Techno-Economic Analysis of Green Hydrogen Production by Hybrid Energy Power to Gas Concepts for Combined Cycle Power Plants in Future Green Hydrogen Hubs

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Dedication

"Deep in the sea are riches beyond compare. But if you seek safety, it is on the shore"

After Allah S.W.T, the Al-Muhaymin, it is my pleasure and an honor for me to dedicate my thesis to my grandparents, my parents, my nephews and nieces, my siblings and, sisters and brothers in law. No amount of dedication can do justice to the support, sacrifices, and efforts that they all rendered in motivating me. It is because of them that I overcame every challenge thrown by life at me, be it enormous or trivial.

I love you all and owe my success to you. May Allah S.W.T grant me more energies to make you all proud and feel honored.

Abstract

The world has embarked on a journey of unleashing the untapped potential of hybrid energy systems to quench the ever-growing thirst for green energy. Being still in its formative stages, Power-to-Gas offers an efficient opportunity to turn renewable energy into "green" hydrogen, establishing an inevitably remunerative spectrum of end-uses. A zesty episode of initiatives announced across the globe that are more yearning, awe-inspiring, and mammoth in size, reflect that it has accomplished substantial inroads in the energy revolution. However, utilizing the produced hydrogen for electricity production is yet ignored. In this spirit, the current paper intends to contribute to the worldwide scientific community by evaluating, from a techno-economic perspective, a hybrid model for sizing hydrogen generation by water electrolysis from renewable energy and using it for electricity production. Modeling of this hybrid system is done using HOMER Pro. Hydrogen is produced using a hybrid energy system and then fed into a hypothetical combined cycle power plant to produce electricity. Hydrogen has economic dominance over batteries in terms of energy storage and cost of energy, as per results. The economic analysis is constructed on economic parameters like payback period, internal rate of return, cost of energy, and multiple configurations of the system. Four scenarios including a baseline case have been simulated. The most feasible configuration yielded a levelized cost of energy being 0.465 USD/kWh, an internal rate of return being 17.3**%,** and a payback period of 2.3 years. Renewable energy sources are thoroughly assessed for coupling with the desalination plant and electrolyzer array. This system can further be expanded on a larger scale to transform the region into a hydrogen hub to produce green, high-energy-density hydrogen to be supplied to and utilized by multiple sectors.

Keywords: Power-to-Gas, Hydrogen hub, Hybrid energy system, Sector coupling, Techno-economic feasibility, Windfarm

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List of Nomenclature

Symbols

α_P	Power Temperature Coefficient [% / °C]
ρ	Air Density [kg/m^3]
C	Cost [USD]
E	Energy
F	Derating Factor [%]
f	Inflation Rate [%]
G	GHI Incident on PV (kW/m^2)
i	Interest Rate [%]
N	Number of Years
n	Transmission Line Infrastructure Life
P	Power [kW]
R	Life [Years]
S	Salvage Value
T	Temperature [°C]
U	Wind Speed [m/s]
Y	Rated Capacity [kW]
Z	Height [m]

Abbreviations

AC	Alternating Current
ACSR	Aluminum Conductors Steel Reinforced
AEDB	Alternative Energy Development Board
AEP	Annual Energy Production
AHP	Annual Hydrogen Produced
CSA	Cross-sectional Area
DC	Direct Current

DL	Deferrable Load
DSP	Desalination Plant
GHI	Global Horizontal Irradiation
GtP	Gas to power
GWEC	Global Wind Energy Council
HES	Hybrid Energy System
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
Li-ion	Lithium-Ion
MW	Megawatt
MWh	Megawatt-hour
NREL	National Renewable Energy Laboratory
NPC	Net Present Cost
OPEX	Operational Expenses
PEM	Proton Exchange Membrane
PMD	Pakistan Meteorological Department
PtG	Power-to-Gas
PV	Photovoltaics
CAPEX	Capital Expenditure
CC	Coefficient of Conductor
CCPP	Combined Cycle Power Plant
CRF	CAPEX Recovery Factor
RE	Renewable Energy
RES	Renewable Energy Sources
ROI	Return on Investment
RoW	Right of Way
SEC	Specific Energy Consumption
SFF	Sinking Fund Factor
SMR	Steam Methane Reforming

STC	Standard Test Conditions
STP	Standard Temperature Pressure
SWD	Seawater Desalination
WB	World Bank
WRF	Weather Resource Forecasting
WTG	Wind Turbine Generator

Chapter 1

Introduction

1.1 Background

Energy is the pivotal ingredient, for any country's fiscal progress and long-term advancement. Many emerging and industrialized countries are turning to alternative renewable energy sources (RES) particularly solar and wind energy because of rising energy requirements, dwindling conventional fuels, and environmental disquietude. Mounting climatic challenges and exponential surge in global energy demand have steered the nations across the world away from conventional fuels and toward a significant advancement in the deployment and utilization of these RES. European Commission had suggested, in the Renewable Energy Roadmap 2021, to set a goal of integrating RE in its total energy mix by up to 20%. Power-to-Gas (PtG) concept is a novelty in this domain that is being adopted to link the gas grids and power grids. If synergized at a global level, PtG can critically contribute to and shape the global energy future [1].

Like many other countries, Pakistan is a developing country and is no exception when it comes to facing multifaceted challenges in the energy domain including the high cost of power generation coupled with the woes of climate change. Being a country that is threatened by climate change the most as well as a struggling economy, Pakistan should employ eco-friendly RES to offset the mounting cost of electricity production, the ever-increasing demand for energy, and the reliance on fossil fuels. This recommendation is supported by the technology's economically feasible start-up and comparatively hassle - free installation, as well as its meager operational expenses. There is ample wind resource as well as the potential for solar energy in areas like Jhimpir. Such renewable energy systems that rely on fluctuating sources have significant brief and seasonal variations in their power production. To overcome this, hybrid power systems efficaciously integrate the attributes of wind and solar energy sources to optimize system stability and lower costs [2]. A smarter approach will be drafting a plan to synergize a greener fuel like hydrogen produced using electricity that is produced by a hybrid power generation system, with existing combined cycle power plants (CCPP) by feeding them with 100% hydrogen or natural gas – hydrogen mixture as such a model will be more efficient.

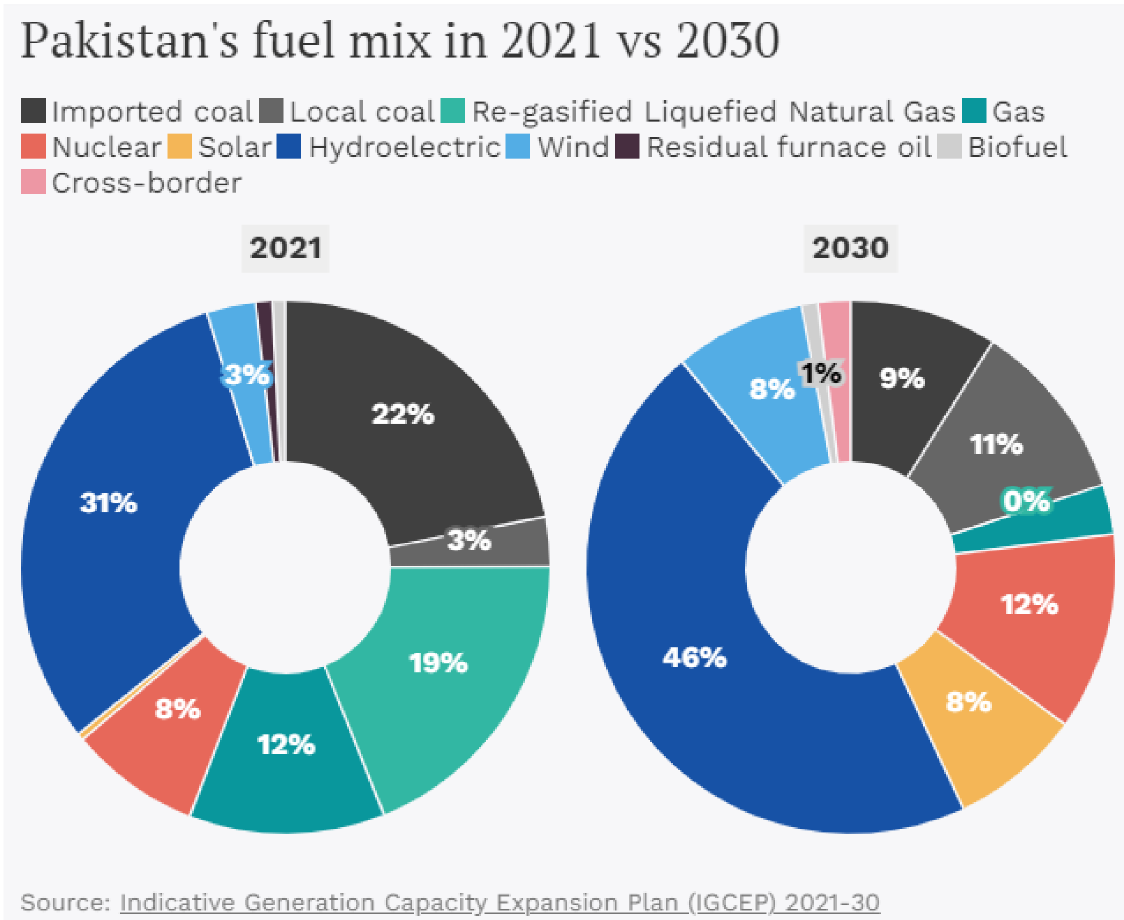

Figure 1.1 - Fuel Mix of Pakistan Over a Decade from 2021 to 2030)
(Source: NEPRA IGCEP, 2021 – 2030)

Thus, a case study for techno-economic feasibility analysis of PtG in Pakistan has been performed in this paper with a view of transforming the region into a future Hydrogen Hub that will cater to national demand for cheap power and will serve as a deterrent against environmental deterioration. Hydrogen is a gas packed with energy density as high as almost three times more than that of conventional fuels like diesel and gasoline. In terms of electrical energy, hydrogen has an energy density of up to 33.3 kWh per kg [3]. It is way more than the energy density of diesel which possesses almost 12 kWh per kg [4]. As an energy retention medium, green hydrogen has a promising future. When employed as a fuel, hydrogen is viable, innocuous, and pure because it only releases water as a residue upon combustion [5]. High - quality hydrogen can be generated using electrolysis, which has a wide range of possible implementations, including transportation fuel and mixing into natural gas grid, as well as existing implementation in fuel refinement and fertilizer manufacturing. Electrolysis can be deployed to produce hydrogen in amplitude ranging from micro scale (cm^3/min) to macro scale (m^3/hour) [6].

1.2 Research Void

Until recent past, hydrogen had been produced using fossil fuels. This approach resulted in a massive amount of CO_2 emissions. Nonetheless, substantial breakthroughs in electrolysis and generation of renewable energy (RE) generation have been made in recent decades, enabling the production of green hydrogen at an affordable price [7]. At present, merely 1% of hydrogen being produced across the globe is green hydrogen despite massive RE resources and potential [8]. Viability, operational collaboration, and competitiveness against fossil-based substitutes are the terms in which the economic feasibility of hydrogen generation using advanced technology is evaluated. Renewable technologies such as PVs and WTG will unquestionably empower decarbonization; but, owing to their intermittency, power grids are becoming unpredictable as dispatchable grid inertia is lost with each additional RES. Earlier studies were limited only to hydrogen production using SMR, biomass, and RES, and supplying it to fueling stations or simulating and analyzing HES for electrification of towns. None of the studies had evaluated the usage of green hydrogen as a 100 percent fuel for power plants.

1.3 Aspiration and Target

Pakistan has tremendous potential for generating power from renewable energy sources like solar energy and wind energy. Plenty of work has been already done in this regard to harness power from renewable energy sources to fight the energy crisis and climate change challenges, while many projects are in pipeline. However, there is a concern regarding exiting facilities that run on conventional fuels. These facilities can have their components like power plants, replaced as well as future power projects can be equipped with the latest components with advanced technologies to run on green fuels like hydrogen, produced from renewable energy sources. This dimension has been ignored and has never been discussed as of yet. Therefore, the focus of this thesis has been dedicated to the techno-economic evaluation of hybrid energy system.

The main objectives of this study are:

- Techno-economic feasibility analysis of HES comprising of PVs and WTGs.
- Harnessing the energy from RES to produce electricity and producing hydrogen using the produced power.
- Modeling the HES using HOMER Pro
- Comparative analysis of four different configurations of the hypothetical HES in HOMER Pro.
- Choosing the best configuration based on winning techno-economic parameters.

1.4 Roadmap of Thesis

The chapters to follow are briefly elaborated below:

Chapter 2 would cover the literature review of the most relevant research on hydrogen production using renewable energy sources (RES) as well as the employment of various RES for energy production. Moreover, economic parameters calculated in these studies will also be discussed.

In Chapter 3, various types of electrolysis for hydrogen production will be discussed briefly along with their pros and cons. A comparison will be drawn between those techniques to choose the most feasible of all for the under-consideration system in this thesis.

Chapter 4 would be dedicated to the detailed methodology of the model. The configuration of the hybrid energy system (HES) will be formulated in HOMER Pro preceded by the solar GHI, temperatures, and wind resources data gathering for the project location, the formulation of the electrical and hydrogen load data, the choice of the Enercon E-115 3 MW wind turbine generators (WTG), the ABB-PSC PStore converter, the Proton

Exchange Membrane (PEM) electrolyzer, and devising multiple architectural scenarios of the HES will be described.

Chapter 5 will comprise the results from the HOMER Pro simulations of all the cases including the baseline case. A contrast between all the results will be drawn and various technical, as well as economic parameters, will be discussed. This would bring us to the conclusion of this study and thus, a summary of major findings and future potentials of the research will be discussed.

Chapter 6 will be consisting of the findings and conclusion of the whole study followed by the future prospects and recommendations.

Summary

This chapter describes the background of this thesis study. The PtG concept offers a promising solution in the face of climatic woes and the ever-growing hunger for green energy. Hydrogen production using fossil fuels may produce clean fuel in form of hydrogen, but during this course, emissions are contributing to the environment with adverse effects. PtG is a novel approach that will aid in cutting down the emissions from fossil fuels to zero by harnessing the power from RES and producing green hydrogen from this power via water electrolysis. Later in this study, this produced hydrogen will in turn be used as a fuel for a combined cycle power plant (CCPP).

