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TECHNO-ECONOMIC EVALUATION OF STORAGE TECHNIQUES OF DC MICROGRID FOR RURAL HEALTH CARE SYSTEM

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ABSTRACT

Socioeconomic development in Pakistan is still a source of contention, especially for the mixed rural and urban areas. In Sindh, most mixed rural populations have a deficiency in the utilization of electricity. Because of that, locals no longer have access to contemporary healthcare. To address the proclaimed issue for remote areas regarding the health care facility, this research presents a techno-economic evaluation of a DC microgrid made up of solar PV with several storage options, including lead acid batteries, lithium-ion batteries, and hydrogen storage systems. According to WHO categorization, Chachro Village in Tharparkar is proposed to have a group II health care system. First, the PV, Lead Acid, and Lithium-ion Battery system are analyzed and then PV, Lead Acid, Lithium Ion, and Hydrogen system is analyzed. Subsequently, the DC microgrid that satisfies the load demand for rural health care based on the lowest cost of energy is determined. As a result, the PV/Hydrogen system is determined to be the least expensive of all systems. The needed design for rural health care with the lowest NPC, ICC, and COE consists of a 5.5 kW solar PV system, 4 kW Fuel cell, 5 kW Electrolyzer, 20 Kg hydrogen tank, and 8 kW converter and the feasibility of a hydrogen storage system for the Chachro Village rural health clinic has been established.

Keywords: DC Microgrid, Solar PV, Hydrogen, Batteries, Techno-Economic Analysis.

I. INTRODUCTION

According to U.N the most prerequisite thing for any nation is the health care system [1]. A statistical report by WHO reveals that four million people die yearly from nearby pollution activities. Due to household pollution, pneumonia, lung cancer, and chronic obstruction pulmonary disease may appear, and these effects can be treated well by medical techniques [2]. Around the world, 1.1bn people lack access to power. The Sustainable Energy Goal of the World Bank seeks to provide universal energy access by 2030. It is predicted that the 7.3bn people who currently live on Earth will grow to 8.5bn by 2030 and 11.2bn by 2100. [3]. The vast majority of those impacted by this circumstance belong to remote areas of Asian and African countries [4]. In contrast, a sizable number of Pakistanis reside in remote areas, most of them lacking access to power. Pakistan, onwards to the developing stairs, is dealing with huge financial crunch, conservation of energy, and with societal progress, which has resulted in drastic increment. The total requirement of power for the country is 25,000 Megawatts (MW), with a projected increase to 40,000 MW by 2030. [5]. However, the majority of rural areas lack access to power. Forty-eight percent of Sindh's population lives in remote areas, and almost 13,500 villages are still not entertained with usage of electricity [6].

Pakistan has been confronted with a variety of environmental issues. Droughts, floods, dengue fever, coastal erosion, and desertification are among the most serious of these concerns. Drought is a recurring occurrence in Sind province's sandy area of Tharparkar. This drought, which began in 2013, has now transformed into a lethal famine, resulting in a severe humanitarian disaster for local residents [7]. Tharparkar is among Sindh's most vulnerable drought-prone locations. This is a desert-like rural region that covers more than 19,000 square kilometers. Merely nine villages in this district are under the jurisdiction of barrages, while the remaining 166 villages rely on rainwater to cultivate food and forage for their cattle[8]. Pakistan has abundant renewable resources, includes PV energy, wind energy, hydro dams energy and biofuel energy with a tendency of 2900 Gigawatt, 346 Gigawatt, 6 Gigawatt and 5 Gigawatt of generation respectively [9]. Also, Sindh has abundant renewable energy (RE) resources, and the government must utilize renewable resources to generate electricity [10].

This research presents a techno-economic evaluation of a DC microgrid made up of solar PV with several storage options, including lead acid batteries, lithium-ion batteries, and hydrogen storage systems to address the power generation issue for remote areas regarding the health care facility.

II. LITERATURE REVIEW

Microgrids are poised to become a vital component of future electricity networks. Renewable energy sources, like small-scale power plants, present numerous benefits in contrast to conventional large-scale power plants. These advantages encompass enhanced power quality and reliability, minimized power losses, and decreased network congestion. This is due to the fact that microgrids are built in close proximity to the sources of distributed energy and utilize renewable generators. A study conducted in 2015 anticipated significant growth in the microgrid industry, projecting a more than 3.5-fold increase by 2020, resulting in a market value exceeding $829 million [11]. Microgrid systems relying on renewable energy sources hold promise for ensuring consistent electricity supply and achieving energy self-sufficiency in agricultural contexts [12]. While AC electricity systems have been widely employed to meet energy needs for decades, challenges emerge when attempting to electrify remote regions with AC electricity. These challenges encompass losses, expenses, and voltage profiles. Utilizing a DC electrical system powered by renewable energy generators like photovoltaic (PV) and fuel cells (FC) emerges as a feasible solution for providing electricity to both rural and urban areas [13]. A variety of studies have delved into DC microgrids employing RPGs as their primary energy source. In a study conducted, a thorough comparison of AC and DC microgrids was performed, taking into consideration various factors, including available loads, control technology, circuit analysis, and efficiency, hence findings indicated that DC microgrids were more efficient and less complex than AC microgrids [14]. When DC microgrids are coupled with efficient storage systems, they can become more dependable than AC microgrids due to on-site power generation capabilities [15].

Supplying energy to health clinics in remote communities can be a challenging task, owing to the rugged terrain and considerable distances from existing power grids. The use of renewable energy sources presents a promising long-term solution to this issue [16]. The use of hybrid renewable energy systems has been explored by various writers as a potential solution to improve rural health care delivery across the globe. Olatomiwa et al. [17] designed technical and financial hybrid power systems that utilized diesel system with PV and Wind for selected locations in Nigeria, using hybrid optimization software (HOMER). The storage component used in the hybrid system was a battery. The authors aimed to improve rural health care by utilizing local renewable energy resources. The study's findings revealed that for Port-Harcourt, hybrid systems comprising of PV/wind/diesel/battery were the most optimal option, whereas for rural health clinics located in different areas in Nigeria, hybrid systems integrating PV, Diesel and battery were the most appropriate choice. In a different study, Babatunde et al. [18] carried out a technical and financial assessment to establish a hybrid off grid renewable system for rural healthcare located in Six districts in Nigeria. To determine the most financially viable option, the study employed PV/wind/diesel/battery system as potential components for the designed off grid system. The PV, diesel and battery combination was feasible for rural health clinics throughout Nigeria, reported a net present cost ranging from $12,779 to $13,646, with a corresponding renewable percentage (RF) ranging between 70% and 80%. The study also reported that (COE) to be within the range of 0.507 to 0.542 $/kWh. In a similar vein, Opoku et al. [19] study was conducted on three distinct Photovoltaic (off grid) systems to enhance energy availability and healthcare services in Ghana. The authors recommended the use of a 3.0 kW solar PV system with a battery, as it would suffice to deliver essential electricity, given that their daily energy requirements ranged between 4.30 to 7.58 kWh.

