cell has high capital cost so it has least contribution in power production because to develop a project having lowest Net Present Cost. On average almost 50% of power is generated from wind turbine, 35% from solar PV and 15% from fuel cell monthly. The average monthly electricity generated from RER and Fuel Cell is obtained using Homer pro software. The total contribution of each source in electricity production per month is represented using **Figure 4.9,** and is calculated using Homer pro software.

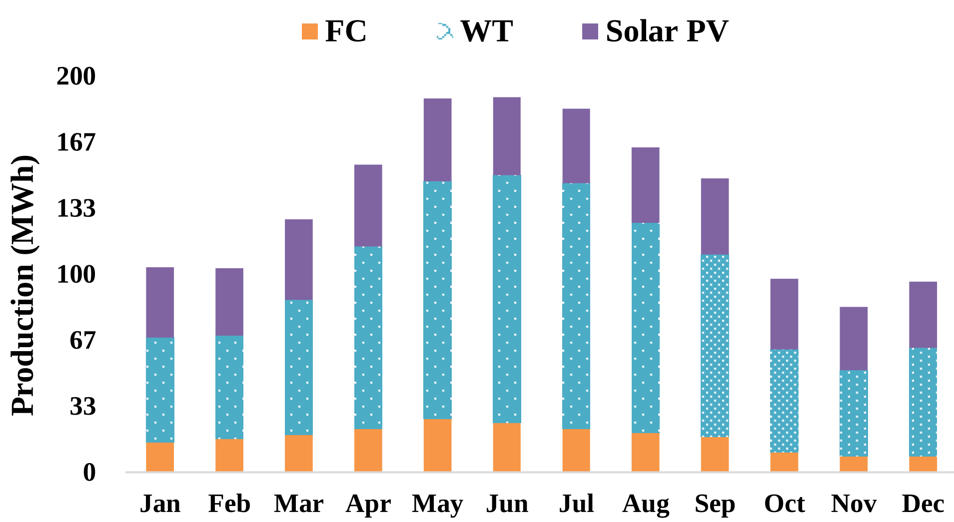


Figure 4.9: Power supplied by FC, RERs, and BESS annually.

4.7 Emission

Furthermore, the total emissions produced in a system summarized in **Table 4.2**, which shows that the system is more sustainable and should be highly adopted as compared to previous studies. The Fuel cell does not produce much carbon dioxide and this proposed system presents that more sustainable projects including fuel cell with Renewable energy resources can be adopted to mitigate emissions.

Table 4.2: Assessment of total emissions per year

QUANTITY	VALUE (KG/YEAR)
CO_2	1340
CO	2230
Unburned Hydrocarbons	1030
SO_2	0
NO_2	490
Particulate Matter	820

SUMMARY

As Pakistan is experiencing some serious electrical issues, and the situation is getting worse now-a-days. For power generation, conventional sources such as thermal, coal, and natural gas are still employed, which are insufficient to meet current load demand and not suitable in sense of environmentally friendly system. Most remote areas which are far away from national grid lack basic electricity infrastructure and required large transmission lines, which are technically impossible and have costly infrastructural difficulties. There’s a need to provide reliable, inexpensive, economical, and environmentally friendly energy to improve people's social lifestyles, as well as to promote development growth related to health, education and other different sectors. By keeping in view of Pakistan’s large potential for non-conventional energy resources as a second option, hybrid renewable energy systems/hybrid micro-grids are better ideal for providing power to rural areas. The main focus of this presented project is to provide an affordable, efficient, and reliable energy to those areas of a country which still lack basic needs to make economic growth of a country.

The depletion of fossil fuels and world energy demand is still rapidly increasing. Many traditional power generating sources are still facing the environmental issues. According to the literature review, many authors suggested non-conventional source of energy should be used to fulfill electrification demand of isolated or rural regions where extension of grid is both costly and not feasible. Numerous research papers on Microgrids or on hybrid mode of renewable energy systems have published in literature, and various tools and methodology for the analysis and design of Microgrids have been offered. Some studies discussed micro-grid electric energy management and control systems, while others discussed the techno-economic and environmental impact of micro-grids in developing nations' rural regions. Similar studies for Pakistan's various rural and urban locations are also reported in the literature. These literature reviews demonstrate relevant information and background for the proposed research project.

This study summaries the economic analysis or technique used to perform this research. Initially, the electric load data, as well as the potential and profiles of remote

village's non-conventional sources, are collected for the designing of hybrid Microgrid. The methodology of the system presented the electric load data, as well as the various daily, monthly, and seasonal electric load profiles. The collected average solar radiation and wind speed per month is also observed and evaluated. The MATLAB/ Simulink is then used to simulate for different cases. Different input variables were required for the simulation. The input variables include different component costs (solar panel, wind turbine and BESS), such as original capital cost, operation cost, maintainance, and replacement cost, which are determined by a market study.

All simulation results and discussions are included. Economical and technical analysis of hybrid Microgrid system is analyzed. The techno-economic analyses the viable technically and economically configuration of PV, WT and Fuel Cell with BSS is performed using both MATLAB/Simulink and Homer pro software.

CHAPTER 5 : CONCLUSIONS AND FUTURE RECOMMENDATIONS

In this chapter the conclusions drawn by integrating RER (Wind, Solar) in a Microgrid with fuel cell is discussed and future innovative possibilities are also mentioned.

5.1 Conclusions

The above results indicate that the presented system defined as an integration of hybrid renewable energy resources like wind and solar with fuel cell, would be helpful for stakeholders to invest more in renewable energy resources as compared to conventional resources shortly due to the extensive usage of electricity in following ways,

- As hydrogen based microgrid system in a hybrid mode is assumed to be more economical and sustainable as compared to other previous studies.
- Average load of 2000 kWh/day is selected for location Nooriabad, Pakistan and peak load of 281 kW in summer (July) is achieved and the results obtained by following the proposed system are significantly better than previous studies.
- The system has approx. $2.9M NPC and 0.1518$/kWh LCOE. It's assumed that in the future, the usage of Renewable energy Resources will be economically more viable and adaptable, especially in Sindh.
- According to the results, the highest load demand is in summer so mean output power of approx. 550kW is attained in summer season and lowest load demand is in winter so average output power of approx. 450kW is obtained in the winter season.
- Other renewable energy resources like Biomass and Hydropower, etc. should also be taken into consideration in combination with different renewable energy resources to establish it in a reliable and economically feasible hybrid system.

5.2 Future Recommendation

The work on this proposed system can be extended in future by integrating FC, Renewable energy resources with Electric Vehicles. The operation hours can also be extended or other renewable energy resources can also be utilized like (Biomass, Hydropower etc.).

- Increment in power of fuel cell, especially AFC, so it can be used in marine. In a case of long term goals, power required for marine system fuel cell, increase steadily to attain goal of fuel cell providing medium to high payload capacity, providing full power to large tonnage ships for intercontinental transportation.
- Ongoing research and development on fuel cell should focus on improving performance of renewable energy systems and fuel cell technology. This includes increasing the conversion of solar energy and wind energy, plus increasing energy and durability of fuel cell.
- Increasing the scale of hydrogen production is an important consideration for the generalization of fuel cell. This includes energy efficiency, biomass conversion and other renewable energy resources to increase efficiency, reduce costs and improve the economy.
- Integrating hybrid renewable energy with fuel cells into smart grids can improve energy production, distribution and use. Advanced grid management technologies such as demand response, power forecasting, and real-time monitoring can help improve the efficiency and reliability of systems.

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