Design and Analysis of a Hybrid Power System for a Remote Natural Gas Pipeline Control Station

Muhammad Waqas, *Member, IEEE*, Mirza Jabbar Aziz Baig, *Member, IEEE*, Mohsin Jamil, *Senior Member, IEEE*

Abstract— **The efficient operation of natural gas pipeline control stations relies on electrical equipment such as data loggers, control systems, surveillance and communication devices etc. These control stations are often located in remote areas, where maintaining reliable, uninterrupted, and continuous power supply poses a significant challenge. In this paper, a hybrid power system (HPS) is proposed to meet the unique requirements of a specific remote natural gas pipeline control station as a case study. Based on the collected site data and load profile for a connected load of 275KW, the proposed system is designed using HOMER Pro software. To ensure continuous and sustainable power supply to the control station, the proposed system combines solar photovoltaic (PV) panels with conventional natural gas generators. The detailed analysis of the capital and energy costs associated with the proposed system reveals that the system is suitable for selected site and can reduce costs substantially.**

Keywords— **Hybrid Power System (HPS), Solar photovoltaic, Homer Pro, Natural gas generator.**

I. Introduction

The sustained development of every country relies on energy, and the utilization of fossil fuels to provide primary energy is indispensable for achieving sustainable development across a range of sectors, including industry, transportation, infrastructure, information technology, agriculture, household applications, and more [1]. Natural gas accounts for a significant portion of Pakistan's energy needs, which is also a major source of electricity generation. In 1952, Pakistan witnessed the discovery of extensive natural gas reserves, approximately amounting to 12 trillion cubic feet, in Sui, Baluchistan province of Pakistan. Following this discovery, an extensive gas infrastructure was established to cater to domestic needs, electricity generation, and industrial applications. The transportation of gas to different regions across the country has been efficiently managed by two key entities, namely Sui Northern Gas Pipelines Limited (SNGPL) and Sui Southern Gas Company Limited (SSGCL). Over time, the consumption of natural gas as a primary energy source in Pakistan exhibited a gradual increase [2].

The transmission and distribution of natural gas via pipeline network rely on a range of electrical equipment, including gas turbines, gas compressors, and various other electrically powered equipment situated within control stations. These control stations are strategically located in geographically remote and sparsely populated areas. Operation and maintenance of these high-pressure natural gas pipeline control stations in such remote locations pose substantial challenges, mainly due to the unreliable electricity supply from nearby grid stations, one the reason for ongoing energy crisis. Metropolitan areas have an uninterrupted supply of electricity throughout the year in contrast to many rural and remote areas. According to 2021 data from the World Bank, approximately 15.5% of the world's rural population and remote areas did not have access to electrical power [3]. Thus, fossil fuels such as diesel and natural gas remain the predominant source of electrical power at such control stations in remote areas.

In today's world, there is growing apprehension regarding environmental issues and society's heavy reliance on fossil fuels [4]. Conventional energy sources, primarily based on fossil fuels, not only contribute substantially to environmental pollution as well as in the midst of an impending depletion crisis. Though, relying solely on fossil fuels for energy generation can have detrimental effects on the environment and the natural world. In Pakistan, other than hydro, electricity production predominantly relies on natural gas, coal, or furnace oil, all of which are non-renewable sources and are imported from various countries. Approximately one-third of Pakistan's energy demand is met through these imports. The heavy reliance on imported energy resources not only burdens end-user with additional costs but also poses a significant challenge to Pakistan's economy, which has consistently faced current account deficits for more than two decades, with only rare exceptions. To cover these deficits, the country has mostly resorted to borrowing funds from friendly nations, issuing international sovereign bonds, and seeking financial assistance from multilateral banks. This approach has been necessary due to the limited flow of foreign direct investments into Pakistan, primarily hindered by bureaucratic inefficiencies and the absence of a conducive political and regulatory environment [5]. To confront these issues, it is imperative to transition toward renewable energy sources, with solar and wind power taking center stage due to their inexhaustible, environmentally friendly nature, and decreasing costs.