Most power grids in many countries rely on large power plants that use fossil fuels or nuclear energy to generate electricity. These power plants are often located far from urban areas, which means that transmission and distribution networks have to be built to provide electricity to metropolitan areas. In rural areas, where access to energy is limited, it is important to find solutions that include these communities in the power system industry. Renewable resources like solar, wind, and water can be more cost-effective and environmentally friendly in some remote areas where it is not practical or affordable to upgrade the electric grid [20]. Luta et al. [21] conducted a study in Napier, an agricultural hamlet situated in South Africa's Western Cape province, utilizing HOMER Pro software to assess the viability of grid expansion and constructing an off-grid hybrid renewable energy system. The primary objective of the authors was to identify the most practical option for providing electricity to the region. To assess the options, they used net present cost (NPC) analysis. The results showed that, compared to grid extension, a renewable energy system was not a cost-effective solution for the specified region.

However, unlike traditional sources, most renewable source-based systems have supply problems because of intermittent characteristics under fluctuating climatic conditions, which affect energy output. Renewable source-based systems can be linked with non-renewable systems or energy storage technologies to solve this problem and guarantee a steady supply of energy. One of the major concerns associated with using renewable energy sources to provide microgrid solutions is their inconsistency concerning factors such as wind speed and sun irradiation [22]. Using battery storage technologies, most frequently deep-cycle lithium-ion batteries, may generally solve this issue [23]. The cost of replacing it three to four times over the life of the microgrid's life is a drawback of this storage technology. Moreover, batteries are recognized as contributing to environmental and health problems if they are not properly discharged [24]. Consequently, hydrogen may be regarded as a prospective storage solution that could address these challenges in the future. Hydrogen storage solutions hold great promise for microgrids powered by renewable energy in remote areas where grid access is financially unfeasible [25]. Recently, metal hydride (MH) storage has become increasingly popular in various systems, including microgrids (G), heat pumps, refrigeration, and thermal energy storage [26]. There are different methods available for storing hydrogen, including in liquid form, high-pressure cylinders, and metal hydride (MH) storage. Among these, MH storage has the highest volumetric efficiency, with a capacity of 150-kilogram cubic meter. In contrast, liquid storage has a capacity of 70-kilogram cubic meter, and high-pressure storage has a capacity of 40-kilogram cubic meter [27]. Compared to low temperature and high-pressure storages, the utilization of Metal-hydride (MH) provides numerous benefits when storing hydrogen in solid form under specific operating temperatures and pressures [28]. The advantages of Metal-hydride (MH) hydrogen storage comprise its portability, security, eco-friendly, versatility, absence of moving components, and a lifespan of 30,000 charging/discharging cycles [29]. The storage technique involves the use of water electrolysis to convert surplus electricity generated from renewable energy systems into hydrogen, which can be reconverted into electricity as needed through fuel cell technology, offering flexibility in generating clean electricity [30]. A comparative study for different renewable (PV/WT/FC) energy combinations is performed and the best system is selected to satisfies the educational load [31, 32]

Several authors have conducted techno-economic analyses of microgrid systems with different power providers and storage methods. For example, Phurailatpam et al. (2018) [33] evaluated the performance of a DC microgrid powered by solar, wind, and diesel generators for rural and urban loads in India, using the HOMER simulation program. Said-Mohamed et al. (2018) [34] proposed a microgrid system with renewable energy sources and hydrogen storage to solve the load shedding issue in Comoros, which was developed and examined using HOMER. Nadaleti et al. (2020) [35] suggested using excess energy from wind and hydropower plants in Brazil to produce hydrogen. The study by Kitson et al. (2018) [36] evaluated the sizing and performance of microgrid components for farther locations in Nepal. The study utilized Photovoltaic and wind generators to power the energy storage system and loads. A system that combines photovoltaic (PV) and biomass technologies was studied by Shahzad et al. (2017) [37] for its techno-economic feasibility in supplying electricity to residential and agricultural loads in a small village in Punjab province, Pakistan. Fathi and Outzourhit [38] reviewed the literature on lead-acid battery energy storage and found that hydrogen storage is an additional efficient energy storage technology for PV generators. Kumar et al. (2019) [28] proposed the utilization of water electrolysis for the production of hydrogen that can be stored in a dedicated storage system.

According to Colbe et al. (2019) [39], efficient storage options for the hydrogen generated by PV include metal hydride (MH) and high-pressure cylinders. According to Kumar et al. (2017) [40], MH storage has exothermic and endothermic processes during hydrogen absorption and desorption, respectively, necessitating the use of cooling and heating systems. Belkhiria et al. (2017) [41] and Kumar et al. (2020) [42] both proposed methods to improve the efficiency of hydrogen discharge in fuel cell (FC) operation by utilizing induction heating and water heating systems to warm the metal hydride (MH) used in the process.

III. METHODOLOGY

Selecting a location to assess, defining resources, stating input-data (monthly-average solar irradiance) for the selected site i-e Village Chachro Tharparkar, analyzing the medical health clinic equipment for group-II rural health clinic system as per the suggestion of WHO, calculating the rural health clinic load demand based on the physical survey, simulation modeling of DC Microgrid of two cases comprising of five scenarios i-e case1 for PV/Li and PV/LA and Case 2 for PV/Hydrogen, PV/Hydrogen/Li and PV/Hydrogen/La and choosing of the most cost-effective situation based on NPC and COE have all been part of this study.