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Chapter 2

Literature Review

Prior to embarking on a project, it is imperative to do a techno-economic study of the system to take crucial decisions. Extensive exists in journals, encompassing sustainability assessment and cost - benefit analysis of hydrogen generation using RES in multiple countries. Hitherto, Sammy et al. [1] executed a simulation and modeling of mathematical models based on techno-economic evaluation for the generation of power for rural areas in Egypt by utilizing a variety of renewable sources of energy. Sizing for Firefly Algorithm was optimized until desired results were achieved. This was followed by a comprehensive comparison of these results with results of two other algorithms Particle Swarm Optimization and Shuffled Frog Leaping Algorithms respectively. Ğökçek et al. [2] investigated the technical as well as the economic feasibility of a hydrogen refueling station in Turkey that was powered by battery backed-up hybrid power plant (Wind-PV) with a levelized cost of hydrogen (LCOH) being USD 7.526 per kilogram and levelized cost of energy (LCOE) being USD 0.16 per kWh. Surplus electricity production was projected to be 41.1 percent. Mojtaba et al. [3], by employing HOMER software, scrutinized the techno-economic viability of a Solar-Wind hybrid power system for the generation of hydrogen in Hendijan, Iran. Their hybrid power generation facility produced almost 31,680 kilograms of green hydrogen along with 31,53,762 kWh of electric power. Ma et al. [4] postulated a high - pressure hydro retention technology to provide off-grid electricity to Hong Kong, and it is seen to be a viable technique for solar energy insertion, especially for micro automated systems in distant regions. The LCOE for the said system was found to be optimal at USD 0.289/kWh. The critical elements of mathematical frameworks are constructed, and system stability and economic constraints are addressed as baselines for enhancement. Glenk [5] drew a techno-economic comparative study between renewable hydrogen produced by PtG route and conventional fuels in terms of functional collaboration, sustainability, and assertiveness or competitiveness. Within and outside the scope of RES, the architectures established by him in his study reflect essential techniques for private equity firms and legislators. Also, four propositions were made and were authenticated by relevant equations followed by LCOE calculations for off-grid wind power system and off-grid PtG facility at two different locations in Germany and Texas. Moreover, LCOH was also determined to be 2.54 €c/kWh and 2.47 €c/kWh respectively, and it was claimed that should the demand ever hold steady, the break-even cost of hydrogen will surge dramatically by 3.21 Euros per kilogram, thus nearly doubling. The economics of hydrogen production with PtG are investigated from three perspectives in terms of sustainability, operational synergies, and competitiveness with fossil-based alternatives. Al-Sharafi et al. [6], at residential scale, evaluated the possibilities and capacities of electricity generation by virtue of photovoltaics (PV) and wind turbine generators (WTG) installed various cities of Kingdom of Saudi Arabia and analyzed the production based on varying climates. Later, to study climatic influence on power production, The lowest LCOE was discovered to be USD 0.609 per kWh in Yanbu with a system containing solar, WTG, and battery storage bank. Whereas LCOH in the city of Abha, where there is ample wind resource, a framework supported by an electrical energy storage system coupled with hydrogen storage infrastructure, was calculated to be $1.208 per kWh. Moreover, a comparison was made with the identical facilities installed in Toronto and Sydney. Viktorsson et al. [7] delved into for grid - connected the Halle, Belgium-based on-grid Renewable Hydrogen Fueling Station powered by Wind-PV hybrid system. LCOH was found to be 10.3 €/kg, as per estimates. Additionally, it was claimed that the attainment of subsidies from the government will further decline the LCOH. To maintain a prolonged viability of clean hydrogen fuel in future power policies, hydrogen filling terminals fueled by RES should be explored further to develop a more practical and cost-effective approach. Yaqoob et al. [8] did techno-economic study for a 50 MW wind facility at various locations in wind resource-rich Sindh province of Pakistan. RETScreen was employed to analyze the feasibility of the project. Hyderabad was identified as the ideal location for the project with a 41.8 percent capacity factor and payback period of 7.4 years. Greiner et al. [9] demonstrated a technique for gauging Wind-PV energy systems on a Norwegian island in an attempt to develop hydrogen for use in H2 boats, that included sequential computations and economic iterations. Rahmouni et al. [10] utilized GIS software for mapping sites in Algeria and pondered upon the possibilities of the production of hydrogen from RES. It was gauged that the sites under consideration had an ample potential for hydrogen production from wind and solar resources being 2.1×10^5 tons/sq. km. and 2.4×10^5 tons/sq. km. respectively. Temiz et al. [11], at an LCOE of USD 0.612/kWh, conceived and reviewed a system that would be producing hydrogen via a floating dock of solar cells. The fuel cell unit with hydrogen generation and storage unit also diminish unmet power load from 49.34 percent to 0.57 percent, according to the conclusions. Kalinci et al. [12] modeled two scenarios encompassing standalone wind only as well as WTG-PV systems hybrid system in HOMER to critically evaluate the power generation. Along with this, to identify the expedient system, various costs incurred and earned were also analyzed to check for the feasibility of the system and effect of interest rate on LCOE and Net present Cost of the project, optimization, and sizing of the system was done. Selamet et al. [13] discussed the steps of construction of a tremendously effectual Proton Exchange Membrane electrolyzer package are discussed in this paper. Initially, a single cell electrolyzer was erected that enhanced the performance. This was lagged by the development of a PEM electrolyzer stack containing ten cells and its functional variables optimization for superior performance. The ten-cell stack, at 1.35 A/cm^2, yielded 0.264 gallons of H_2 per minute. Hernández- Gómez [14] compiled and analyzed the published models to elaborate the electrical scope of PEM electrolyzer functioning. Besides this, dynamic operating concerns are discussed, as well as subsequent work on simulating the kinetics followed by evaluation of specific energy consumption (SEC) and consumption of the electrolyzer. Koponen et al. [15] investigated the SEC (kWh per m^3) of the Proton Exchange Membrane electrolyzer at ambient and enhanced hydrogen exit pressures. As per their experimental results, doubling the hydrogen pressure from 20 bar to 40 bar at the electrolyzer exit had a negligible impact on SEC. Lee et al. [16] undertook an economic comparative analysis between H_2O electrolysis and SMR in the purview of per unit H_2 manufacturing cost, profitability, and sensitivity in the Korean market. Three contestants in the comparison included Proton Exchange Membrane electrolysis, Alkaline electrolysis, and SMR. As per their estimations for 30 Nm^3/hour proton exchange membrane (PEM) system did cost 16.54 USD per kg of H_2. Whereas, for a system of 300 Nm^3/hour, the unit cost for H_2 production was found to be 7.72 USD per kg of H_2. Tjarks et al. [17] analyzed the energy consumed by gas compression phase in electrolyzer and then honed the net power required by a PtG facility while contemplating upon drying of H_2 by temperature swing adsorption and pressurization. Moreover, they observed that appropriate $P_{OPERATING}$ relies on density of current (A/cm^2) in electrolyzer stack as well as H_2 pressure for storage and efficiencies up to 73 percent are achievable by regulating the pressure. Parra et al. [18] developed a dynamic PtG paradigm and studied the impact of electrolyzer aging on its $\eta_{OVERALL}$ by referring to the polarization curve. They also studied the potential, LCOE and financial gains made by selling gas in market by enhancing the rating of the electrolyzer at kW scale. Saba et al. [19] investigated the previous economic parameters including capital expenditure (CAPEX) and made projections for next decade. Also, they did the cost comparative analysis between PEM and alkaline electrolyzers. As per their estimations, the investment expenditure for Proton Exchange Membrane electrolyzer in next decade are shrunk to 397 – 955 € per kilowatt output at HHV which could further decline by enhancements in increased instrumentation and automation. Ghalavand et al. [20] examined and analyzed systems that are employed predominantly in the seawater desalination (SWD) sector. The operational fundamentals, implementations, and challenges were outlined and addressed. Various SWD techniques were evaluated against each other on basis of SEC and operational expenses (OPEX) (USD per m^3). Khalil et al. [21] designed a hybrid framework comprising PVs, WTGs, and convertors at the sea shore of the province of Balochistan utilizing HOMER Pro to simulate multiple scenario configurations. The winning structure had an NPC of 180,026 USD. Moreover, the proposed hybrid system resulted in a decline of criterion air pollutants and emissions by 64 percent as well as reduction in OPEX. Khalid et al. [22] developed and investigated an incorporated hydrogen energy infrastructure for domestic sector. Whole system's energy as well as exergy effectiveness were taken into account. Energy efficiency of the recommended system was calculated as 26 percent followed by exergy efficiency which yielded to be 26.8 percent. Electrolyzer, as per their simulations, generated 1,492 kilograms of H_2 per year and fuel cell dissipated 1,523 kilograms of H_2 per year. LCOE for their proposed system was reported to be 0.862 USD per kWh.

Earlier studies were limited only to hydrogen production using SMR, biomass, and RES, and supplying it to fueling stations or simulating and analyzing HES for electrification of towns. None of the studies had evaluated the usage of green hydrogen as a 100 percent fuel for power plants.

2.1 Evaluation of Hybrid Resource Potential at Jhimpir

Pakistan, being rich in natural resources, enjoys a unique geostrategic location in Southeast Asia. In this technoeconomic feasibility study, a hybrid RES system for the production of H_2 is installed at Jhimpir situated at 25.0243 degrees North 68.009 degrees East, a location quite rich in the wind as well as PV resource in Sindh province of Pakistan. According to the estimations made by the Institute of Energy Economics and Financial Analysis (IEEFA), the share of RE in the energy mix of Pakistan will reach 28 percent by the year 2030 [23]. The Pakistani government has put into action a comprehensive strategy for the constructive participation of private corporations in the generation of RE. The Ministry of Energy and Power has constituted AEDB to incentivize and assist the execution of RE projects in the country. To promote and assist the development of RE projects throughout the country, AEDB and World Bank are now carrying out an

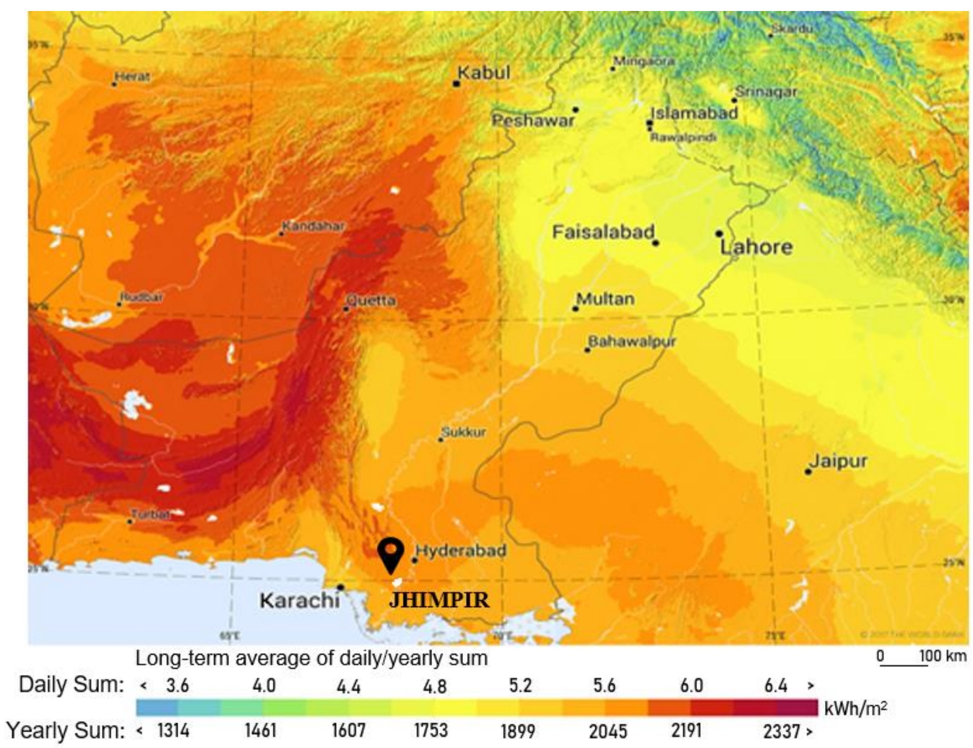

Figure 2.1 - Long term average of annual and daily tallies of GHI (Source: Solargis)

evaluation and mapping of RES in key areas of Pakistan. The program is largely financed by the WB's ESMAP, and its endeavors are focused on examining RE potential, including GIS modeling, the ground surface gathering of data, and geospatial strategizing [24].

2.1.1 Solar Potential

The region, in which Pakistan is located, receives abundant direct sunlight the whole day, making it ideal for solar thermal and PV uses. The annual average horizontal solar radiation per day in these areas is 5 – 7 kWh/m^2/day. A major portion of the country's SEO for PV ranges from 1400 kWh per kWp and 1600 kWh per kWp. Provinces of Balochistan, Sindh, and S. Punjab get solar irradiance of more than 2 MWh per m^2 annually. Figure 2.2 reveals the cleanness or clarity index and mean solar radiation potential of Jhimpir in relation to global horizontal radiation. The yearly annual mean average solar irradiance received by Northern Sindh has been recorded to be 6 kWh per m^2 [25]. As indicated in Figure 2.1, the maximum GHI is found in the west of Pakistan, where mean annual tallies can exceed 2330 kWh per m^2 [26].

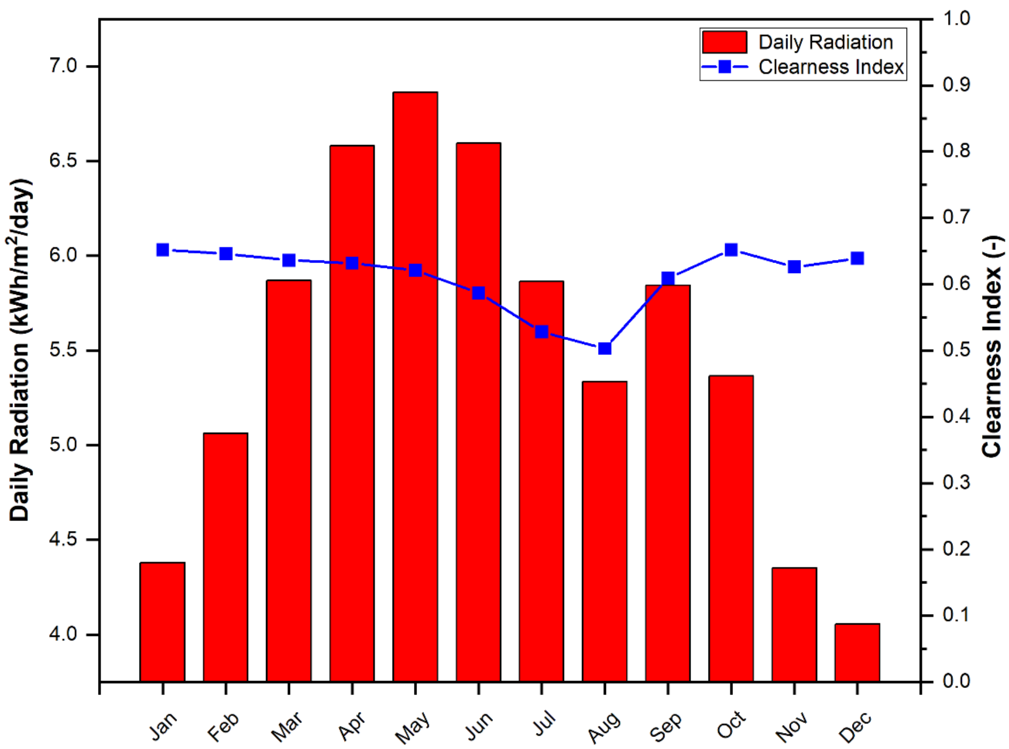

Figure 2.2 - Monthly Solar Irradiation of Jhimpir

(Source: NREL – National Solar Radiation Database)

2.1.2 Wind Potential

Global onshore total installed potential of wind power has reached 708 GW. Overall, 399 GW is expected to be developed from 2021 to 2025. According to the estimations made by experts, by the end of the year 2050, cumulative installations level worldwide would quadruplicate [27]. Figure 2.3 depicts the total global installed capacity of wind power, showing tremendous growth. Moreover, 89 GW wind potential has been added in just