Given the intermittent nature of renewable energy sources, hybrid power systems that combine renewable energy sources and conventional energy sources are used to generate electricity [6]. Solar energy is regarded as the most suitable renewable energy source for Pakistan. Pakistan's solar energy potential stands at approximately 5500 terawatt-hours per year, surpassing its present electricity consumption by more than fivefold. With an average daily solar insolation of 5.30 kWh/m^2 and the potential for a solar energy output of up to 10,000 GW, Pakistan boasts substantial solar energy prospects. Figure 1 illustrates the distribution of solar insolation across Pakistan, providing clear evidence of the abundant solar resources available for utilization [7]. Hence the use of solar energy to generate electricity particularly in remote areas is encouraged after consideration of these facts.

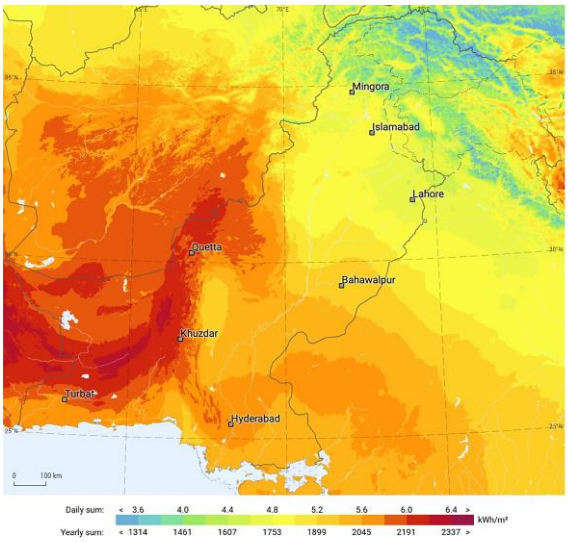


Fig. 1. Solar insolation levels in Pakistan

II. SELECTED SITE DETAILS AND LOAD ANALYSIS

A. Site Selection

Sui Northern Gas Pipelines Limited (SNGPL) stands as the largest integrated natural gas company providing natural gas to more than 7.22 million consumers in North Central Pakistan through an extensive network that spans in Punjab, Khyber Pakhtunkhwa and Azad Jammu & Kashmir. SNGPL transmission network comprises of 9,239 KM high-pressure gas pipelines. The distribution network of company consists of 142,998 KM low pressure gas pipeline. The transportation of natural gas from gas wells to end consumers involves compression and pressure enhancement of natural gas at compressors stations, also known as control stations. These control stations are strategically located at different remote locations along with the transmission network. SNGPL operates 11 compressor stations to facilitate compression of natural gas so that it could be delivered to doorsteps of end consumers.

The site selected as a part of this study is one of natural gas compressor stations of SNGPL located in unpopulated and remote area of Pakistan known as Gali Jagir, Fateh Jhang (33.427522,72.625862). Figure 2 depicts the aerial view along with the coordinates of selected site on google map.

Fig. 2. Aerial view selected site on google map.

Figure 3 shows the actual view of selected site which is a control station for high pressure natural gas pipeline network in remote area of Pakistan. This site has a total area of 11 acre which consists of 6-acre compressor station area and 5-acre residential block area. There is sufficient space available at selected site (both rooftop and ground space) which can be utilized for installation of solar PV panels.

Fig. 3. Actual view of selected site

B. Solar Global Horizontal Irradiance

Solar Global Horizontal Irradiance (GHI) is an important factor in assessing site feasibility. It represents the amount of sunlight energy measured at a specific location. As shown in Figure 3, it is evident that solar radiation is consistently available at the selected location throughout the year, with values ranging from 2.97 kWh/m^2/day to 7.43 kWh/m^2/day. Likewise, clearness index is another important factor taken into account while evaluating site feasibility. It is measure of clearness of atmosphere and it is an arbitrary, dimensionless number that ranges from 0 to 1 with higher values occurring during clear and sunny conditions, and lower values during dusty or cloudy conditions. For selected site its value varies between 0.552 to 0.689 as shown in figure 3. Homer Pro software is used to get solar GHI and clearness index data for selected site.