Tharparkar is a district of Sindh located in southern Pakistan with a population of 20,000, and it is an area rich in culture where people rely on subsistence farming. Unfortunately, the locals face severe shortages of food and water, and numerous other social issues like health care problems, environmental problems, and epidemics such as measles and diarrhea. The most critical problems requiring urgent attention are the shortages of food and water, which are leading to the deaths of people in the area. The Sindh government declared Tharparkar a drought-hit zone, yet the residents have not received effective aid. The absence of immediate facilities has resulted in the death of over 2000 children below five years due to hunger and waterborne diseases since 2011. [43]

This study aims to provide a solution to the electricity power challenges faced by remote areas of THAR and other parts of Pakistan. The study focuses on the technical feasibility of utilizing storage technologies with renewable energy sources (RES).

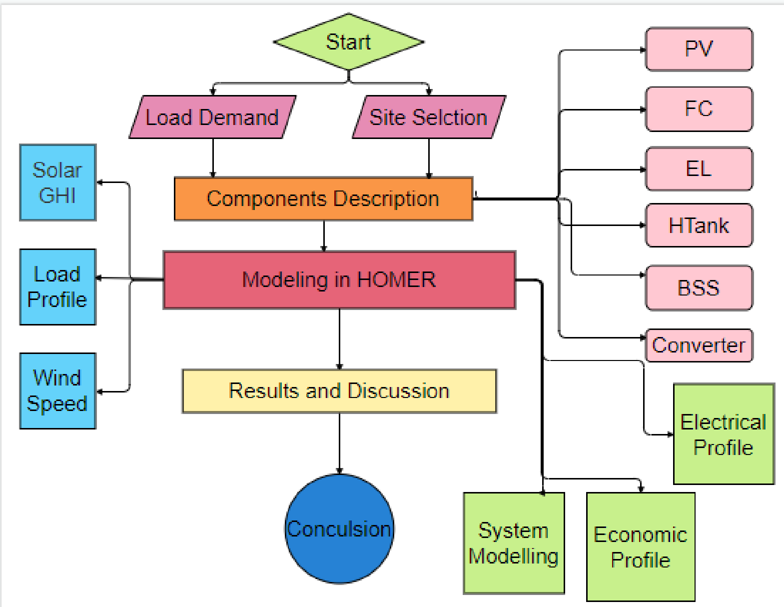

Figure 1: Research framework for Current study in Tharparkar

A study was carried out to assess the potential of solar irradiation to supply electricity to rural areas in five regions of Sindh: Panoaqil, Badin, Mirpukhas, Nawabshah, and Kambar. The findings indicate that an off-grid system utilizing solar power can provide electricity at a significantly lower cost of 6.87/kwh Pakistani rupees, compared to the cost of conventional electricity which is 20.79/kwh Pakistani rupees. The recommended tilt angle for optimal power production has also been provided for these locations. Moreover, the study explores the possibility of utilizing solar energy for generating electricity and determines the highest amount of annual

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solar irradiation in the Nawabshah region (5.49 kWh/m2), followed by Kambar (5.48 kWh/m2), Panoaqil (5.45 kWh/m2), Mirpurkhas (5.41 kWh/m2), and Badin (5.39 kWh/m2) [44].

This study focuses on the village of Chachro in Tharparkar, and uses data from NASA database to analyze solar irradiation levels in the area. This information is presented in Figure 2 and Table 1.

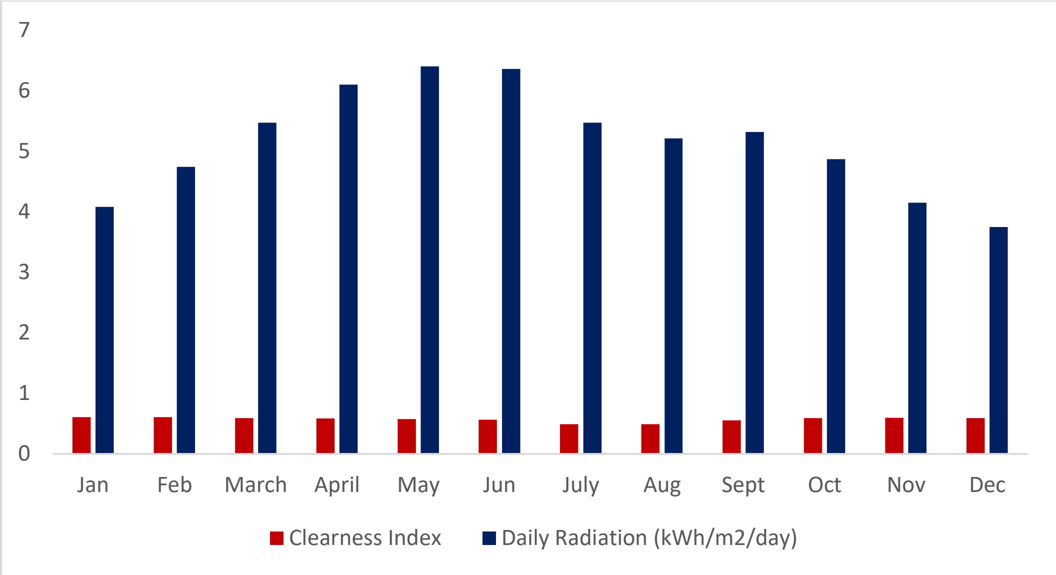

Figure 2: Solar Irradiation Data for Chachro Village Tharparkar

Table 1: Annual Average Irradiation for Chachro Village Tharparkar

Month	Clearness Index	Daily Radiation (Kwh/m^2/day)
January	0.609	4.080
February	0.606	4.740
March	0.593	5.470
April	0.586	6.100
May	0.579	6.400
June	0.566	6.360
July	0.492	5.470
August	0.492	5.210
September	0.554	5.320
October	0.593	4.870
November	0.598	4.150
December	0.592	3.750

MODELING OF LOAD

The study analyzed the group-II rural health clinic system according to the WHO classification based on the population of the village, and the medical equipment list issued by the WHO for group-II rural health care system. The energy requirement for the group-II health care system falls between 10-20kwh per day. A physical survey revealed that the population of Chachro is approximately 3500 and is located about 50-60 km away from the national grid at MITHI, with several small villages linked to it. While a government dispensary is present in the area, it is not advanced enough to provide facilities to the locals, and people have to go to the capital of THARPARKAR for advanced treatment. The common diseases observed in the area are T.B, appendix, diarrhea, allergy, fever, surgery, B.P, malaria, and cough. Based on the prevalent diseases, Table 2 suggests the installation of specific equipment.