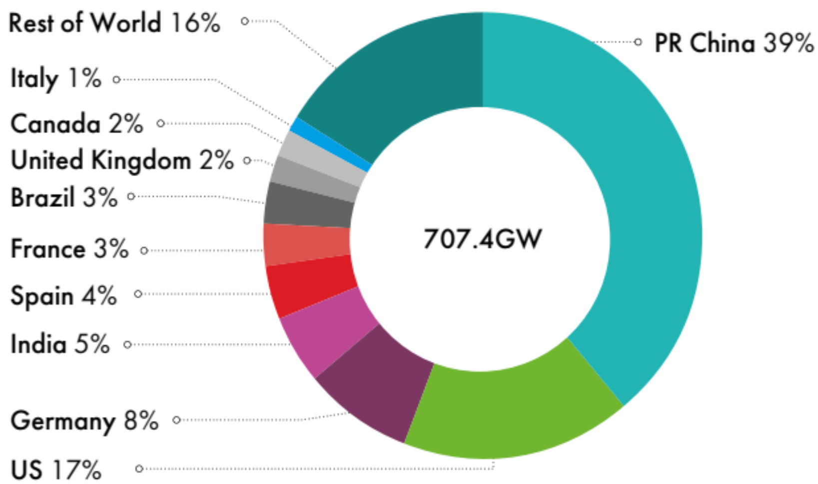

Figure 2.3 - Global Cumulative Installed Wind Potential (Source: GWEC)

one year. Pakistan has a guesstimated wind resource potential of 346 Gigawatts [24]. Wind resource evaluation is mandatory to detect viable sites for wind project implementation. Figure 2.5 shows the wind class potential of Pakistan. Wind energy category 3 and higher, as per NREL, are suitable for profitable wind power retrieval and the erection of commercial level wind generators. Three main entities engaged in wind energy advancement are Pakistan's government institutions, including AEDB and the PMD, as well as the National NREL in the United States. The southern part of Sindh province is a naturally gifted wind corridor where winds blow with speeds of 5 m/s to 12 m/s making it ideal for wind projects to harness the power from unlimited this RES. By 2020, the cumulative installed potential of wind power projects in Pakistan had reached 1.287 GW and continues to increase as more projects are in pipeline [27]. Out of this 1.287 GW, the share of Jhimpir is 1 GW [28]. The project site in Jhimpir has wind speeds

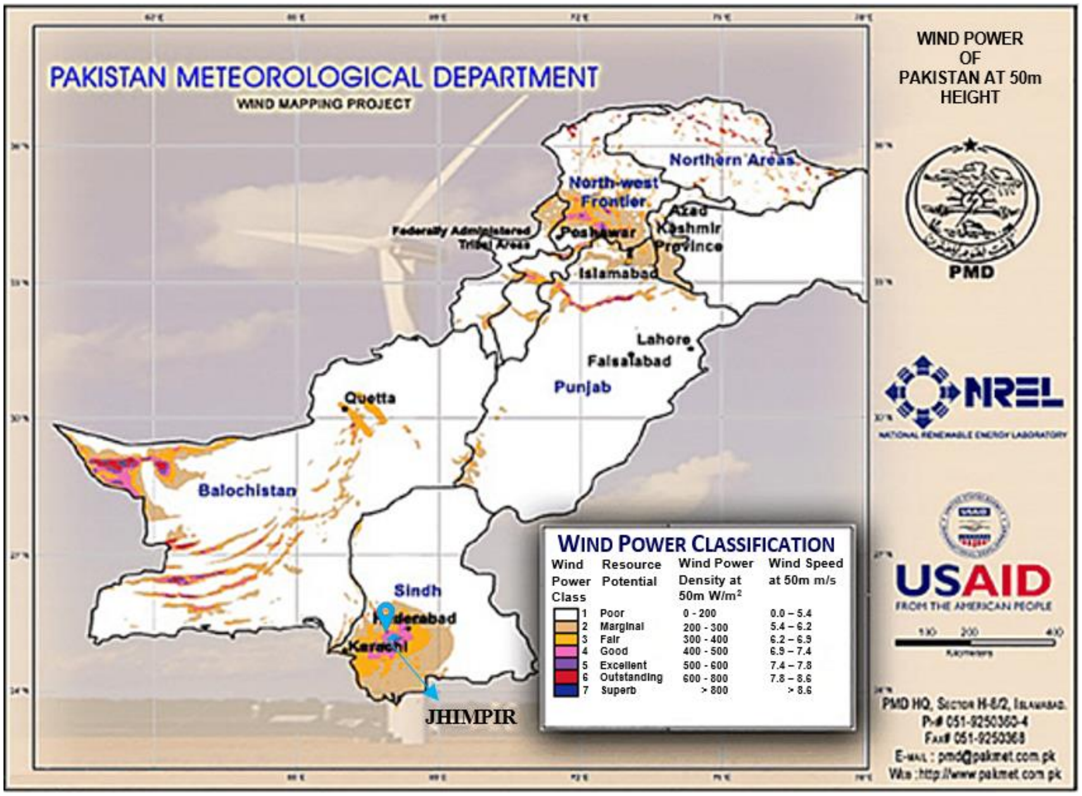

Figure 2.5 - NREL Wind Power Categorization map of Pakistan showing Jhimpir Wind Corridor (Source: AEDB)

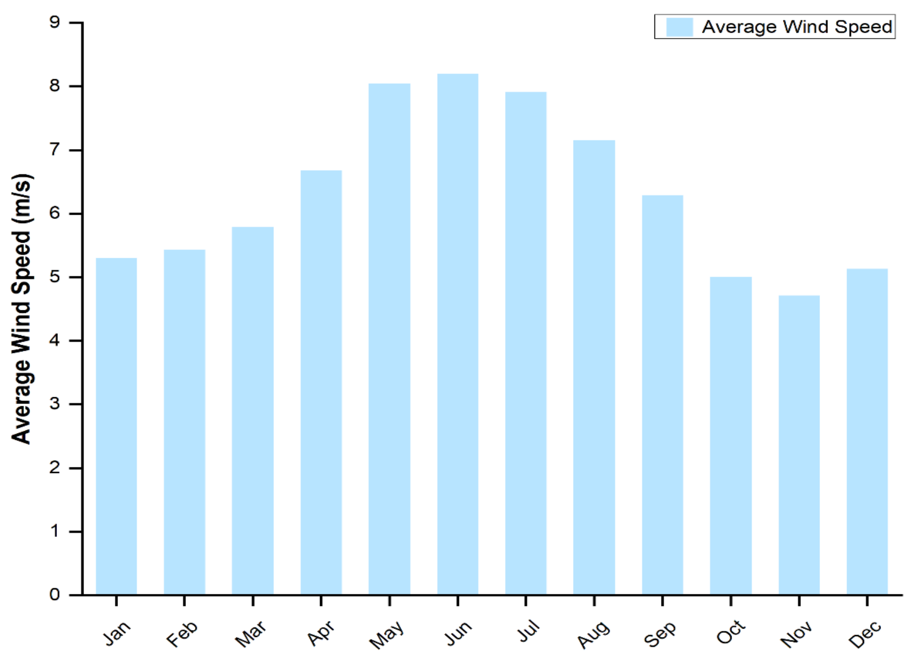

Figure 2.4 - Mean Monthly Wind Velocity

ranging from 5.30 m/s to 8.20 m/s. The government of Pakistan plans to inculcate additional 1.01 GW capacity wind power projects by the year 2025. By 2023, Jhimpir will have an additional 0.48 GW of wind projects and 0.25 GW of solar projects making it a hybrid RE hub [29]. Figure 2.4 shows mean wind velocities, recorded by NASA, at the location where the system under consideration is to be installed.

2.1.3 H_2 Potential

Weather Resource Forecasting (WRF) is a precise wind resource assessment technique for wind power production farms. As per WRF model simulations, the H_2 production potential of the Jhimpir region with turbine 3 MW Enercon E-115 having $\eta_{Theoretical}$ of 30% and PEM electrolyzer having $\eta_{Theoretical}$ of 80%, is shown in Figure 2.6.

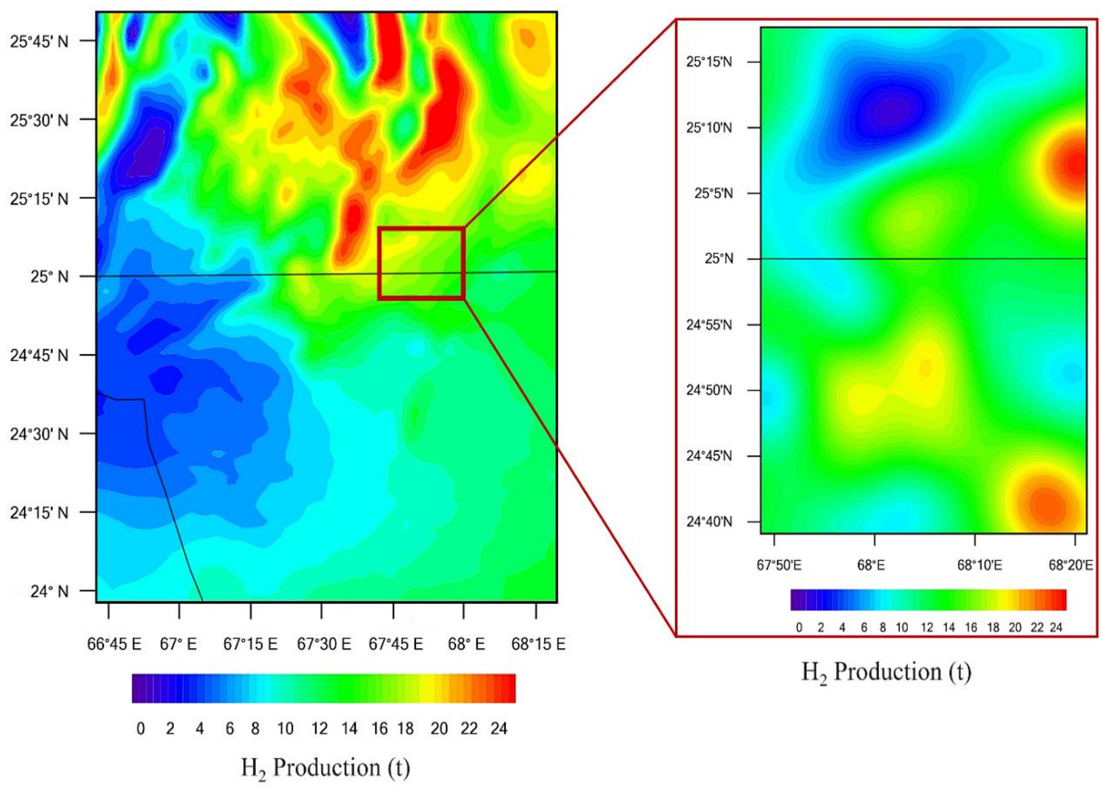

Figure 2.6 - H2 Production Potential of Jhimpir estimated by WRF

Summary

This chapter covers the discussion over the literature that has been reviewed in order to form a foundation for and a link to the current study. Numerous journal papers, review papers, conference papers, and reports issued by various international organizations were brought under the scope of discussion with respect to the current thesis. Moreover, this chapter also takes into account the wind resource potential, solar resource potential, and hydrogen production potential at the project site i.e., at Jhimpir, Sindh – Pakistan. Wind resource data while performing the simulations in HOMER Pro, were obtained from the NASA dataset. For the solar resource potential of Jhimpir, the data was obtained from the NREL. Whereas for hydrogen production potential, a tool called Weather Resource Forecasting (WRF) was used. According to the data providers as well as per the simulations results, Jhimpir has massive potential to harness energy from abundant wind and solar resources.

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Chapter 3

Hydrogen Production via Electrolysis and Types of Electrolyzers

3.1 Hydrogen Production and Electrolysis

Hydrogen gas may be produced in a variety of methods. Using natural gas in steam-methane reforming, partial oxidation of oil, coal gasification, and electrolysis are the most common production techniques. It is estimated that only 4 percent of the global h2 is produced by electrolysis [1]. Water and electricity are used as raw materials in electrolysis to generate hydrogen. It is critical that the power required for electrolysis is supplied in a

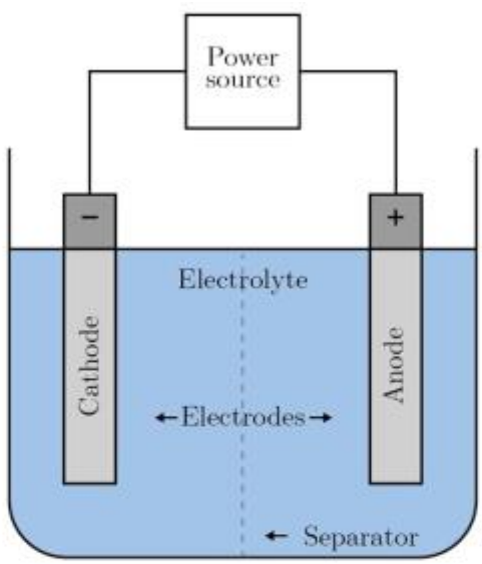

Figure 3.1 - Schematic of a Typical Electrolyzer

stable manner in order to achieve uninterrupted hydrogen generation [1]. Water electrolysis is an electrochemical process that occurs within the layers of cells. Through the process of electrolysis, the electrical energy is transformed into the chemical energy to produce the hydrogen. In the operation of electrolysis, an electrolyzer utilizes electricity to split water into hydrogen and oxygen. The electrolyzer system generates hydrogen gas by electrolysis. An electrolyzer consists of a cathode (negatively charged), an anode (positively charged), and a membrane in its most primitive sense. A conventional electro-chemical cell contains two electrodes, an electrolyte, and a partition that splits the cell into two half-cells. It also has a power supply that provides adequate energy to propel the reactions forward. Electrons are the charge carriers in the electrolyzer's power source and electrode section. The charge is carried by the free ions in the electrolyte [1]. Figure 3.1 below shows the schematic view of the typical electrolyzer. An electrolyzer is generally constructed up of multiple of these cells that are joined in series or parallel. An electrolyzer stack alludes to a group of cells. An oxidation activity occurs at the anode, whereas a reduction reaction happens at the cathode.

3.2 Types of Electrolyzers for H_2O Electrolysis

The electrolyzers may be configured to fit a wide spectrum of upstream and downstream ranges, from minor industrial units deployed in shipping containers to massive, concentrated manufacturing plants capable of delivering hydrogen via trucks or pipes. Electrolyzers for water electrolysis can be classified into two criterion types: (a) non-membrane based electrolyzers and, (b) membrane based electrolyzers [2]. These various electrolyzers operate in varying modes based on the materials included. Both alkaline and PEM electrolyzers can produce on-requisition hydrogen, compressed hydrogen without using a compressor, and hydrogen that is 99.999 percent purified, moisture-free, and carbon-free. Here in this chapter of the thesis, three main types of electrolyzers used for hydrogen production via electrolysis will be discussed and compared against each other in order to choose the best suitable type for under-consideration HES.

3.2.1 Alkaline Electrolyzers

To date, the most fundamental and sustainable technique for water electrolysis is the AEL with a lifespan of up to 30 years and operational hours life ranging from 60,000 hours to 100,000 hours. The AEL functions at operating temperatures of 60 °C to 90 °C. Water is mixed with an aqueous electrolyte solution including potassium hydroxide (KOH) and maybe sodium hydroxide (NaOH). Water is oxidized out at the anode and reduced there at the cathode in an alkaline electrolyzer. A "cell," constituted of an anode, cathode, and membrane, manufactures hydrogen. The cells are generally connected series - wise in a

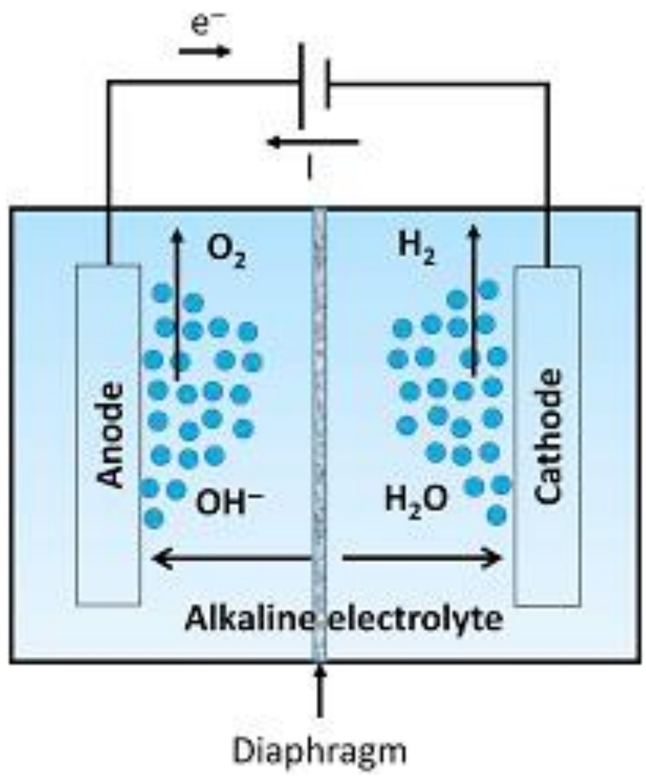

Figure 3.2 - Alkaline Water Electrolyzer Schematic

cell stack which generates increased hydrogen and oxygen as the number of cells extends. As current is supplied to the cell stack, hydroxyl ions (OH-) flow through the electrolyte solution from the cathode to the anode of every cell, creating hydrogen gas bubbles on the cathode and oxygen gas on the anode, as shown in Figure 3.2. After production, hydrogen is compressed as upon production, its pressure is too low to store or transport it.