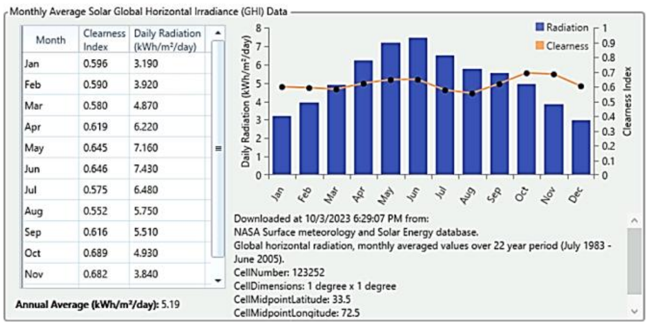


Fig. 4. Solar GHI and clearness index of selected site

C. Electrical Load Analysis

The electrical load at the selected site is categorized into two major groups. First one is gas compressor station load and second one is residential load (staff colony load). Station load mainly consists of control equipment for natural gas turbines, air compressors, gas discharge cooling system, fire suppression system, metering equipment and other related equipment. The residential load consists of domestic load for approximately 30 quarters for staff which is operating the gas compressor station. The hourly load data for year 2022 and corresponding load profile has been shown in figure 4.

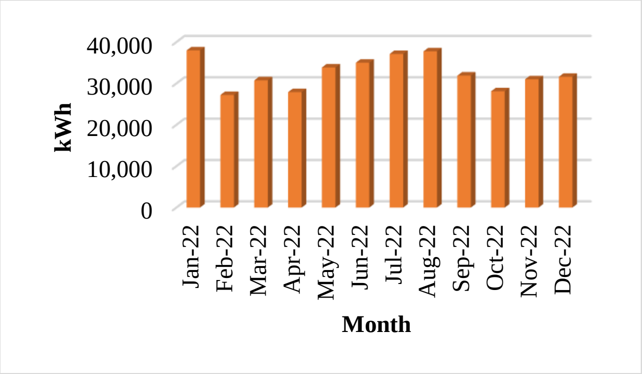


Fig. 5. Monthly electrical consumption (Year 2022)

III. Proposed Hybrid Power System

The proposed hybrid system for selected site includes a DC power source which consists of PV panels and battery bank and alongside an AC power source which is natural gas genset. Hence it comprises of both AC bus and DC bus, while the bus configuration is designed for operational and maintenance flexibility while ensuring uninterrupted power supply. Since a constant power supply is required for the reliable operation of natural gas compressor stations, the proposed hybrid system is effectively built with backup resources to deliver uninterrupted power. The block diagram of proposed hybrid system is shown in figure 6.

The current power generation source at the selected site relies solely on natural gas generators, primarily due to the consistent availability of natural gas, regardless of the energy cost per kWh. However, in the proposed hybrid power system PV panels and battery bank are incorporated which will be optimally utilized at maximum and natural gas generator will be mainly utilized during peak load demand, otherwise it will act as backup. The detailed structure for proposed hybrid power system is discussed below:

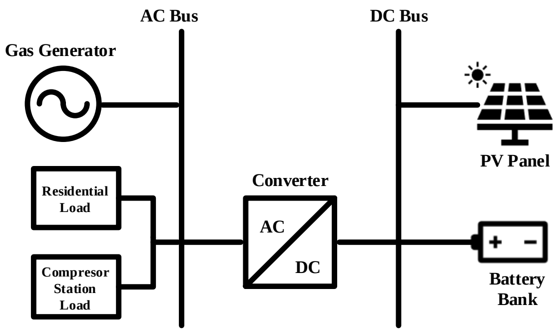


Fig. 6. Proposed hybrid power system

A. Gas Generator

A natural gas generator is a device that generates electricity by burning natural gas as its fuel source. It operates on the principle of converting the chemical energy stored in natural gas into electrical energy. The equation (1) can be used to find heat content or energy value of fuels in mmBTU.

$$mmBTU = \frac{Hm^3 * GCV}{281.7385} \tag{1}$$

Considering a daily average load off 1172 kWh/day and a peak load of 180k, a 200kW gas generator has been selected for proposed system. The relationship between natural gas engine efficiency and electric load is influenced by specific operating conditions and the engine's design. Proper load management, control systems, and maintenance are essential to ensure that the engine operates at its optimal efficiency while meeting the variable demands of the electric load [8]. Gas engine efficiency load curve is shown in figure 7.