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Table 2: List of Equipment suggested for group-II rural Health clinic system

Sr.no	Equipment	Quantity	Power ratings (W)
1	Refrigerator Vaccine	1	70
2	Refrigerator Blood Bank	1	90
3	Refrigerator Non-Medical	1	150
4	Nebulizer	2	50
5	Ultrasound Machine	1	600
6	Incubator	1	500
7	Microscopes	2	10
8	Hematology Analyzer	1	200
9	Labautoclave	1	1800
10	Vaccumaspirator	1	80
11	Suction Apparatus	1	150
12	X-Ray Machine	1	2000
13	ECG	1	70
14	Oxygen Concentrator	1	300
15	Savors	8	25
16	Fan	4	70
17	Motor	1	600
18	Mobile Charger	4	5
19	TV	1	120

Table 3: Load Modelling for rural health clinic system

		Quantity	Power	Total	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	Refrigerator Vaccine	1	70	70						70	70	70	70	70	70	70	70	70	70	70	70	70						
2	Refrigerator Blood Bank	1	90	90							90	90	90	90	90	90	90	90	90	90	90							
3	Refrigerator Non-Medical	1	150	150								150				150	150						150					
4	Nebulizer	2	50	100												100	100											
5	Ultrasound Machine	1	600	600												600	600	600										
6	Incubator	1	500	500												500	500	500	500									
7	Microscopes	2	10	20												20	20	20	20									
8	Hematology Analyzer	1	200	200													200	200										
9	Labautoclave	1	1800	1800									1800					1800										
10	Vaccumaspirator	1	80	80													80	80										
11	Suction Apparatus	1	150	150													150	150										
12	X-Ray Machine	1	2000	2000													2000											
13	ECG	1	70	70													70	70										
14	Oxygen Concentrator	1	300	300												300	300	300	300									
15	Savors	8	25	200	200	200	200	200	200	200												200	200	200	200	200	200	200
16	Fan	4	70	280											280	280	280	280	280	280	280							

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The load profile for the location (village Chachro District Tharparkar) was developed by conducting surveys to determine the frequency of patients visiting the government dispensary in the area. Based on the records of the dispensary, the load was modeled and is presented in Table 3.

Based on the load modelling, the total connected load of the rural healthcare system in Chachro is estimated to be 7.35 kW, with the highest average peak demand of 7.65 kW per day. The average peak per day is calculated to be 14.83 kWh.

DETAILS CHARACTERISTICS FOR HYBRID ENERGY SYSTEM COMPONENTS

Climate variables, especially sun irradiance and system temperatures, greatly influence how well a photovoltaic module works. Four non-linear climatic factors that appear to affect a solar module's performance include temperatures, radiation intensity, exposure inclination, and radiation period. Using the scatter factor principle, the highest possible power output offered by the photovoltaic cells may be represented as follows [45].

$$P_{pv} = V_{oc} \times I_{SCV} \times \eta_{MPPT} \qquad (1)$$

Here V_{oc} is the open-circuit voltage, I_{sc} is the short-circuit current, and MPPT is the maximum output tracking efficiency of the photovoltaic cell since solar panels are frequently equipped with one to maximize the output power.

The efficiency of an Electrolyzer is the rate during which electricity is converted to hydrogen and is proportional to the energy contents of hydrogen based on the larger heating value divided by the amount of electricity used.

The calculation of hydrogen tank independently is used to determine the power capacity of the mentioned hydrogen storage tank regarding the electricity demand. HOMER uses the equation below to calculate a hydrogen tank's independence. [46].

$$A_{htank} = \frac{Y_{htank} LHV_{H2}\left(24\frac{h}{d}\right)}{L_{prim,avg}\left(3.6\frac{Mj}{kWh}\right)} \qquad (2)$$

where Yhtank is the weight in kilograms of the hydrogen tank, LHVH2 is the energy content of hydrogen (lower heating value), that is 120 MJ per kilogram, and Lprim, ave is the average daily main load in kilowatt hours.

The HOMER program calculates a fuel cell's electrical efficiency as the produced electric power divided by the chemical energy of the fuel it consumes, as illustrated below [47].

$$\eta_{FC} = \frac{3.6 E_{FC}}{M_{H2} \cdot LHV_{H2}} \qquad (3)$$

In the preceding equation, the letters E_{FC}, M_{H2}, and LHV_{H2} represent the fuel cell's total annual hydrogen consumption in kilograms, megajoules per kilogram, and kilojoules, respectively.

DC electricity produced by solar and hydrogen fuel cell modules is stored in battery banks. The resulting power meets the minimal electrical requirements of remote areas at any time the energy-producing systems are unable to provide sufficient power. The autonomy and longevity of the batteries represent important considerations when deciding the battery banks' capacity. The following describes how HOMER evaluates the battery's performance over a period of time.(R_{batt}): eq (5) [48].

$$R_{batt} = \begin{cases} \frac{N_{batt} \times Q_{lifetime}}{Q_{thrpt}} & \text{if limited by throughput} \\ R_{batt,f} & \text{if limited by time} \\ MIM\left(\frac{N_{batt} \times Q_{lifetime}}{Q_{thrpt}} \times R_{batt,f}\right) & \text{if limited by throughput and time} \end{cases} \qquad (4)$$

The acronyms Nbatt, Qlifetime, Qthrpt, and Rbatt refer to the quantity of batteries in a storage bank, the amount of energy that can be stored for a lifetime (in kWh), the amount of energy that can be stored annually (in kWh/yr), along with the amount of time that reserves can be left floating.

Bi-directional converters are necessary for both AC to DC and DC to AC conversion since all renewable energy (RE) resources convey DC power instead of the necessary AC power. HOMER adjusts the size of the bi-directional converter when the power transfer depends on energy sources like solar and fuel cells that have different consumption timings.