3.2.2 Proton Exchange Membrane Electrolyzers

Proton Exchange Membrane electrolyzers are also operated at low temperatures of 80 °C. PEM electrolyzers incorporate a solid polymer electrolyte in the form of a proton exchange membrane. The operational lifespan of these electrolyzers is up to 20 years or up to 60,000 running hours. The electrolyte is commonly polymeric, which is chosen for its excellent conductivity. Platinum or even other noble metals are used as electrodes.

Nafion, a fluorinated polymer, is widely used as a membrane. Water segregates into hydrogen and oxygen as current is introduced to the cell stack, and the hydrogen ions i.e., protons flow through the membrane to generate H_2 gas on the cathode compartment [2]. Figure 3.3 below shows the schematic of the PEM electrolyzer cell.

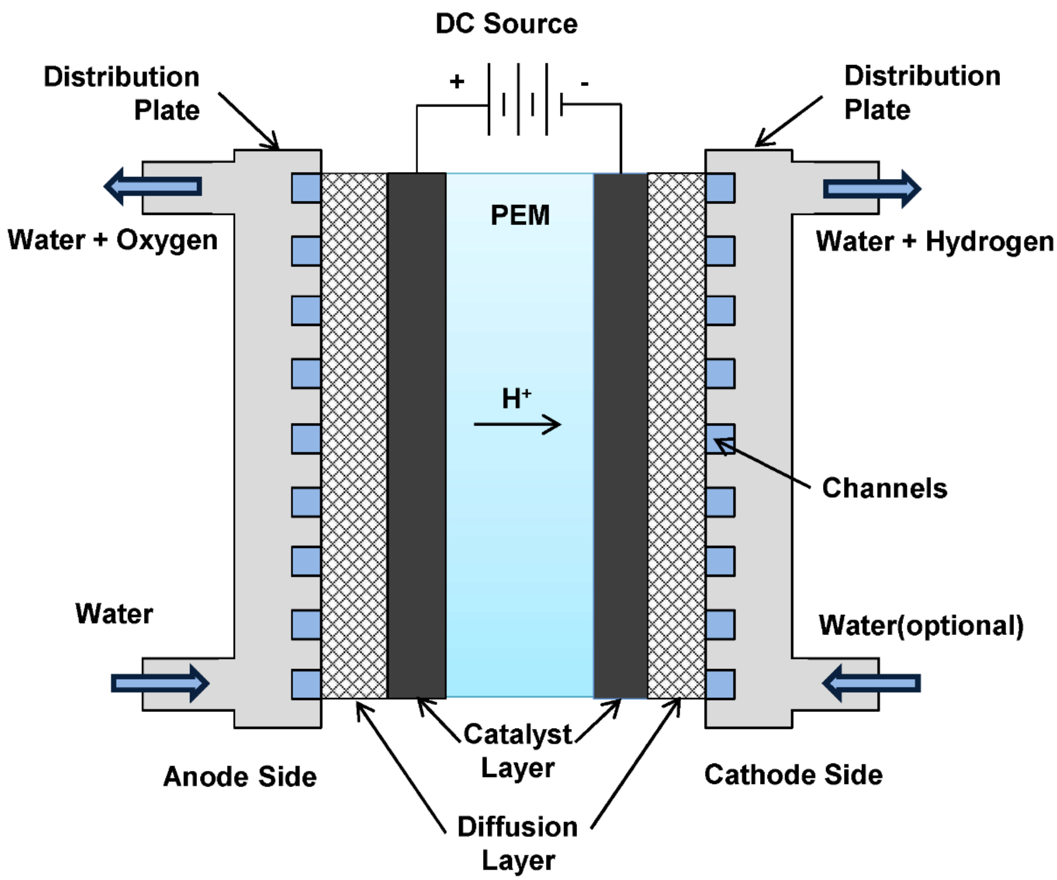

Figure 3.3 - PEM Electrolyzer Cell Schematic

3.2.3 Solid Oxide Electrolyzers

These are high temperature prototype electrolyzers. SOEC operates at temperatures ranging from 650 to 1000°C [2]. These electrolyzers have an operational lifespan of 10,000 hours, which will improve further as the technology develops and matures. Ceramic, mainly zirconia, is used as the electrolyte in SOEC. Ceramic compounds are

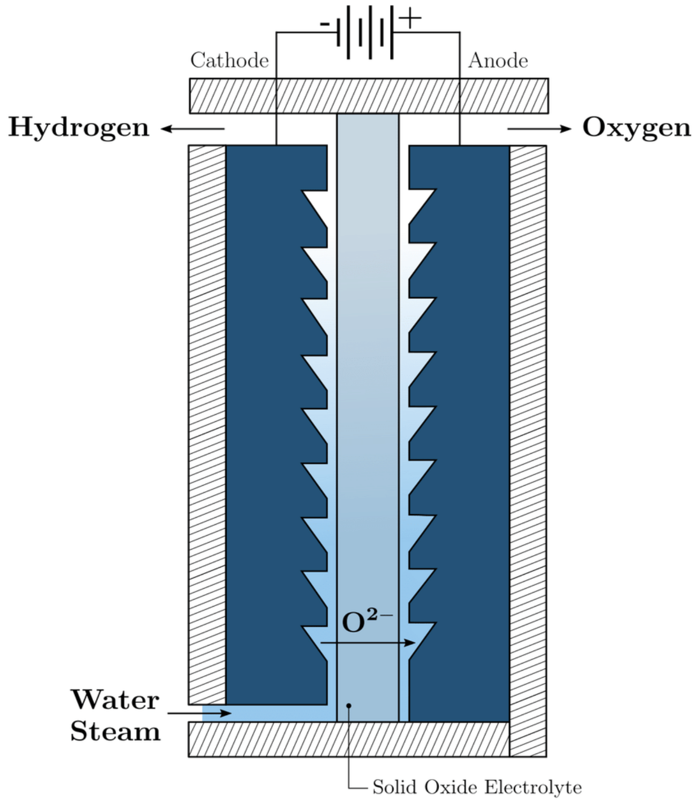

Figure 3.4 - Solid Oxide Electrolyzer Schematic

also used for the electrodes, which are ordinarily porous cement electrodes coated with nickel or zirconia. At the cathode, electrons from the external circuit react with water to generate hydrogen gas and negative ions. After flowing through the slid membrane materials composed of ceramics, oxygen interacts at the anode to produce oxygen gas and electrons. SOECs function at a substantially higher temperature as compared to alkaline and PEM electrolyzers (up to 80°C) and possess the capacity to be far more competitive [3]. Figure 3.4 shows the schematic of the SOEC electrolyzer. Table 3.1 summarizes the H_2 generation by H_2O disintegration techniques with the classification of membranes employed, pros, cons, and efficiencies.

Table 3.1 - Comparison between Alkaline, Proton Exchange Membrane, and Solid Oxide Electrolyzers

Parameter	**Unit**	**AEL**	**PEM**	**SOEC**
Temperature	°C	60 - 80	50 - 80	650 - 1000
Pressure	bar	< 30	< 30	< 25
Lifetime	1000 h	60 - 100	20 - 60	< 10
Maturity Status	-	Mature	Commercial	Prototype
Hydrogen Purity	%	> 99.5	99.99	99.9
Efficiency	%	60 - 80	70 - 90	90 - 100
Membrane Type	-	No membrane. Only asbestos/ceramic diaphragm	Nafion, Polyethylene	O_2 ion ceramic membrane
Pros	-	• Economical • Durable • Low $T_{Operating}$ • Inexpensive electrocatalyst	• High H_2 purity • Dynamic operation • No compression required	• Dual functionality • Efficient ionic conductivity • Excellent η

Cons	-	• Corrosive electrolytes • Low η_{Energy} • Low gas purity • Low operating pressures	• Expensive catalyst • Expensive membrane • Cost of stack materials higher than AEL	• Energy intensive • Economically unviable • Ultra-high $T_{Operating}$

Summary

This chapter has encapsulated in it the summary of one of the methods of hydrogen production, the electrolysis. Electrolysis is mainly divided into two criterion types: membrane based electrolysis and non-membrane based electrolysis. Three of the major types of electrolyzers considered for electrolysis operation have also been discussed. These include the Alkaline electrolyzers, Proton Exchange Membrane (PEM) electrolyzers, and Solid Oxide (SOEC) electrolyzers. Furthermore, a comparison has been drawn between these electrolyzers on the basis of various parameters including operating temperatures, operating pressures, lifetime, efficiencies, hydrogen gas purity, and their pros and cons. Alkaline electrolyzers are a proven as well as matured technology. However, the hydrogen produced by them needs to be compressed in order to store it or utilize it. On the other hand, PEM is a technology on a commercial scale that does not require its product to be compressed, unlike AEL. SOECs are the most promising electrolyzers when it comes to efficiency. However, they are not viable economically as well as still on the prototype scale. This makes PEM electrolyzers an attractive choice to be used under consideration HES

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Chapter 4

Components Selection and Implementation of HOMER Pro for Technoeconomic Analysis of Multiple Configurations of HES

4.1 Outline of the Study

The core objective of the under-consideration system is to produce green hydrogen by procuring green electricity generated by PVs and WTGs. Following this, the turbine of a hypothetical CCPP will be fed with 100 percent hydrogen to churn out electricity. Hybrid Optimization Model of Electric Renewables (HOMER), a tool developed by NREL, had been deployed while performing iterations and simulations to evaluate the technical and economic feasibility and applicability of the system energized by PVs and WTGs. It disentangles the chore of analyzing design alternatives for diverse off-grid as well as grid-connected frameworks for automated, secluded, and distributive production purposes.

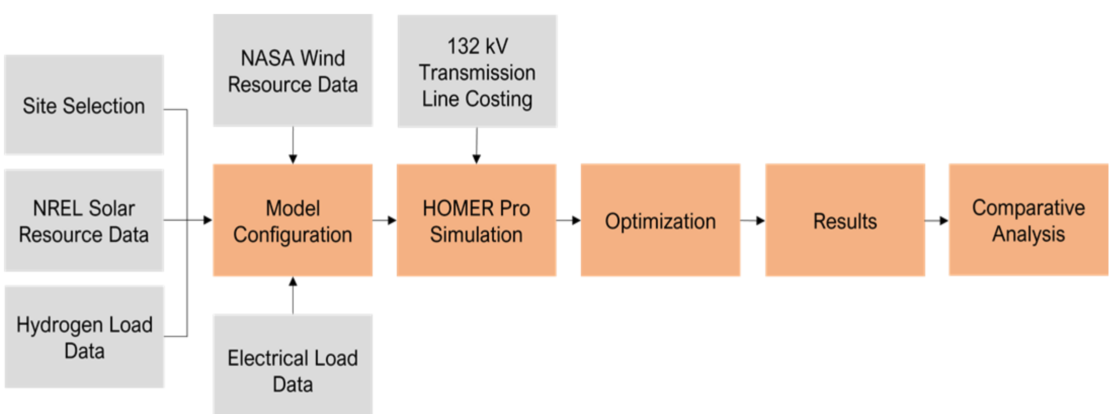


Figure 4.1 - Methodology of Research

Figure 4.1 illustrates the methodology chart of this study. HOMER enables the draftsperson to contrast a wide range of available alternatives, considering the technoeconomic characteristics of components of the system and offering an approach to determine the least costly framework focused on the energy original dataset, elements of the system, and a specified load capacity. It also assists experts in fathoming and estimating the outcomes of unreliability or fluctuations in inputs [1][2]. Besides the baseline case, three scenarios have been deliberated upon. Thus, making it four scenarios in total. The base case in which all the components are included. In the baseline case, the genset is included that would be running on the stored hydrogen as fuel. In the first scenario, the system has a configuration in which PV and genset are there, but batteries are excluded. Surplus hydrogen, whenever in excess and if any, is stored in the storage tank after fulfilling the CCPP demand of hydrogen. Second, the HES has architecture with genset excluded but inclusive of PVs and batteries. Third, both the genset and batteries

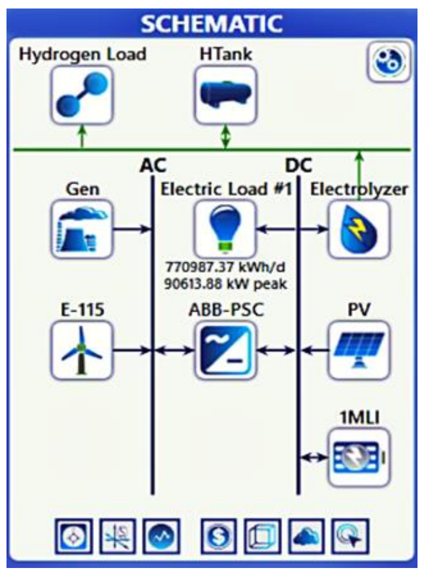


Figure 4.2 - Architecture for Baseline Case of Proposed HES for Hydrogen Production

are included but PVs are excluded. Besides the baseline case, for the third scenario, to meet the energy required as per load, there should be an ample surplus amount of source to produce hydrogen to fulfill the CCPP demand of hydrogen after excluding PVs. To achieve this, the system will have to be expanded more resulting in surged system

CAPEX, OPEX, and LCOE. This is not at all economically viable. In scenario 2, HOMER excludes genset and thus, hydrogen demand by genset is eliminated as well. In this case, batteries ensure to store the power during peak production and later provide the electrolyzer with sufficient power during the time of low resource availability. Thus, the ultimate long-term target is the sector coupling by transforming the region into a Hydrogen Hub by tapping the wind and solar potential of the region and producing green electricity to generate green hydrogen which encapsulates energy density as high as three times more than that of natural gas and feeds future CCPP with this hydrogen. Figure 4.2 illustrates the constitution of the baseline case for HES for the production of hydrogen later to be fed into the turbine of CCPP. The hypothetical HES system has been dissected into two blocks to be deliberated upon. The first block is installed at Jhimpir and encapsulates WTGs, PVs, converters, and batteries. Whereas block 2 is installed in Karachi near the seashore and houses the electrolyzer package (including desalination plant (DSP) for SWD) and a hypothetical CCPP, which is fed in with hydrogen produced by the electrolyzer package to produce green electricity.