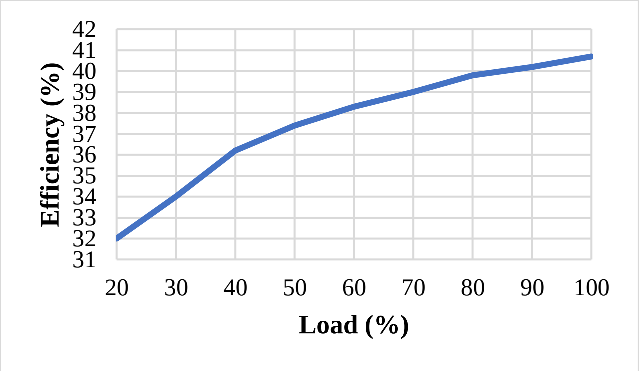


Fig. 7. Gas engine efficiency curve

B. PV Panels

The PV panel selected for this project is of Longi Solar, model no. LR6-72PH-365M. It is monocrystalline solar panel having a maximum power rating of 365 watt and 18.80% efficiency. A solar cell is a PN junction diode in which current flows in the reverse direction. PV modules are constructed by combination of many solar cells. The diode current and voltage characteristics for a single solar panel is given by equations (2) and (3) [9].

$$I_d = I_o\{\exp[\frac{V_d}{V_T}] - 1\} \tag{2}$$

$$V_T = \frac{KT}{q} * nl * N_{cell} \tag{3}$$

Where I_d and I_o represent diode current and diode saturation current respectively. V_d is diode voltage, 'K' is Boltzmann constant having a value of 1.380649×10^{-23} J·K^{-1}. T represents temperature of cell, *nl* represents ideality factor of diode and N_{cell} is the total number of cells connected in series in a PV module.

C. Battery Bank

The primary function of the battery bank within the proposed hybrid power system is to store surplus electrical energy generated by the solar PV system and to supply this stored energy to the electrical loads during periods when the PV system is not fully operational, such as at night or in the absence of sunlight. A 12V lead acid battery having current rating of 201Ah has been selected for the proposed hybrid power system. To ensure high lifetime of battery during cyclic applications, the depth of discharge for battery at 30% has been maintained.

D. DC to AC Converter (Inverter)

An inverter is an electrical device that converts direct current (DC) into alternating current (AC) at the desired amplitude and frequency, making it symmetrical. To meet the peak load of 180 kW, a 250-kW inverter, exceeding the peak load by at least 25%, has been chosen for the proposed system. Multilevel inverters are widely employed in high-voltage applications, and their performance surpasses that of conventional two-level inverters by exhibiting reduced harmonic distortion, lower electromagnetic interference, and higher DC link voltages.

IV. Optimization of Proposed HPS using HOMER Pro

For optimization of the proposed hybrid power system, a software tool called Hybrid Optimization Model for Multiple Energy Sources (HOMER Pro), developed by the National Renewable Energy Laboratory is utilized. It simulates every possible system configuration in a single execution and subsequently arranges these systems based on the selected optimization variable. The configuration of proposed HPS designed in Homer Pro is shown in figure 8.