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HOMER SOFTWARE

HOMER stands for Hybrid Optimization Systems for Electric Renewables. It's one of the most widely used programs. HOMER was developed in 1993 by Canadian company Mistaya Engineering for the American National Renewable Energy Laboratory (NREL). A micropower optimization method is used to assess designs of both grid-connected and off-grid hybrid systems for several uses. HOMER does both sensitivity analysis and optimization. With the help of HOMER, the system analyses the power equilibrium while considering different element counts and configurations. According to Total Net Present Cost (TNPC), the program has displayed a collection of configuration outcomes in an organized manner. The system calculates costs for things like gasoline, interest, replacement, operating, and maintenance fees. Sensitivity analysis can be used to quantify several factors, such as solar radiation and fuel cost. It is simpler to identify between configurations and evaluate their financial viability thanks to the way HOMER displays simulation findings in various tables and graphs. Figure 3 shows the input steps HOMER follows during the simulation process.

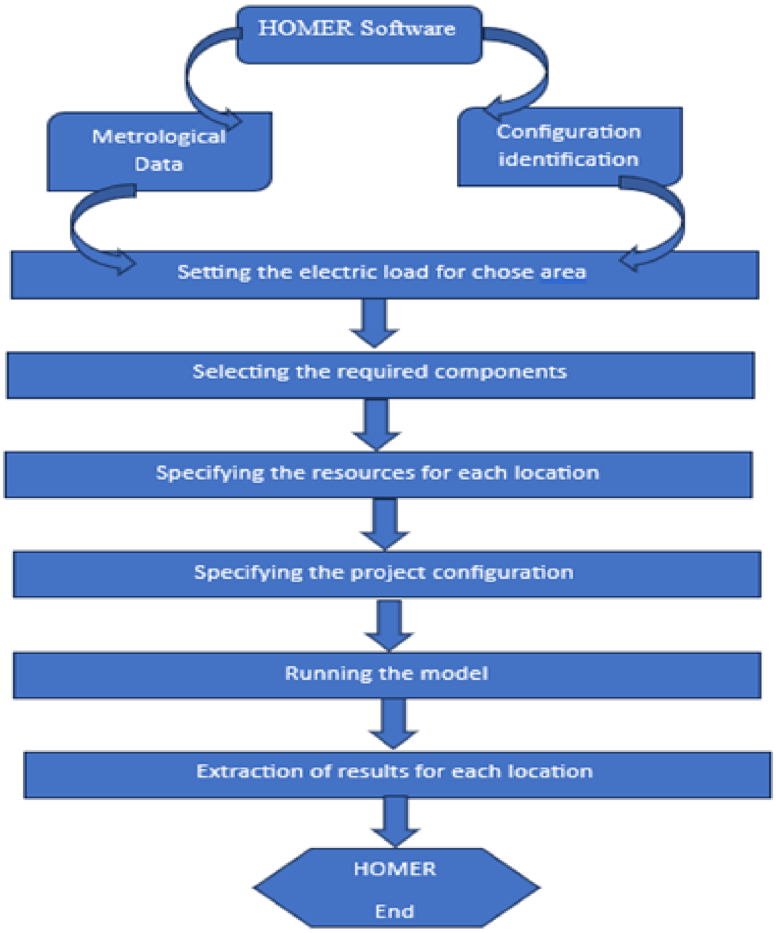

Figure 3: Steps utilized in HOMER software.

The concept of microgrids involves creating a small, self-contained energy network that connects localized power generation sources, energy storage systems, and users. There are two modes of operation for microgrids: grid-connected and stand-alone. The three primary components of a microgrid are power generation, energy storage, and loads, with the load being the driving factor for power generation. Utilizing renewable energy sources like solar and wind can ensure the power production of a microgrid is entirely eco-friendly, but these sources are dependent on environmental factors, leading to intermittent generation. To mitigate this issue, energy storage systems are necessary.

A DC Micro-Grid system has been designed and simulated to provide power to the rural health clinic load using storage techniques. The system has been modeled using HOMER software and the results have been illustrated in Figure 4.

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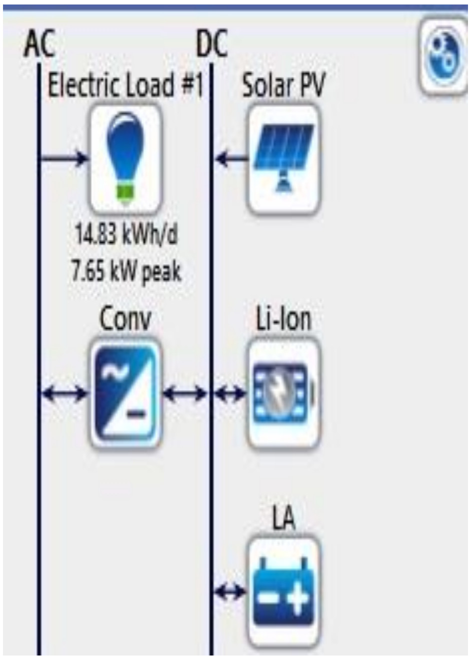

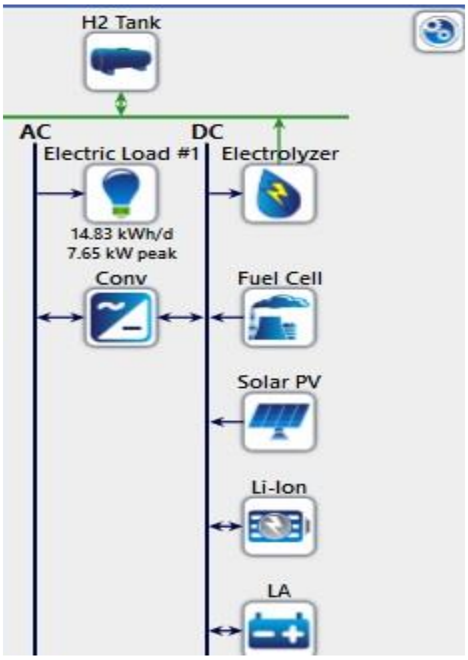

Figure 4: (a) Simulation model for case 1 **Figure 4: (b)** Simulation model for case 2

The study report examines the implementation of a DC microgrid system that incorporates LA and Li-ion batteries, alongside hydrogen storage coupled with fuel cell, electrolyzers, and hydrogen tank. These technologies are utilized to support the intermittent power supply from sources such as solar and wind, where LA and Li-ion batteries serve as backup power sources. Notable distinctions between LA and Li-ion batteries encompass energy density, cycle life, self-discharge rate, cost, maintenance requirements, and weight. Furthermore, the study investigates a hydrogen-based energy storage system, employing an electrolyzer to generate hydrogen from excess energy, a hydrogen tank for storage, and a fuel cell to convert hydrogen into electricity during periods of low energy generation. This particular system presents enhanced performance and the environmental advantage of depleting hydrogen without detrimental effects. Additionally, hydrogen storage remains unaffected by temperature or storage duration.