4.2 Exegesis of Data Inputs

4.2.1 Load Profile

It is a prerequisite in modus operandi to have electrical load recorded on an hourly basis to depict the contour of nominal utilization by the HES under deliberation. Because of weather fluctuations in power consumption for HES, it is deemed necessary to correctly state the hourly industrial power demands throughout a year, which is rarely attainable. The HOMER algorithm has been used in the study to artificially construct the industrial hour-by-hour electricity load. To execute this, the hourly load data logged for a normal day in the regular year is the least desideratum. Whereupon, leveraging this hourly load pattern and including arbitrary variance parameters, termed as day-to-day fluctuation and time-step to time-step fluctuation, HOMER is adept in integrating the 8760 industrial electrical load readings on an hourly basis for a complete year. Each of these values is proximate to be nearly 2 percent each to each and between [3]. Figure 4.3 shows the scaled data daily pattern for a complete year. A normal day electrical load pattern in winters (Nov

– Mar) as well as in summers (Apr – Oct) depicts that power demand fluctuates around the day and peak demand hours are in the afternoon because most offices, markets, and factories are running and open during the daytime.

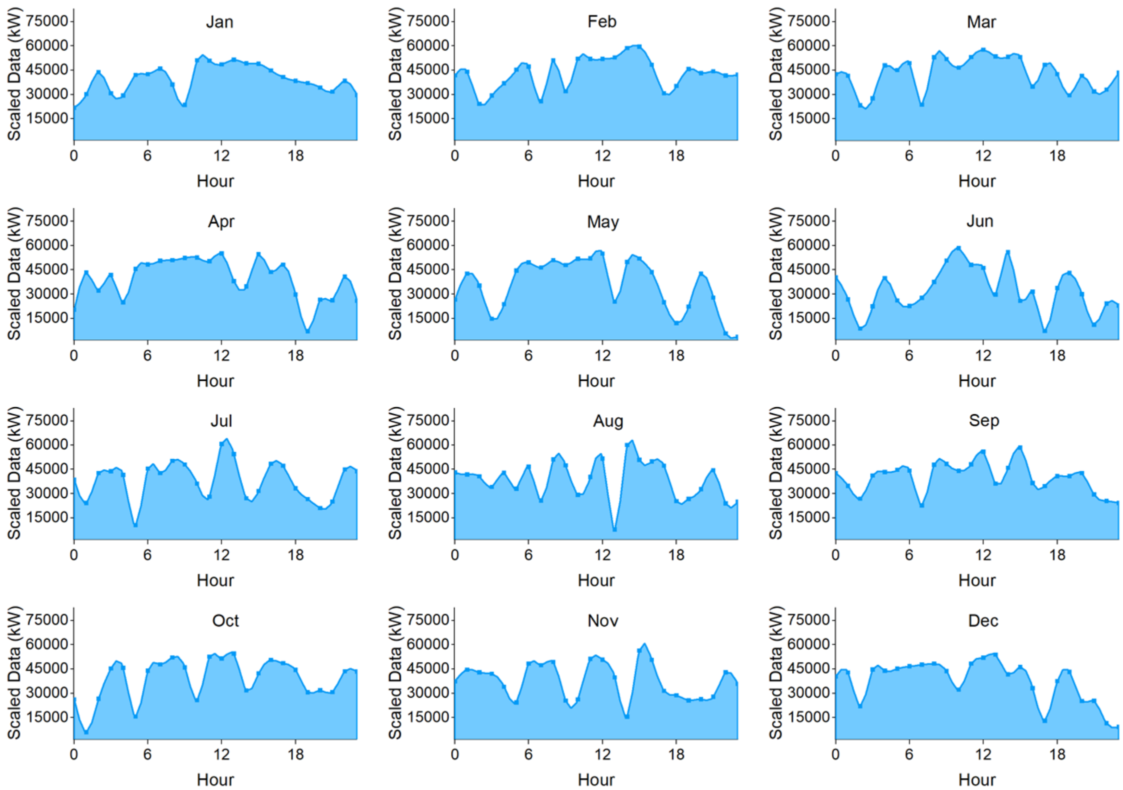


Figure 4.3 - Scaled Electrical Load Data Daily Profile

In summers, air-conditioning demands are at their peak as well in the afternoon. Nevertheless, in the early morning hours and at the night, the energy demand is less compared to that in the afternoon.

4.2.2 Ambient Temperature

Mean monthly T_{air} for Jhimpir has been acquired from the database of NASA – POWER. To determine the PV array power, the impact of ambient temperature has been taken into consideration. Figure 4.4 is showing the average monthly temperatures of Jhimpir. The scaled annual mean temperature is recorded to be 27.45 °C. It is evident from the figure that the peak temperature has been recorded as 33.99 °C in June (summers), while the lowest temperature is 17.55 °C in January (winters).

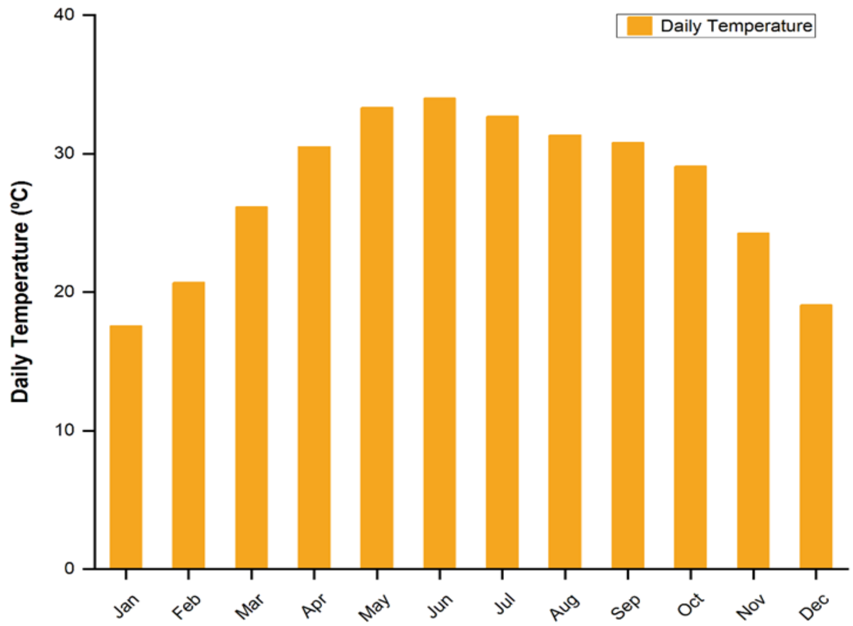


Figure 4.4 - Monthly mean T_{air} for Jhimpir, Pakistan.

4.2.3 Hydrogen Load

Hydrogen load was determined and set according to baseline case on an hourly basis and day-to-day basis as well. Talking about the baseline case, on an hourly and daily basis,

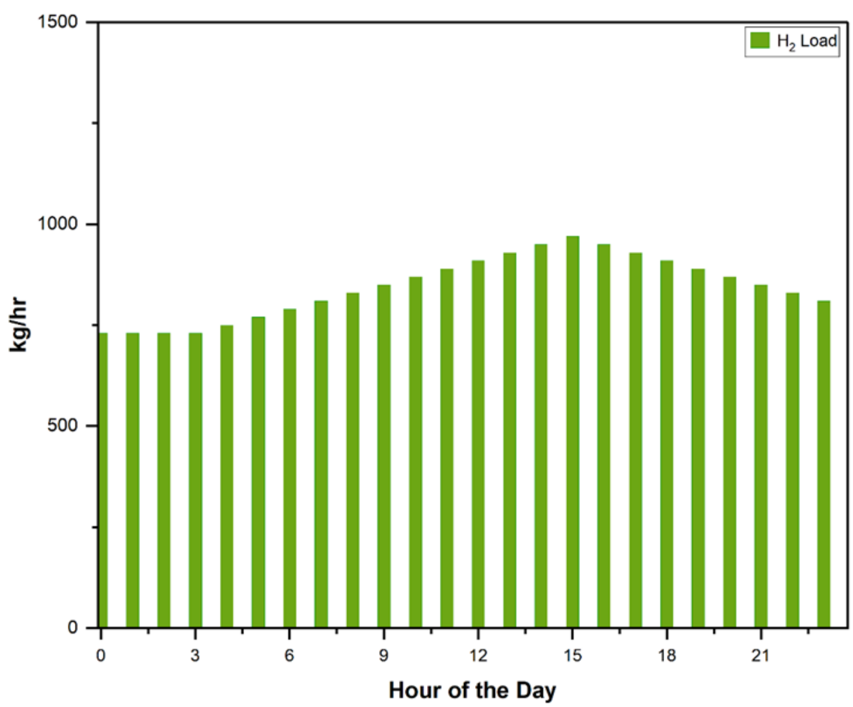


Figure 4.5 - Hourly Hydrogen Load

the hypothetical system was to fulfill 545 kg/hr and 13,080 kg/day hydrogen demand respectively. On the contrary, the more realistic calculations performed by HOMER after having included the most efficacious PEM electrolyzer and evaluating by taking into account various losses, the scaled annual average for hourly and daily hydrogen loads with WTGs and PVs were assessed as 833 kg/hr and 20,000 kg/day. Figure 4.5 shows the hydrogen load pattern on an hourly basis for the under consideration supposed HES.

4.3 Components of the System

4.3.1 WTG System

WTGs considered for the system are Enercon E-115 3 MW gearless variable speed turbines with a hub height of 122 meters. HOMER calculates WTG productivity by incorporating and interpolating linearly at locations logged to develop the power curve. Beyond this power curve, the WTG output remains zero. The turbine halts when the velocity of the wind vital to drive the turbine is either too decreased to generate electricity or too intense to jeopardize the turbine [4]. Figure 4.6 shows the wind power curve of E-

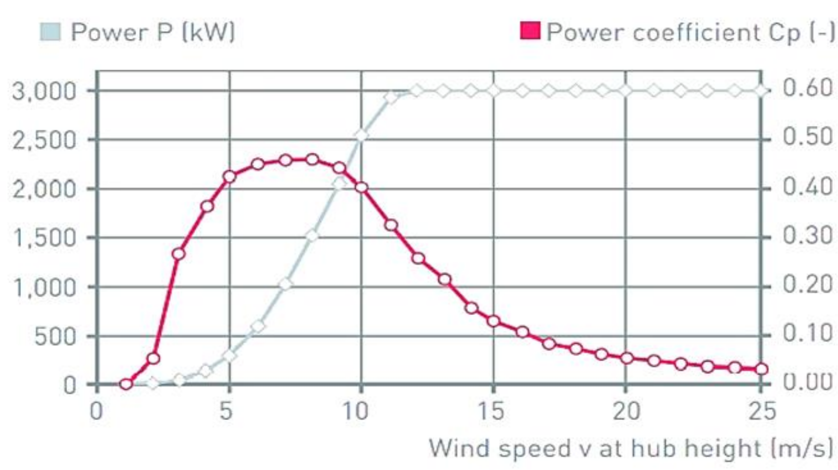


Figure 4.6 - Enercon E-115 Wind – Power Curve

115 as provided by the manufacturer [5]. Mean wind velocity on annual basis at the location, logged by an anemometer at the height of 40 m, is 6.3 m/s. HOMER adopts a triple tier approach to estimate the energy production of the wind turbine at every time

interval. Firstly, HOMER computes the wind velocity at the WTG's hub height. Second, WTG's power generation is then computed at that wind velocity at standard air density. Lastly, HOMER modifies the generated power value to account for the real air density. In this study, power law has been considered to determine the wind profile. To execute these steps, HOMER makes use of equations (4.1), (4.2), and (4.3) as stated below.

$$U_{hub} \;=\; U_{anem} \;.\; (\frac{Z_{hub}}{Z_{anem}})^{\alpha} \tag{4.1}$$

where,

U_{hub} = the wind speed at hub height (m/s)

U_{anem} = the wind speed at anemometer height (m/s)

Z_{hub} = the hub height of wind turbine (m)

Z_{anem} = the hub height of wind turbine (m)

α = the power law coefficient

$$P_{WTG} \;=\; P_{WTG,STP} \;.\; [\{U(t^3) - \; U_{anem}^3 \; - \; U_{Ci}^3 \;\}] \tag{4.2}$$

P_{WTG} = $P_{WTG,STP}$, $U_{Co} \leq \; U \; \leq \; U_{anem}$

P_{WTG} = 0 , $U_{Co} \; \leq \; U \; \leq \; U_{Ci}$

where,

P_{WTG} = the wind turbine output (kW)

$P_{WTG,STP}$ = the wind turbine output at STP (kW)

$$P_{WTG} \;=\; \left(\frac{\rho}{\rho_{\circ}}\right) . \; P_{WTG,STP} \tag{4.3}$$

where,

ρ = the actual air density (kg/m^3)

ρ_0 = the actual air density (kg/m^3)

4.3.2 PV System

Independent of voltage and temperature, DC electricity is generated by PV arrays in HOMER in direct proportionality to GHI [6]. The power produced by the PV system may be computed by using the relation shown in equation (). Light coming directly from the sun is converted into DC by PVs and is directly supplied to the electrolyzer for hydrogen production. The mean annual average GHI at Jhimpir is 5.51 kWh/m^2/day. The data is composed of two sets, TMY3 and TMY2 respectively, dispensed by NREL. During the HES simulation, the local market was surveyed for per kW CAPEX, OPEX, and

$$P_{PV} = Y_{PV} \times f_{PV} \left[\frac{G_T}{G_{T,STC}}\right] \left[1 + \alpha_P \left(T_c - T_{c,STC}\right)\right] \tag{4.4}$$

substitution costs.

where,

Y_{PV} = rated capacity or output power output of PV at standard test conditions (kW)

f_{PV} = Derating factor for PV (%)

G_T = GHI incident on PV in present time step (kW/m^2)

$G_{T,STC}$ = GHI incident on PV at STC (1 kW/m^2)

α_P = Power temperature coefficient (% / °C)

T_C = Temperature of PV cell at current time step (°C)

4.3.3 Battery Storage Pack

HES system contains Generic 1 MW Li-ion batteries as storage devices. These batteries have round trip efficiency of 90 percent, nominal bus voltage of 600 volts, and are connected in series to yield maximum energy storage capacity. As per HOMER optimization, there is only one string comprising twenty-five batteries after accounting for low availability of wind resources and zero availability of solar resources during nights and cloudy. For the baseline case, the setup is established in such a way that the whole pack produces 62,029,258 kWh throughout its life.

4.3.4 132 kV Power Transmission Line from Jhimpir to Karachi

Transmission cables are built to carry electricity as cost effectively as possible while maintaining the highest levels of protection, security, and dependability. RoW, meteorological constraints, conducting metals and their arrangement, insulator layout, tower geometry and topologies, foundations, and environmental concerns are all critical elements in the design, installation, and operation of these lines [7].

Figure 4.7 - 132 kV Transmission Line Poles

After an extensive market survey for the transmission lines and poles component prices, for this hypothetical system, cost estimation has been performed for a 150 km long 132 kV double circuit transmission line between Jhimpir, where WTGs and PVs are installed, and Karachi, where electrolyzer package is installed. The conductor type is ACSR, and insulators are of disc type. Figure 4.7 shows the schematic of a 132 kV transmission line pole.

4.3.5 Convertor

To sustain the current of energy between the DC components and AC components, a convertor is required to convert the AC to DC and vice versa. The convertor that has been included in this HES, is ABB PStore – PCS. The rationale behind choosing this convertor is its exceptional overload potential of up to 200 percent. Not only this, ABB-PSC has remarkable efficiency of 96 percent and 2880 kVA of continuous rated power. Moreover, it has a capacity factor of up to 24.7 percent. HOMER optimizes the size of the convertor and yield of the convertor in kWh of energy per year on its own in accordance with the architecture scenario under consideration.