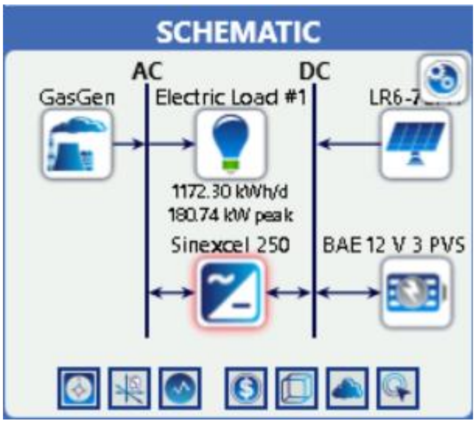


Fig. 8. Configuration of proposed system in HOMER Pro

This configuration incorporates two separate buses: one for Alternating Current (AC) and the other for Direct Current (DC). A 840V DC bus is used and interfaced with a 12-volt, 201Ah lead-acid battery bank and 365-watt flat plate solar modules from Longi Solar. A derating factor of 85% is applied to account for the impact of dust and high temperatures. Gas genset and AC load are connected with AC bus. Sinexcel 250kW inverter is used to interlink AC bus with DC bus. The system is designed in such a way that there is no limitation on power generation through PV modules and PV modules will be used at maximum to optimize the overall system performance. The various system configurations evaluation and subsequently system sizing done by HOMER Pro is shown in figure 9. As it is evident from simulation results in figure 9 that HOMER Pro has provided different configurations by using different combination of available power sources and the most optimum configuration selected is combination of PV panels, battery bank and gas genset because the Net Present Cost (NPC) is $1.30M and Cost of Energy (COE) is $0.234 in this case, which is minimum among all configurations.

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results

Architecture						
LR6-72PH (kW)	GasGen (kW)	BAE 12 V	Sinexcel 250 (kW)	Dispatch	NPC ($)	COE ($)
282	200	280	190	LF	$1.30M	$0.234
	200	140	66.8	CC	$1.85M	$0.335
	200			CC	$2.11M	$0.382
582		1,260	201	CC	$2.12M	$0.383
6.11	200		1.42	CC	$2.12M	$0.383

Fig. 9. HOMER Pro optimization results for proposed HPS

In this configuration PV modules will generate 282 kW power, so a total of 773 solar panels, along with 250 kW Sinexcel inverter and 280 12V batteries are required to meet the load demand of selected site. As selected DC bus has a voltage rating of 840V and 280 batteries are required to meet load demand so 4 battery strings having 70 batteries of 12V in each string will be used. According to Fig. 10 below, the optimal system suggested by HOMER pro only uses gas generators for 15.5% of its total electricity and obtains 84.5% of its power from solar energy.

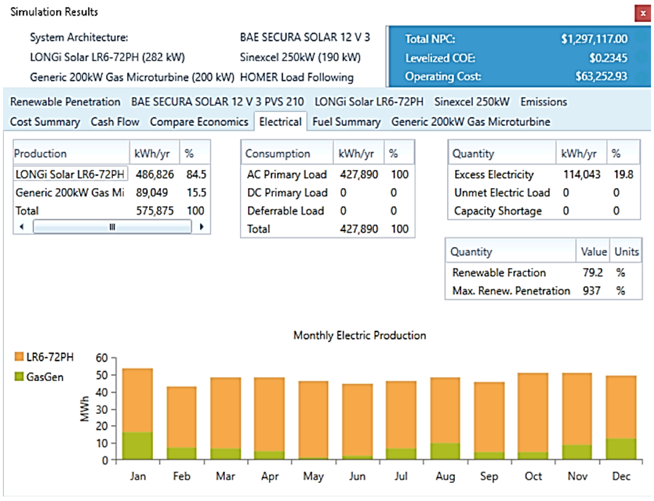


Fig. 10. HOMER Pro simulation results for proposed HPS

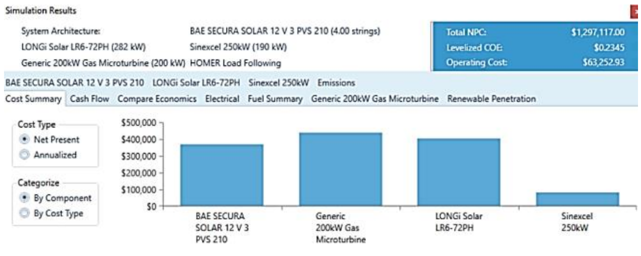
Table 1 shows information regarding rating and relative pricing of various components used in proposed HPS.