The table 4 displays the financial information of the components used in the proposed model, as input into HOMER. (T.R Ayodele et al. 2021 [49], Mohd Alam et al. 2020 [50], Kuldeep Kumar et al. 2019 [28] & M. Kashif Shahzad et al. 2017 [37].

Table 4: Financial data of system components

Name	Capital ($)	O&M ($/yr)	Replacement ($)
PV	1000	55	750
Fuel Cell	4000	0.01	3000
Electrolyzer	1100	10	825
Li Battery	2500	300	1000
Lead acid Battery	2000	200	1000
Hydrogen Tank	1000	00.0	750
Converter	400	10	300

IV. RESULTS AND DISCUSSION

In this study, a stand-alone DC microgrid with three distinct storage systems LA and Li-ion batteries, and hydrogen is being analyzed from a techno-economic perspective. The goal is to produce power with renewable energy by using solar cells. Surplus solar energy can be either transferred to an electrolyzer for a chemical reaction that creates hydrogen gas and stores it in a hydrogen storage, or it can be stored in batteries. A fuel cell is then utilized to produce power using hydrogen gas.

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HOMER replicates every system configuration for the chosen location that can manage the indicated load under the specified renewable resource circumstances. In ascending order of energy cost, it calculates the energy balance for each possible system configuration.

CASE 1

In this case, HOMER simulates the use of PV/Li batteries and PV/La batteries to meet the load demand, as depicted in Figure 5.

Architecture					Cost				
Solar PV (kW)	Li-Ion	LA	Conv (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	O&M ($/yr)
7.80	15		8.00	CC	$1.64	$113,254	$5,009	$48,500	$5,009
7.80		21	8.00	CC	$1.87	$128,752	$5,860	$53,000	$4,709

Figure 5: PV/Li and PV/La scenario

Based on the optimization results, the PV/Li Battery system has the most cost-effective Net Present Cost (NPC) of $113,254 with a corresponding Cost of Energy (COE) of $1.64. Detailed information regarding the Net Present Cost data for each DC Micro Grid system component for every scenario can be found in the table 5 and 6.

Table 4: Net Present Cost data for PV/Li Scenario

Element	Capital ($)	Replacement ($)	O & M ($)	Salvage ($)	Total ($)
PV	7,800	0.00	5,545.90	0.00	13,345.90
Lithium Ion Battery	37,500	0.00	58,173.82	0.00	95,673.82
Generic large free converter	3,200	0.00	1,034.20	0.00	4,234.20
System	48,500	0.00	64,753.93	0.00	113,253.93

Table 5: Net Present Cost data for PV/La Scenario

Element	Capital ($)	Replacement ($)	O & M ($)	Salvage ($)	Total ($)
PV	7,800	0.00	5,545.90	Rs0.00	13,345.90
Lead Acid Battery	42,000	17,925.40	54,295.57	3,048.63	111,172.34
Generic large free converter	3,200	0.00	1,034.20	Rs0.00	4,234.20
System	53,000	17,925.40	60,875.68	3,048.63	128,752.45

CASE 2

Architecture								Cost				
Solar PV (kW)	Fuel Cell (kW)	Li-Ion	LA	Electrolyzer (kW)	H2 Tank (kg)	Conv (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	O&M ($/yr)
5.50	4.00			5.00	20.0	8.00	CC	$0.831	$57,936	$598.45	$50,200	$670.06
5.50	2.50	3		5.00	10.0	8.00	LF	$0.859	$59,437	$1,372	$41,700	$1,442
5.50	3.00		3	5.00	20.0	8.00	LF	$0.960	$66,869	$1,135	$52,200	$1,197

Figure 6: PV/Hydrogen, PV/Hydrogen/Li and PV/Hydrogen/La scenario

In the second case, Homer simulates PV/Hydrogen, PV/Hydrogen/Li Battery, and PV/Hydrogen/La Battery to meet the load demand. As shown in Figure 6.

According to the optimization analysis, the PV/Hydrogen hybrid system demonstrated the lowest NPC, amounting to $57,936 and corresponding COE of $0.831. Specific information regarding the Net Present Cost

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data for each DC Micro Grid system component under various scenarios is available in the tables illustrated in Table 7, 8 and 9.

Table 6: Net Present Cost data for PV/Hydrogen scenario

Component	Capital ($)	Replacement ($)	O & M (Rs)	Salvage (Rs)	Total (Rs.)
PV	5,500	0.00	3,910.57	0.00	9,410.57
Fuel Cell	1,6000	0.00	3,071.06	925.74	18,145.32
Electrolyzer	5,500	0.00	646.38	0.00	6,146.38
Hydrogen Tank	20,000	0.00	0.00	0.00	20,000
Generic large free converter	3,200	0.00	1,034.20	0.00	4,234.20
System	50,200	0.00	8,662.21	925.74	57,936.47

Table 7: Net Present Cost data for PV/Hydrogen/Li scenario

Component	Capital ($)	Replacement ($)	O & M ($)	Salvage ($)	Total ($)
PV	5,500	0.00	3,910.57	0.00	9,410.57
Fuel Cell	10,000	0.00	1,411.68	900.80	10,510.88
Electrolyzer	5,500	0.00	645.38	0.00	6,146.38
Hydrogen Tank	10,000	0.00	0.00	0.00	10,000
Lithium Ion Battery	7,500	0.00	11,634.76	0.00	19,134.76
Generic large free converter	3,200	0.00	1,034.20	0.00	4,234.20
System	41,700	0.00	18,637.60	900.80	59,436.80

Table 8: Net Present Cost data for PV/Hydrogen/La scenario

Component	Capital ($)	Replacement ($)	O & M ($)	Salvage ($)	Total ($)
PV	5,500	0.00	3,910.57	0.00	9,410.57
Fuel Cell	1,200	0.00	2,127.22	806.05	13,321.18
Electrolyzer	5,500	0.00	646.38	0.00	6,146.38
Hydrogen Tank	20,000	0.00	0.00	0.00	20,000
Lead Acid Battery	6,000	0.00	7,756.51	0.00	13,756.51
Generic large free converter	3,200	0.00	1,034.20	0.00	4,234.20
System	52,200	0.00	15,474.88	806.05	66,868.84

The monthly electrical power produced by PV panels and fuel cells for the PV/Hydrogen system in the best optimization results is displayed in Figure 7. The average annual electricity produced by PV panels is about 9,829 kWh/yr (83.5% of the total electricity generated), while the average annual electricity produced by fuel cells is approximately 1,946 kWh/yr (16.5% of the total electricity generated).