4.3.6 Electrolyzer Package

A typical electrolyzer consumes 46.4 kW to produce 1 kilogram of H_2 gas [8]. The electrolyzer that has been considered for deliberation HES, is Hydrogenics HyLYZER-300-30 PEM electrolyzer having 99.98 percent H_2 purity. HyLYZER-300-30 has a nominal H_2 flow of 300 Nm^3 per hour with nominal input power of 1.5 MW and consumes 5.4 kW [9]. Excessive capacity has been considered with a viewpoint of expansion of likewise HES in the future. PEM electrolyzers are adept at responding to fluctuations and adjust accordingly promptly. They exclude the need for H_2 compression after electrolysis unlike alkaline electrolyzers where a compressor is included in the electrolyzer pack as the gas produces has pressure too low. The minimum electrolyzer load ratio has been taken as 10% because for PEM electrolyzer, it ranges from 0% to 10% [10]. Moreover, the purity of H_2 gas is high, and overall maintenance costs are low in the case of PEM. This makes the PEM electrolyzer an ideal choice for electrolysis. Desalinated water is the raw material of the electrolyzer out of which the electrolyzer extracts hydrogen gas. DSP and electrolyzers are installed in Karachi near the seashore. In this study, DSP has been considered to be included within the electrolyzer package and costs have been entered in the HOMER accordingly after combining. Due to promising yields and performance, the efficiency of the electrolyzer was set to 85 percent while performing the study. The minimum load ratio is kept at 10 and component life is 25 years.

4.3.7 Hydrogen Tank

Being an energy carrier, H_2 is supposed to be dispensed to acclimatize to intermittent fickleness between RE demand and supply. Thus, to cater to this issue, a hydrogen storage tank is a prerequisite.

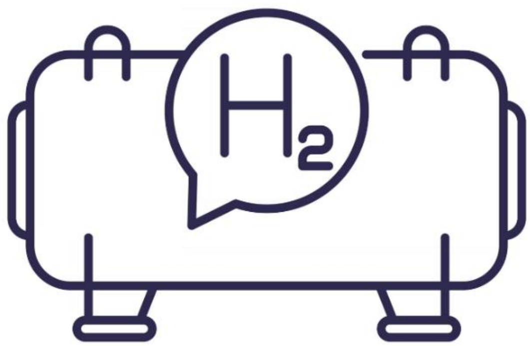


Figure 4.8 - Hydrogen Tank

The storage capacity of the hydrogen tank while simulating the hypothetical system was taken as 10,000 kilograms and the life of the tank was 25 years. CAPEX of this 10-ton tank is 15,000 USD per ton. The hydrogen tank is protected from direct sunlight and is installed in a desiccated, cool, and cross-ventilated environment.

4.3.7 Gas Turbine

Many power industry giant manufacturers have already started developing power plants with gas turbines that will run on 100 percent hydrogen in near future. In lieu of these advancements, the proposed HES will produce hydrogen and provide this hydrogen to a medium-sized hypothetical CCPP of 1 x 1 configuration. Many manufacturers like GE, Kawasaki, Wartsila, Siemens, and Jenbacher have achieved the 100 percent pure hydrogen mark in combustion as a fuel in their medium-sized gas turbines. SIEMENS plans to run turbines on 100% hydrogen on a mega industrial scale. SGT-800 has currently reached 75

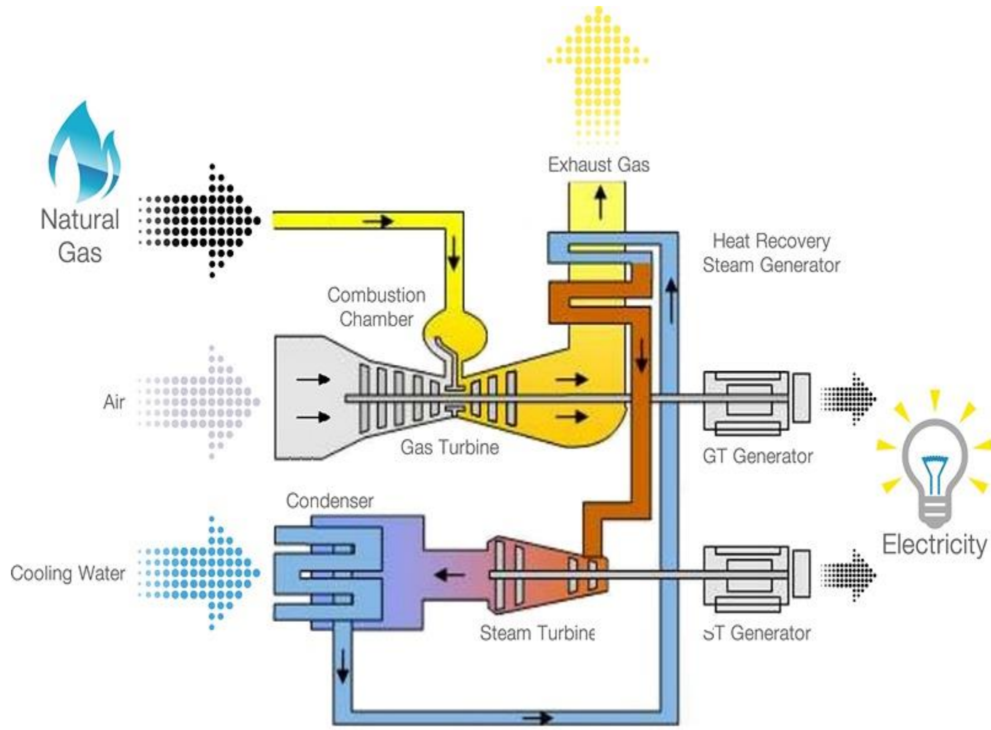


Figure 4.9 - A schematic of CCPP

percent hydrogen with DLE dry low emission systems. In this regard, recent test results on SGT-800 burners have demonstrated promising results and the ability to achieve 100 percent carbon-free combustion in the coming years. In near future, these turbines will be available for the market on a mega industrial scale because highly advanced and modified combustors for these turbines are under development that will enable 100 percent hydrogen intake as fuel. Consideration has been made that this hypothetical CCPP is installed in Karachi near the seashore right next to the electrolyzer package. Figure 4.9 shows the schematic of a combined cycle power plant.

4.4 Configuration of the System

4.4.1 For the Base Case

The components that the base case houses, are a genset, WTGs, PVs, batteries, converter, electrolyzer, and hydrogen tank. Hydrogen load and electric load were defined on the basis of hydrogen required by the gas turbine of a medium-scale CCPP as a fuel. Table 4. 1 below shows the configuration details of the architecture of possible multiple scenarios for HES simulated by HOMER Pro. In the base case, to cater to the defined electric load, HOMER Pro includes all of the components in the simulation and sizes the system optimally for the hydrogen production process.

4.4.2 For Scenario 1

For scenario 1, the system has been analyzed economically and technically by excluding Li-Ion batteries and the genset is supposed to provide backup power during hours of no wind and solar resources. Genset will utilize stored hydrogen to generate power that will run an electrolyzer to produce more hydrogen. This produced hydrogen, packed with high energy density, will serve as fuel for a gas turbine of a medium-scale power plant which in turn will produce green electricity with zero emissions. The electric load and hydrogen load have been kept the same as that in the base case. The number of WTGs and the capacity of PVs were not fixed.

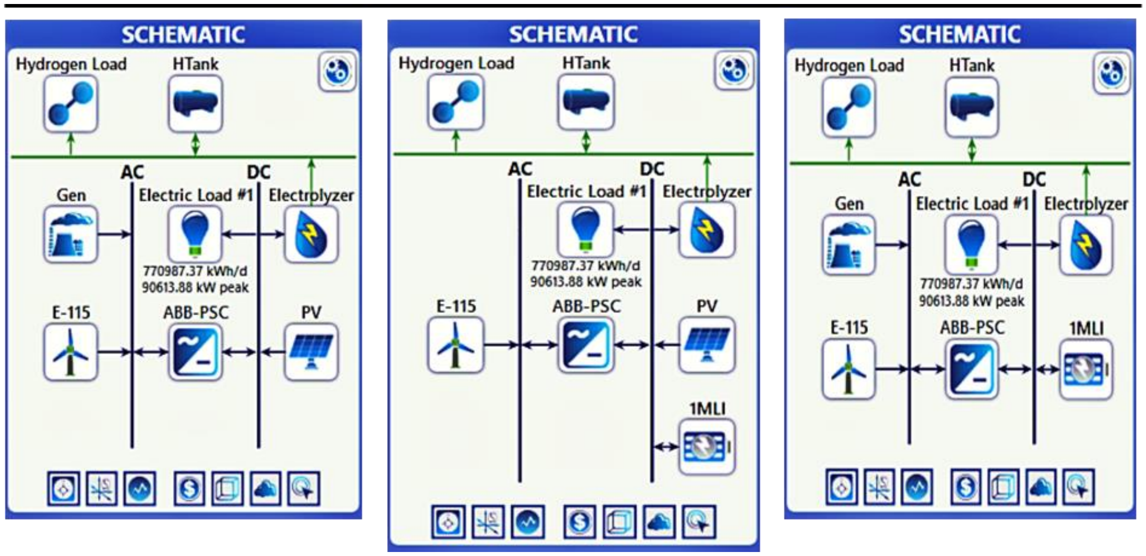
Table 4. 1 - Multiple HES Configurational Scenarios for HOMER PRO Simulation

Component	Base Case	Scenario 1	Scenario 2	Scenario 3
Enercon E-115 3.0 MW WTGs	✓	✓	✓	✓
Auto-sized Genset	✓	✓	×	✓
PVs 80,000 kW	✓	✓	✓	×
ABB PStore-PCS 2880 kW Convertor	✓	✓	✓	✓

1 MWh Li-Ion Batteries	✓	×	✓	✓
Electrolyzer Package 10,000 kW	✓	✓	✓	✓
Hydrogen tank 10,000 kg	✓	✓	✓	✓

Rather HOMER Pro Optimizer was permitted to determine the required number of WTGs and capacity of PVs as well as auto-size the genset on its own to cater to the defined electric load and compensate for the absence of batteries. Figure 4.10 shows the architectural configuration of the components of HES in scenario 1.

4.4.3 For Scenario 2



Scenario 1 *Scenario 2* *Scenario 3*

Figure 4.10 - Scenarios for HES Architectural Configuration

For scenario 2, techno-economic feasibility analysis has been performed by terminating the auto-sized genset. In its place, Li-Ion batteries have been included in the system architecture to provide backup power to the electrolyzer during hours of intermittency, so that electrolyzer operation for producing the hydrogen is not interrupted. Likewise, in this scenario as well, the electric load has been kept the same as that in the base case and HOMER Pro optimized and sized the number of system components automatically to meet the demand. This architecture of HES in scenario 2 is also shown in Figure 4.10.

4.4.4 For Scenario 3

In scenario 3, the system is inclusive of both the auto-sized genset as well as the batteries. However, PVs have been factored out here in this scenario. Here again, electric load demand has been kept the same as it was in the baseline case. This has been done to compare and evaluate all the three architectures in scenario 1, scenario2, and scenario3 respectively against the same reference demand. HOMER Pro simulated and gave the results with automatically sized components. Figure 4.10 illustrates the configuration of scenario 3 as well.

4.5 Economic Assessment

Analyzing a project economically is vital for its viability of implementation. NPC of a system is the present worth of complete expenses that the system will induce throughout its operational life subtracted from the present worth of total profits that the system will bag during its operational life. CAPEX, OPEX, maintenance costs, components substitution or surrogation costs, fuel expenses, and penance on emissions fall under the umbrella of costs or expenses. Whereas profits encompass salvage value and the worth of energy or hydrogen sold to the grid or power plants. HOMER Pro deploys several equations to calculate various expenses and profits incurred by a specific component as well as the overall system. Equation (4.5) calculates the total NPC of the system.

$$C_{(NPC,T)} = C_{TA}/CRF\left(i, R_{Proj}\right) \tag{4.5}$$

where, $C_{NPC,T}$ is the total net present cost of the system (USD), C_{TA} is the total yearly cost (USD/year), CRF is the recovery factor for CAPEX, and i is the real rate of discount on a yearly basis (%), R_{Proj} is the project life (years). Here for the system under consideration, project life has been taken as 23 years. Equation (4.6) below calculates the real discount rate over the life of the project. Thus, the real discount rate can be expressed in terms of the nominal discount rate by this equation.

$$i = \frac{i' - f}{1 + f} \tag{4.6}$$

where, i′ is the nominal rate of discount at which the money was borrowed, and f is the rate of inflation. In the model, the inflation rate, as per set by the government, is taken as 9%. And the discount rate is taken as 12%. For the calculation of Capital Recovery Factor (CRF), HOMER Pro makes use of the following equation (4.7).

$$CRF_{(i,N)} = \frac{i(1 + i)^N}{(1 + i)^N - 1} \tag{4.7}$$

where N is representing the years. If NPC is calculated on yearly basis, it becomes the total yearly cost. It is calculated by HOMER by the following equation (4.8):

The overall yearly cost of HES is computed by using equation (4.9):

$$C_{TY} = CRF\left(i, R_{Proj}\right) . C_{(NPC,T)} \tag{4.8}$$

$$C_{TY} = C_{CAPEX,Y} + C_{Sub,Y} + C_{OM,Y} \tag{4.9}$$

where, $C_{CAPEX,Y}$ represents the yearly CAPEX (USD), $C_{Sub,Y}$ shows yearly replacement or component substitution or surrogation cost (USD), and $C_{OM,Y}$ depicts the yearly operation and maintenance cost (USD) of the HES. To calculate the yearly CAPEX of a specific component of HES, the following is the equation (4.10):

$$C_{CAPEX,Y} = C_{CAPEX,In} . CRF\left(i, R_{Proj}\right) \tag{4.10}$$

where, $C_{CAPEX,\ Y}$ is the capital cost of a specific component divided on yearly basis. To calculate the yearly surrogation cost of a specific component of HES, equation (4.11) is used.

$$C_{Sub,Y} = C_{Sub} \,.\, F_{Sub} \,.\, SFF(i, N_{Component}) - S \,.\, SFF(i, R_{Proj}) \qquad (4.11)$$

where C_{Sub} is the substitution cost of the component, $N_{Component}$ is the number of years of component, s is the salvage worth of the component, SFF is the sinking fund factor and F_{Sub} represents the substitution factor of the component of HES. SFF is a series of the uniform yearly flow of cash, and it is calculated by HOMER by applying the following equation (4.12). Whereas worth of the component at the conclusion of the project, also called salvage value, is found by using equation (4.13).

$$SFF(i, N_{Component}) = \frac{i}{(1 + i)^N - 1} \qquad (4.12)$$

$$S = C_{Sub} \,.\, \frac{R_{Remaining}}{R_{Component}} \qquad (4.13)$$

where, $R_{Remaining}$ is the life of a specific component that is left at the conclusion of the project, and $R_{Component}$ is the total lifetime of the component.