Table 1. Rating and cost of components used in proposed HPS

Component	PV Panel	Inverter	Battery Bank	Gas Genset
Rating per unit	0.365 kW	250kW	12V, 201Ah	200kW
No. of units required.	773	1	280	1
Total rating	282kW	250kW	840V, 804Ah	200kW
Cost per unit	$229	$38600	$385.32	$165300
Total cost	$176788	$38600	$107890	$165300

The area of one PV panel which is selected for this project is 1.937m^2. Thus, to install 773 PV panels, a total of 1498m^2 area is required. The total rooftop area available at selected site is calculated using google earth and it is equivalent to 2525m^2 which is sufficient for installation of required PV panels. Other than rooftop area, sufficient ground space is also available which can be utilized for future expansion considering the total load requirement.

HOMER Pro also performs cost analysis to find the best optimum system. Based on per unit price provided to HOMER Pro, it calculates total cost of the system and suggests the most optimum solution. The cost analysis done by HOMER Pro is shown in figure 11.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
BAE SECURA SOLAR 12 V 3 PVS 210	$107,889.60	$122,685.43	$139,467.22	$0.00	-$1,214.20	$368,828.04
Generic 200kW Gas Microturbine	$165,350.00	$0.00	$29,393.36	$252,182.12	-$8,159.55	$438,765.93
LONGi Solar LR6-72PH	$176,812.13	$0.00	$228,574.17	$0.00	$0.00	$405,386.30
Sinexcel 250kW	$29,362.02	$19,454.64	$37,957.80	$0.00	-$2,637.71	$84,136.74
System	$479,413.75	$142,140.06	$435,392.55	$252,182.12	-$12,011.47	$1,297,117.01

Fig. 11. Cost summary of proposed HPS in HOMER Pro

Like cost analysis, cash flow analysis is also performed by HOMER Pro which is shown in figure 12. Cash flow analysis considers capital cost, operating cost, fuel cost for gas genset, replacement cost and salvage cost. The cash flow analysis has been done for 25 years. A capital investment of $479,413.75 is required and there will be an operating cost of $33,679.52 and fuel cost of $19,507.39 per year. Replacement cost will also incur at during year 7,10,13 and 20 and during 25th year the salvage value of system will be equivalent to $50,140.

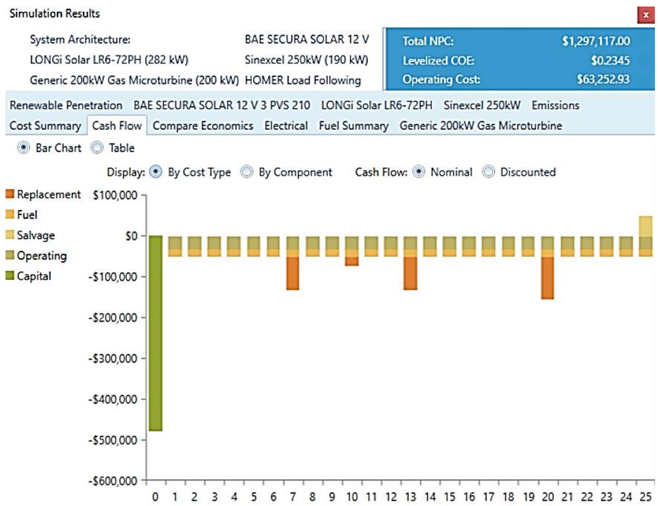


Fig. 12. Cash flow analysis in HOMER Pro

V. Conclusion

Due to significant increase in prices of petroleum products over the recent years and to conserve the fossil fuels, it is critical to use of renewable energy sources for power generation specially in remote areas. But due to intermittent nature of renewable energy sources, hybrid power systems are the most appealing and feasible solution. In this paper a hybrid power system is designed for a remote natural gas pipeline facility which not only addresses the energy challenges faced by such facilities but also emphasizes that the adoption of hybrid power systems can lead to significant financial gains while aligning with broader energy sustainability goals. By reducing energy costs by $0.148 in comparison to already existing conventional practices, this study paves the way for more efficient, cost-effective, and environmentally responsible energy solutions in remote industrial settings.

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