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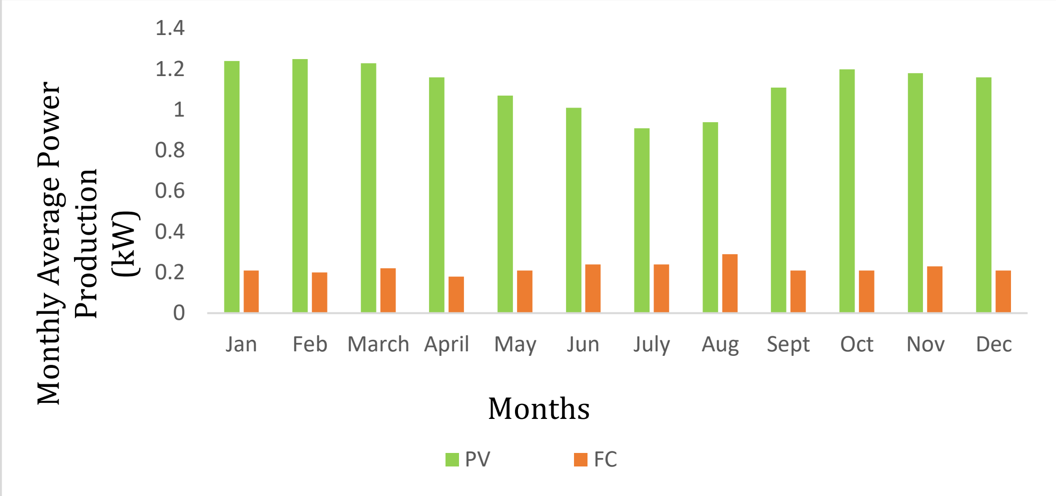

Figure 7: Monthly Electricity production by PV and FC

The fuel cell, hydrogen tank, and Electrolyzer serve as the storage for the DC Microgrid. It is vital to remember that the system shown in Figures 4 (a) and 4 (b) only includes lithium ion and lead acid batteries in order to compare techno-economic assessments of different storage technologies. Therefore, it is evident from both figures that, out of all the options, PV/Hydrogen is the most economical system for supplying power to Chachro Village's rural healthcare system with the lowest COE ($0.831). Table 10 shows that a 5.5 KW solar PV and an 8 KW converter are part of the system required to satisfy the electrical needs of rural health care. A 20 kg hydrogen tank, a 5 KW Electrolyzer, and a 4 KW fuel cell are needed for the storage system.

Table 9: Sizing of DC Microgrid

Sizing of DC Microgrid elements				
Solar PV	Converter	Fuel Cell	Electrolyzer	Hydrogen Tank
5.5 KW	8 KW	4 KW	5 KW	20 Kg

Table 11 displays the electrical output of each energy-producing element that makes up the micro grid. The table shows that 9,829 Kwh/yr, or 83.5% of the total energy, is produced by solar PV. It is clear from the Fuel Cell's contribution of 1,946 Kwh/yr, or 16.5% of the remaining energy, that it is only meant to be used as a backup and not for continuous power generation. Because of the intermittent nature of renewable resource, it only produces when PV production is insufficient. Fuel cells and solar PV have capacity factors of 20.4% and 5.5%, respectively.

Table 10: Annual Electricity production by PV/Hydrogen scenario

Electricity production by component of DC Micro grid			
Components	Solar (PV)	Fuel Cell (FC)	Total
Annual Production	9,829 (Kwh/yr)	1,946 (Kwh/yr)	11,775 (Kwh/yr)
Percentage	83.5 %	16.5 %	100 %
Capacity Factor	20.4 %	5.5 %	25.9 %

When renewable energy sources are in excess, the electrolyzer uses the water electrolysis method to produce hydrogen. Table 12 displays the electrolyzer as a storage system component's operational parameters, and Table 13 displays the hydrogen tank's energy storage capability. The electrolyzer has a capacity factor of 13.8% and a specific power usage of 52.6 Kwh/Kg. It can be inferred that renewable energy sources alone are insufficient to meet the energy needs of the rural healthcare system for about 62.2% of the year, since the electrolyzer operates for only 3,310 hours per year, or 37.8% of the total hours. Therefore, stored hydrogen in a fuel cell must be used to fulfill the remaining energy requirements

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Table 11: Electrolyzer Characteristics

Characteristics of electrolyzer						
Quantity						
Mean O/P	Maximum O/P	Total Production	Specific Consumption	Total I/P Energy	Capacity Factor	Hours of Operation
0.0132 Kg/hr	0.0951 Kg/hr	115 Kg/hr	52.6 Kwh/Kg	6,064 Kwh/yr	13.8 %	3,310 hr/yr

20 kg of hydrogen may be stored in the hydrogen tank at all times. This translates to a tank autonomy of 1079 hours and a storage capacity for electrical energy of 667 Kwh.

Table 12: Hydrogen tank specifications

Specification of hydrogen tank		
Quantity		
Hydrogen Storage Capacity	Energy Storage Capacity	Tank Autonomy
20 Kg	667 Kwh	1079 hr

ECONOMIC ANALYSIS

In HOMER Pro Simulation Software, the economic viability of renewable energy configuration is evaluated mainly from the net present cost of the energy system as well as the levelized cost of energy [17]. Homer uses the calculations below to compute NPC and COE (T.R Ayodele et al. [46], T.R Ayodele et al. [02], Olubayo Moses Babtunde et al. [19] & M. Kashif Shahzad et al. 2017 [36])

$$C_{NPC} = \frac{C_{TALC}}{CRF(i,N)} \quad (5)$$

Where C_{TALC}, is total annualized cost of the DC microgrid system in ($/yr) and can be calculated as follows:

$$C_{TALC} = \sum_{j=1}^{n} C_{ALC(j)} \quad (6)$$

Where n is the total number, j is the counting index and C_{ALC} annualized cost for each component that makes up the DC microgrid configuration. C_{ALC} can be calculated as follows:

$$C_{ALC} = C_{init} \times CRF(i, N) \quad (7)$$

Where C_{init} is the initial capital cost of the component and CRF is the capital recovery factor for each component and can be calculated as follows:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (8)$$

Where i is the real interest rate and N is the lifetime (year) of the component.