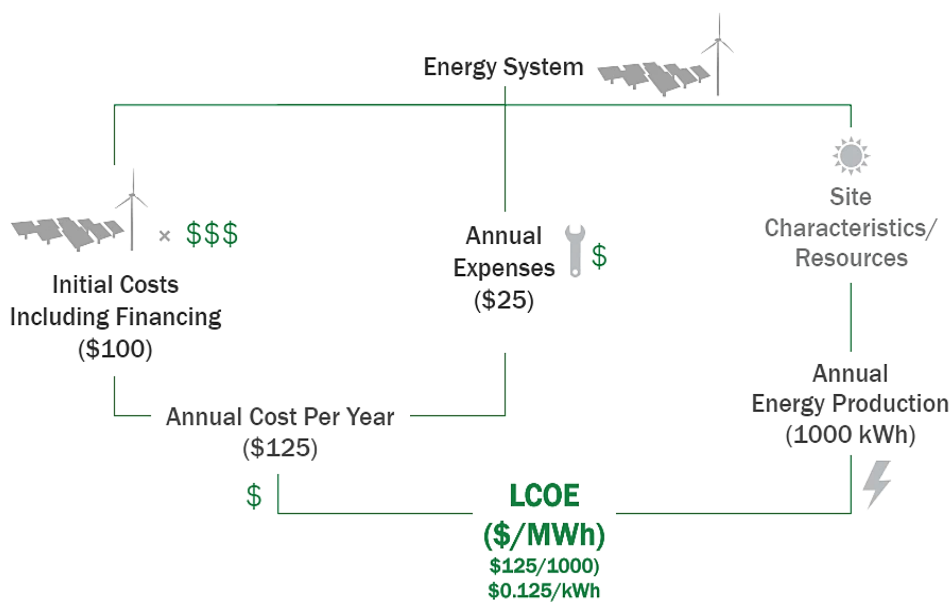


Figure 4.11 - Simple Concept of LCOE

Per kWh mean price of utilitarian electrical energy generated by HES is actually the levelized cost of energy LCOE. Figure 4.11 shows the generalized concept of the LCOE for a prompt understanding. To compute LCOE, the yearly expense of the generation of electricity is divided by the total load fulfilled. Equation (4.14) is used specifically to perform this task by HOMER for yearly basis [11].

$$LCOE = \frac{Life\ Cycle\ Costs}{Life\ Time\ Energy\ Production}$$

$$LCOE = \frac{C_{TY}}{E_G + E_{PL} + E_{DL}} \quad (4.14)$$

where E_G shows the total sale of energy to the grid, E_{PL} is the primary AC and DC load fulfilled on yearly basis (kWh/year) [12], E_{DL} represents the fulfilled deferrable load in a specific year (kWh/year). To calculate the return on investment (ROI) of HES, HOMER Pro exploits the following equation (4.15).

$$ROI = \frac{\sum_{i=0}^{R_{Project}} C_{i,Ref} - C_i}{R_{Proj} - (C_{CAPEX} - C_{CAPEX,Ref})} \quad (4.15)$$

Summary

This chapter has brought to light the methodology adopted for the progression of this thesis. Various prerequisites required by HOMER Pro in the form of the input data like electrical load data, hydrogen load data, etc. have also been discussed extensively. This was followed by components selection for HES that included WTGs, PVs, battery pack, convertor, electrolyzer package, hydrogen tank, and gas turbine. Equations deployed by HOMER Pro to conduct the technoeconomic calculations for the HES are also discussed in this chapter. Moreover, apart from the baseline case, three configurations comprising varying system architectures considered for the technoeconomic analysis of the HES in this study have also been described. In addition to this, the crucial segment of this chapter covers the economic assessment portion for this hypothetical HES. This particular portion of this chapter focused on the approach adopted by HOMER Pro for the calculation of LCOE, ROI, capital costs, salvage value, and payback period.

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Chapter 5

Results and Discussions

5.1 Transmission Line Cost Estimation

Cost estimation of 150 km long 132 kV double circuit transmission line was performed based on the firsthand market survey regarding the contemporary prices of the components. The inter-pole distance was taken to be 500 meters making it 300 poles in total over a distance of 150 km. Various costs include the cost of material for 300 towers, installation cost, conductor stringing cost, conductor supply, and implementation cost, civil works cost, and insulator cost. RoW cost was taken to be 4% of the total cost [1]. Overall costs are segregated into two categories. The first one inculcates the costs that do not depend on the CSA of cable and the second one includes the costs directly linked to CSA. Equations (5.1), and (5.2) were used for the study as well [2]. Moreover, taking all the market surveyed prices data into account, equation (5.3) was deployed in the cost estimation and assessment of the transmission line system.

$$C_T = C_C + C_O \tag{5.1}$$

where,

C_T = Total cost of transmission cables that used covered conductors

C_C = Total CAPEX during installation unassociated from CSA of covered conductor cables

C_O = Miscellaneous costs associated with CSA of cables

$$C_T = \int_{t=0}^{n} [C_C(t) + C_F(t) + C_R(t)]\, dt \tag{5.2}$$

where,

C_F = Initial fixed cost inclusive of emergencies costs

C_R = Total operating costs

n = Lifetime of transmission infrastructure

$$C_{TL} = [C_{BT} \times CC \times CS \times CRe \times TC \times Kilometers] + [C_{RoW} \times Kilometers] \tag{5.3}$$

where,

C_{TL} = Transmission line cost

C_{BT} = Cost of base transmission

CC = Coefficient of conductor

SC = Coefficient of structure

CRe = Coefficient of reconductoring

TC = Coefficient of terrain

C_{RoW} = Cost of Right of Way

Equation (5.4) gives the C_{RoW} as:

$$C_{RoW} = (RoW\ acres\ per\ kilometer) \times (Land\ cost\ per\ acre) \tag{5.4}$$

Based on the baseline case, HOMER Pro suggested and highlighted the vanquishing scenario by evaluating various factors like LCOE, CAPEX, and OPEX, generation, and production of hydrogen. For the HES under consideration, Enercon E-115 turbines having a rated capacity of 3 MW were used and iterated. Figure 4.10 shows three scenarios of the architectural configuration of HES. Components and RES wise results for all scenarios are discussed in the next segment of this chapter.

Moreover, the breakup of the total cost for the transmission line is described in Table 5.1:

Table 5.1 - Cost Breakup of 150 km Long132 kV Double Circuit Transmission Line

Cost Type	Cost (million USD)
Material cost for 300 towers	0.624018
Total installation cost for 300 towers	0.0824740
ACSR conductor cost	1.0000500
Civil works cost for 300 towers	0.5314400
Basic Capital (supply, implementation) cost for 150 km double circuit conductor	35.4949500
Insulator cost for 241 mm^2 cables for 300 towers	5.9400000
RoW cost	1.7469170
Total cost of transmission line	**45.419849**

5.2 Baseline Case

For the baseline case, the total NPC of HES is computed by HOMER Pro to be 819.330288 million USD. Whereas OPEX for this system is discovered to be 5.030166 million USD. LCOE here in this case as per the software is 0.4889 USD. The initial CAPEX of the system in this baseline case is 734.445 million USD, the overall O&M cost is 125,055,158 USD, and the component substitution or replacement cost is 2.357904 million USD. However, the salvage value of the HES in the baseline case at the end of the project life is calculated to be 42.527774 million USD.

5.2.1 WTGs

For the baseline case, which is inclusive of all the components, to cater to the load, HOMER Pro calculated the number of WTGs required for the system. WTGs were calculated to be 145 in this baseline case with a total rated capacity of 435,000 kW or 435 MW. The mean output of WTGs in this scenario was 108,734 kW or 108.734 MW. Capacity factor remained at 25% and total simulated AEP by 145 E-115 WTGs was found to be 952,512,190 kWh/year. WTGs remained operational for 8,663 hours per year. The maximum power output remained at 262,321 kW. The power output of WTGs installed in the system is shown in Figure 5.1. Levelized cost for just the WTG system in the baseline case, as per calculation, was 0.0411 USD/kWh.

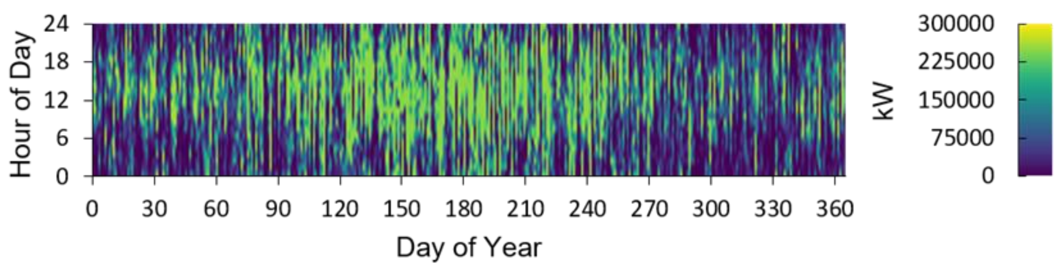

Figure 5.1 - WTG Power Output in Baseline Case

5.2.2 PV System

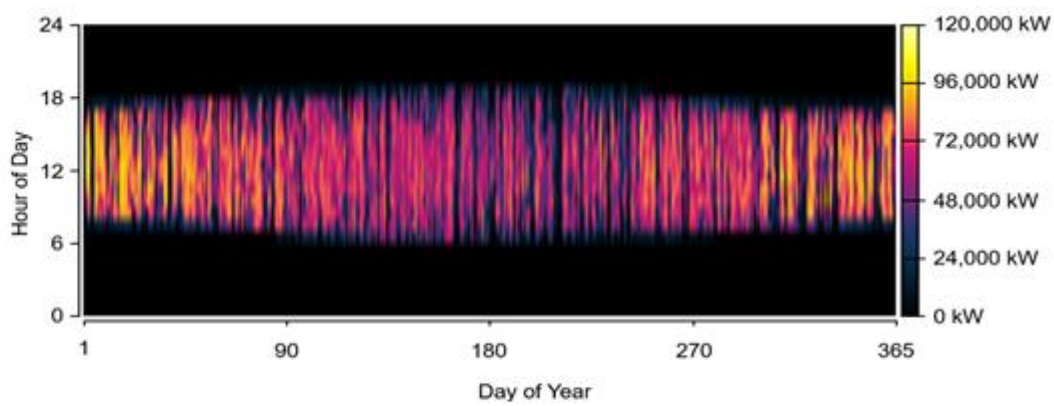

Figure 5.2 - PV Power Output in Baseline Case

In the baseline case, to fulfill the load, HOMER Pro calculated the size of the PV system mandatory for the HES. The size of the PV system turned out after calculations to be with a total rated capacity of 102,423 kW or 102.423 MW. The mean output of the PV system in this scenario was 25,400 kW per hour. The capacity factor remained at 24.8% and the total simulated AEP was found to be 222,503,485 kWh per year. PV system remained functional for 4,399 hours/year. Maximum power output remained at 100,219 kW. The power output pattern of the PV system installed in HES is shown in Figure 5.2. Levelized cost for the PV system in the baseline case, as per simulation, was 0.0258 USD/kWh.

5.2.3 Auto-size Genset

The need for a backup genset in light of the intermittence of RES is indispensable as per HOMER Pro. Thus, genset is included in the system. It is auto sized by the software keeping in view the size of the load. This is sized up to 130 MW in simulations. However, when the calculations and simulations are performed, the software predicts that there is excessive wind and solar resource potential in the region, and it can prove to be adequate to generate sufficient energy to handle the load demands. It is because of the resource abundance that even after having the genset included in the system, the need to run the genset does not arise, as per simulations. Had it been necessary to take genset into operation, the electricity fixed generation cost by genset would have been 4,126 USD per hour.

5.2.4 Batteries

To match up to the load in the baseline case, HOMER Pro calculated the quantity of the batteries required to be embedded in the HES. The number of batteries, after calculations, turned out to be 23 per string. The autonomy of the batteries is 1.55 hours. The expected lifetime of the batteries was taken as 15 years. The nominal capacity of the battery pack is 23,000 kWh and the usable nominal capacity is 18,400 kWh. The lifetime thorough output of the battery pack was found to be 61,381,011 kWh. The annual thorough output

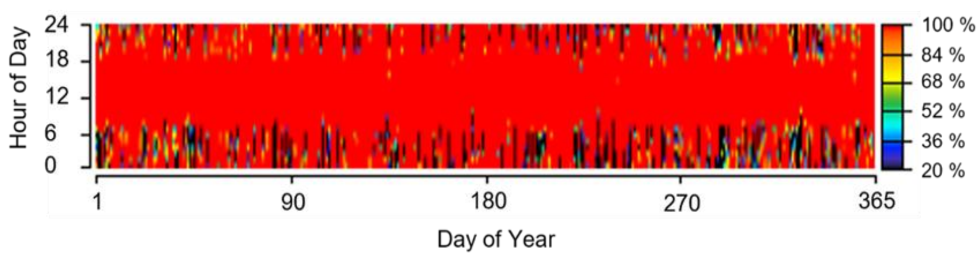

Figure 5.3 - Battery Pack State of Charge in Baseline Case

of the pack is 4,092,070 kWh per year. The state of charge of the battery pack is shown in Figure 5.3.

5.2.5 Electrolyzer

The electrolyzer is the primary load in this HES. It was sized while keeping the hydrogen load in view. It was found that a 35,000 kW rated capacity electrolyzer pack will meet the scaled hydrogen load. The mean input for the electrolyzer is 27,029 kW. Total input energy for the electrolyzer was 236,776,198 kWh per year and the capacity factor of the

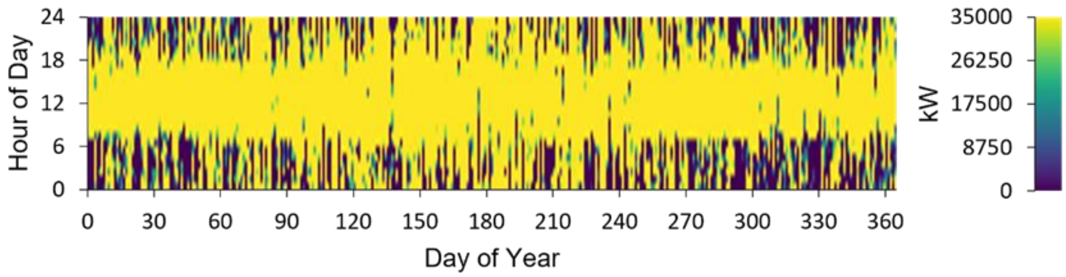

Figure 5.4 - Electrolyzer Power Input

electrolyzer was 77.3%. The mean output of the electrolyzer remained 583 kg H_2 per hour. While the maximum hourly hydrogen generated by the electrolyzer stood at 754 kg. Total AHP by the electrolyzer was computed to be 5,102,360 kg. Whereas the energy consumed by the electrolyzer to produce one kg of hydrogen was 46.4 kWh. Figure 5.4 depicts the power input required by the electrolyzer, as per HOMER.

5.2.6 ABB PStore-PCS Convertor

For the baseline case, the software revamped the convertor size to 88,682 kW which would suffice to convert electrical energy from AC to DC bus in accordance with load requirement. The mean output of the convertor rectifier in the baseline case turned out to be 19,864 kW. The capacity factor stood at 22.6% and the convertor remained operational for 6,123 hours annually. The maximum output from the convertor was 79,269 kW.

5.2.7 Hydrogen and Hydrogen Tank

The storage capacity of the hydrogen tank was taken as 10,000 kg. The energy storage capacity encapsulated in this 10,000 kg hydrogen tank is 333,333 kWh. The autonomy of the tank remained at 28 hours. At the beginning of the year, the year was 1,000 kg.

Electrolyzer produces 5,102,360 kg H_2 annually. Figure 5.5 (a) and (b) represent monthly and hourly hydrogen tank levels respectively.