The Cost of energy (COE) is defined as the average cost per kwh of useful energy produced by the system and can be determined as

$$COE = \frac{\sum_{j=1}^{n} C_{ALC(j)}}{E_{AC}} \quad (9)$$

Where E_{AC} is the total rural health clinic load (Kwh/yr).

So, the economic viability for particular Chachro Village Tharparkar is summarized in below graph in which all the five possibilities that are shown in two cases are compared based on Net Present Cost, Initial Capital Cost, and Energy Cost. A comparison reveals that the PV/hydrogen system appears to be a realistic alternative because of its lowest NPC, ICC, and COE, which are $57,936, $50,200, and $0.831 as shown in figure 8.

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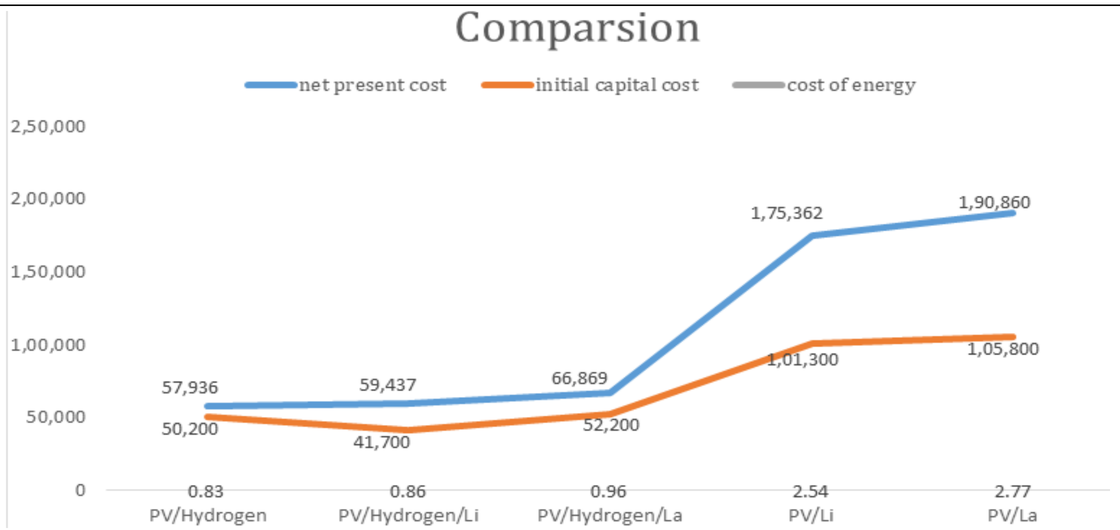

Figure 8: Comparison of all five scenarios based on NPC, ICC and COE

Comparison between the proposed HRESS mentioned in the literature

Table 9 compares the recommended system in Tharparkar to the numerous system arrangements that have been investigated and studied in the past by the stated researchers in the published literature for various domains. This assessment relates to the ideally developed HRES findings. According to costs, the outcomes are contrasted. Depending on the initial costs of the components utilized in the entire system, the typical energy consumption of the whole system, and the sizes of its components, the TNPC amount is not equal to the suggested HRESs. Nevertheless, COE value is an alternate metric for contrasting various RES configurations. The table demonstrates that South Africa has a significantly higher COE than the remaining boundaries, with Nigeria coming in second. In the meantime, when compared to the listed countries, Egypt and India had the cheapest prices for electricity. Compared to the intended research, favorable outcomes could have been acquired at low costs, according to the findings presented in this techno-economic inquiry. Soon, it is anticipated that RES improvement will become clearer.

Table 14: Comparison between the proposed HRESS mentioned in the literature

Countries	**Resources**							**Cost**		**Source**
	PV	WT	DG	FC	BSS	BMS	Converter	TNPC (M$)	COE ($)	
Benin	Yes	No	Yes	No	Yes	No	Yes	00.556	0.207	[51]
Ethiopia	Yes	Yes	Yes	No	Yes	No	Yes	00.083	0.207	[52]
Algeria	Yes	No	Yes	No	Yes	No	Yes	0.009	0.380	[53]
Nigeria	Yes	Yes	Yes	No	Yes	No	Yes	00.011	0.459	[54]
South Africa	Yes	Yes	No	Yes	No	No	Yes	38.400	7.540	[21]
India	Yes	No	Yes	No	Yes	Yes	Yes	00.124	0.145	[55]
Egypt	Yes	Yes	Yes	No	Yes	No	Yes	01.684	0.190	[56]
Canada	Yes	Yes	Yes	No	Yes	Yes	Yes	23.900	0.285	[57]
Saudi Arabia	No	Yes	Yes	Yes	Yes	No	Yes	07.045	0.271	[58]
Pakistan Case-1	Yes	No	No	No	Yes	No	Yes	0.1133	1.64	Current study
Pakistan Case-2	Yes	No	No	Yes	Yes	No	Yes	0.0579	0.831	Current study

V. CONCLUSION

The study evaluated the feasibility of using renewable energy sources to power a Group II rural healthcare facility in Chachro village, Tharparkar district, Pakistan. After determining the most cost-effective DC microgrid architecture, it was found that the facility would require 14.83 kilo watt-hr/day, with peak demand of 7.65 Kilowatt. The DC microgrid system was composed of a 5.5 kW solar PV system, a 4 Kilowatt FC, a 5 Kilowatt Electrolyzer, a 20 Kilogram hydrogen tank, and an 8 Kilowatt converter, which could meet the energy demand, with NPC of $57,936 and a CC (capital cost) of $50,200. The COE (cost of energy) for the entire DC microgrid system is $0.831. Thus, based on the study, it can be inferred that a DC microgrid integrated with solar PV and hydrogen storage systems can serve as a feasible and sustainable alternative for fulfilling the energy requirements of rural healthcare facilities. Future research can focus on exploring various hydrogen storage technologies, intermittent renewable energy generator power systems, and dynamic fuel cell/Electrolyzer models.

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