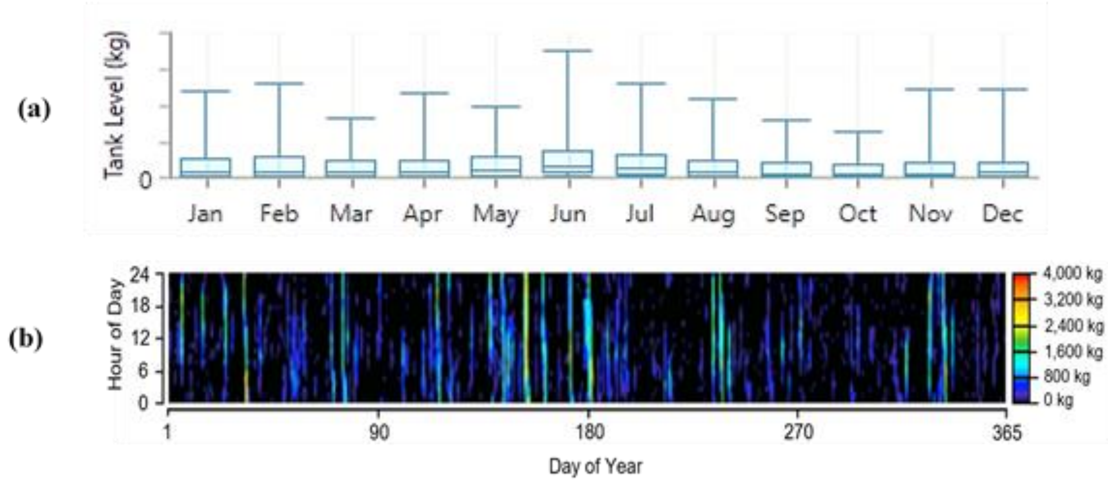

Figure 5.5 - Hydrogen Tank Levels (a) Monthly Basis; (b) Daily Basis

5.3 Scenario – 1

In this scenario, batteries have been excluded from the system. The total NPC of HES is computed by HOMER Pro to be 3,027,835,000 USD. While OPEX for this system is perceived to be 23,418,860 USD. LCOE here has gone up to 1.80 USD. Other costs have been calculated too. Initial CAPEX of the system in this scenario is 2,632,636,366 USD, overall O&M cost is 487,808,035 USD, component substitution cost is 758,048 USD. However, the salvage value of the HES in the baseline case at the end of the project life is 93,367,138 USD.

5.3.1 WTGs

In scenario 1, to handle the load, HOMER Pro calculated the number of WTGs required for the system, and it has shot up to 622 making it a major cost contributor to the overall system cost with a total rated capacity of 1,866,000 kW or 1,866 MW. The mean output of WTGs in this scenario was 466,433 kW or 466.433 MW. The capacity factor remained at 25% and total AEP wind turbines were found to be 4,085,984,844 kWh/year. WTGs remained operational for 8,663 hours per year. Maximum power output remained at

1,125,266 kW. The power output of WTGs in this scenario is identical to that of the baseline case. Levelized cost for just the WTG system also remained the same as that was in the baseline case. Figure 5.6 shows the WTGs power output for scenario 1.

5.3.2 PV System

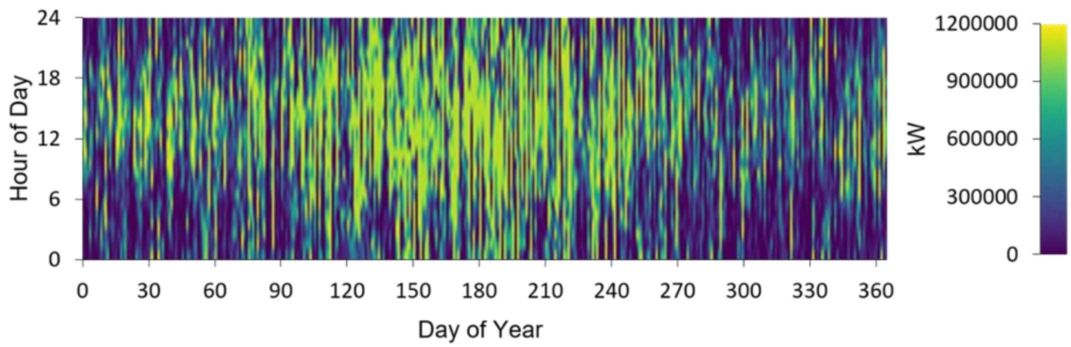

Figure 5.6 - WTG Power Output in Scenario 1

For this case, HOMER Pro iterated the size of the PV system mandatory for the HES. The size of the PV system, after computations, was required to be having a total rated capacity

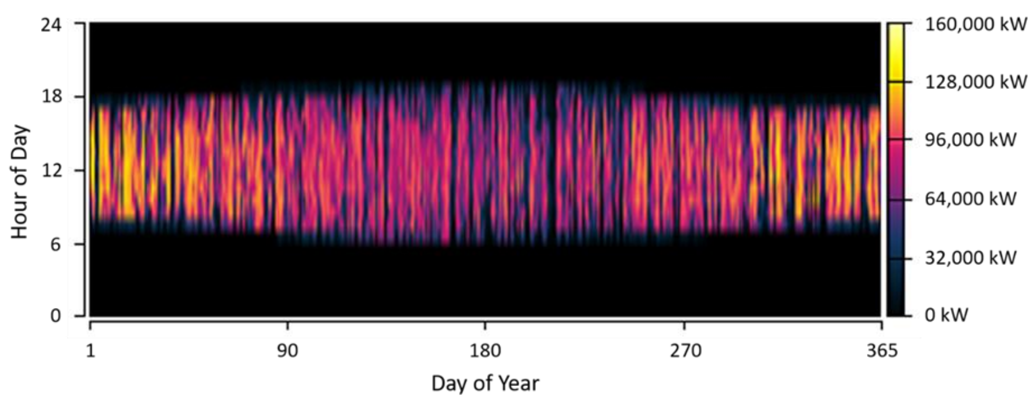

Figure 5.7 - PVs Power Output in Scenario 1

of 154,253 kW or 154.253 MW. The mean output of the PV system in this scenario was 38,253 kW/hour. The capacity factor remained the same and the total simulated AEP by a 154.253 MW PV system was found to be 335,100,065 kW/year. PV system remained functional for 4,399 hours/year. Maximum power output remained at 150,934 kW. The power output pattern of the PV system installed in HES is shown in Figure 5.7. Levelized cost for the PV system remained the same as that was in the baseline case.

5.3.3 Auto-size Genset

Like in the baseline case, here in scenario 1, genset was a component of the HES. However, HOMER Pro enhanced the WTGs and PVs to make use of the extensive RE resource of the region. Thus, it was installed as a backup in case of prolonged absence of wind and solar resources, but the need to take it into operation did not arise.

5.3.4 Electrolyzer

For scenario 1, electrolyzer pack rated capacity remained the same as was in the baseline

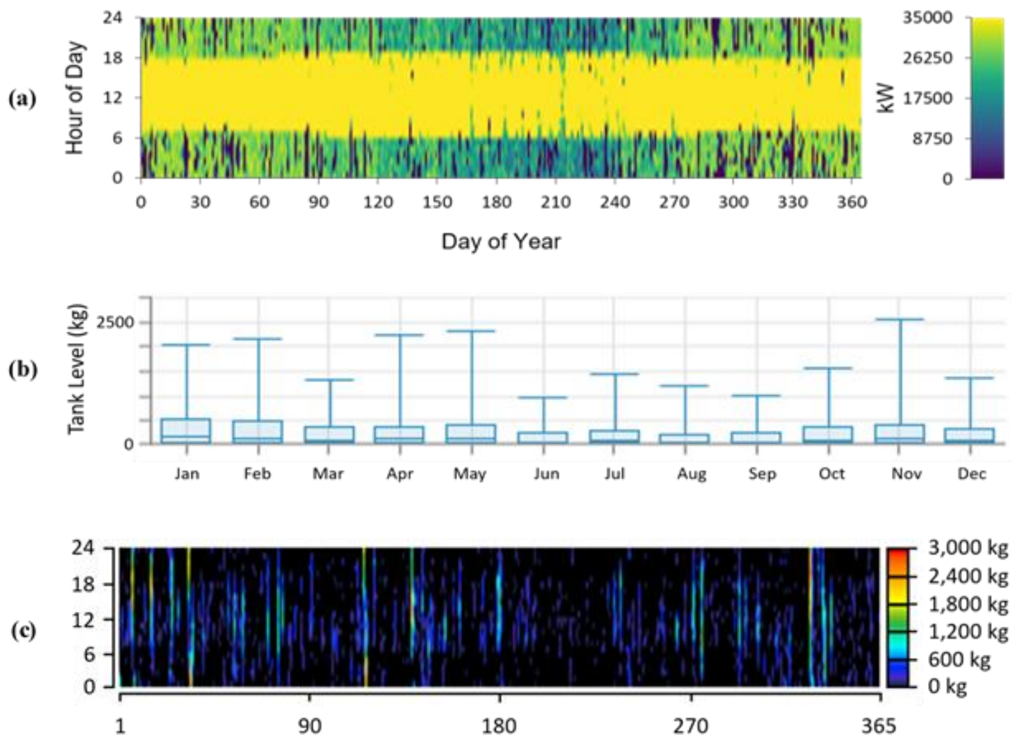

Figure 5.8 - Electrolyzer and Hydrogen Tank Stats in Scenario 1: (a) Power Input Required by Electrolyzer; (b) Monthly Hydrogen Tank Levels; and (c) Hourly Hydrogen Tank Levels

case i.e., 35,000 kW. The mean input for the electrolyzer is 27,545 kW. Total input energy for the electrolyzer was 241,291,155 kWh per year and the capacity factor of the electrolyzer was 79%. Mean output remained 631 kg H_2 per hour. While the maximum hourly hydrogen generated by the electrolyzer stood at 754 kg. Total AHP by the electrolyzer was computed to be 5,200,654 kg. Figure 5.8 (a) depicts the power input required by the electrolyzer in scenario 1, followed by (b) and (c) representing monthly and hourly H_2 levels in tank.

5.3.5 ABB PStore-PCS Convertor

HOMER Pro optimized the size of the converter to 159,496 kW which would be sufficient to convert electricity from AC to DC bus in proportion to load demands. The mean output of the convertor rectifier is 37,205 kW. The capacity factor stood at 50.4% and the convertor remained operational for 5,548 hours annually. Figure 5.9 shows the ABS PStore-PCS rectifier output for this scenario. Electrolyzer Power Input in Scenario 1, Monthly H_2 Tank level in Scenario 1.

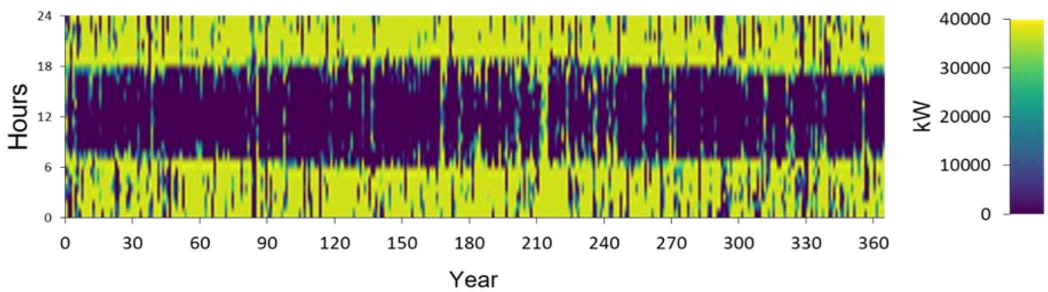

Figure 5.9 - ABB PSTORE-PCS Rectifier Output (kW)

5.4 Scenario – 2

HES architecture in this scenario is exclusive of genset, and total NPC is quantified to be 778.137 million USD. OPEX for this system is determined to be 6.440919 million USD. LCOE with this architecture has emerged as 0.4652 USD. Miscellaneous costs have been calculated too. Initial CAPEX of the system in this genset exclusive framework is 669.445 million USD, O&M cost is 125.055158 million USD, and replacement costs are 2.357904 million USD. Moreover, the salvage value of the HES with this configuration, computed by HOMER Pro is 18.720981 million USD.

5.4.1 WTGs

Here in this genset exclusive system architecture, HOMER Pro determined the number of WTGs required to meet the load to be the same as that in the baseline case. Mean output, total AEP by WTGs, and maximum power output also remained consistent. Figure 5.1 renders the power output of E-115 WTGs commissioned in the HES. Moreover, the levelized cost for the energy generated by the WTG system was also constant i.e., 0.0411 USD/kWh.

5.4.2 PV System

PV system size in this scenario also remained the same as it was for the baseline case, as per the simulations i.e., 141,192 kW. Mean output also remained unchanged. While capacity factor turned out to be 24.8% in this case as well. Moreover, hours of operation and other parameters including levelized cost for PV system were also consistent. The power output pattern of the PV system is shown in Figure 5.2.

5.4.3 Batteries

The number of batteries and string size in this architecture of HES were also consistent as were in the baseline case according to HOMER Pro calculations. Other factors like autonomy, nominal and usable nominal capacity, lifetime thorough output of the battery pack, and annual thorough output of the pack remained unvaried as well. Figure 5.3 shows the state of charge of the battery pack.

5.4.4 Electrolyzer

Electrolyzer size in this scenario, to satisfy the load, was also found to be equivalent to that of the baseline case i.e., 35,000 kW. Mean input, total energy input and capacity factor for the electrolyzer turned out to be 27,029 kW, 236,776,167 kWh per year, and 77.3% respectively. Furthermore, the mean output was also unchanged sustaining at 583 kg H_2/hour. While maximum hourly hydrogen was generated, AHP was also steady. Figure 14 depicts the power input required by the electrolyzer. Figure 5.10 shows the total electrical load served by the HES in this configuration without a genset. The size of the converter and hydrogen tank levels also remained unvaried from what it was in the baseline case.

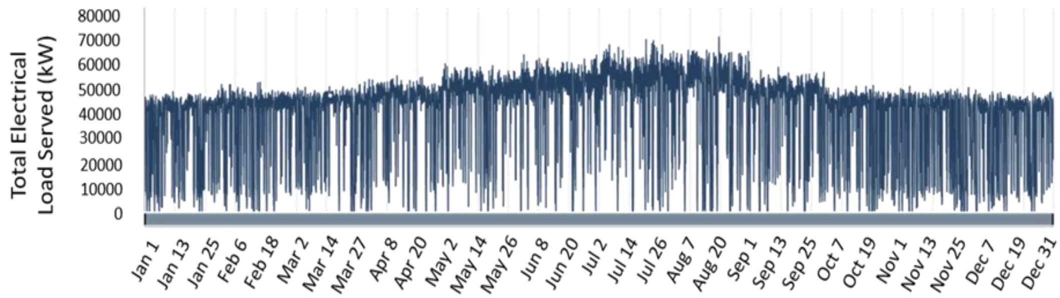

Figure 5.10 - Total Electrical Load Served in Genset Exclusive Scenario 2

5.5 Scenario – 3

Configuration of HES architecture having PV system excluded takes the total NPC to 1358.604 million USD. OPEX for this configuration turned out to be 10.09286 million USD. LCOE with this configuration has raised slightly to 0.7732 USD. Miscellaneous costs have been calculated too. The initial CAPEX of HES in this scenario is 1188.284437 million USD, O&M cost is 219.407866 million USD, and replacement costs are 8.760085 million USD. Whereas, the salvage value, computed by HOMER Pro is 57.84853 million USD.

5.5.1 WTGs

In this scenario, HES was simulated after factoring out the PV system. The software calculated the number of WTGs for this configuration which, as per simulation results has risen up to 280 with a total rated capacity of 840,000 kW or 840 MW. The mean output of WTGs in this scenario is 209,970 kW or 209.97 MW. The capacity factor remained unchanged and the total AEP by 280 wind turbines is calculated to be 1,839,333,885 kWh/year. WTGs remained operational for 8,663 hours annually. The maximum power output remained 506,550 kW. While levelized cost for the WTG system remained the same as that was in the baseline case. The monthly and bi-weekly power output of 280 WTGs for this scenario is shown in Figure 5.11 (a) and (b).

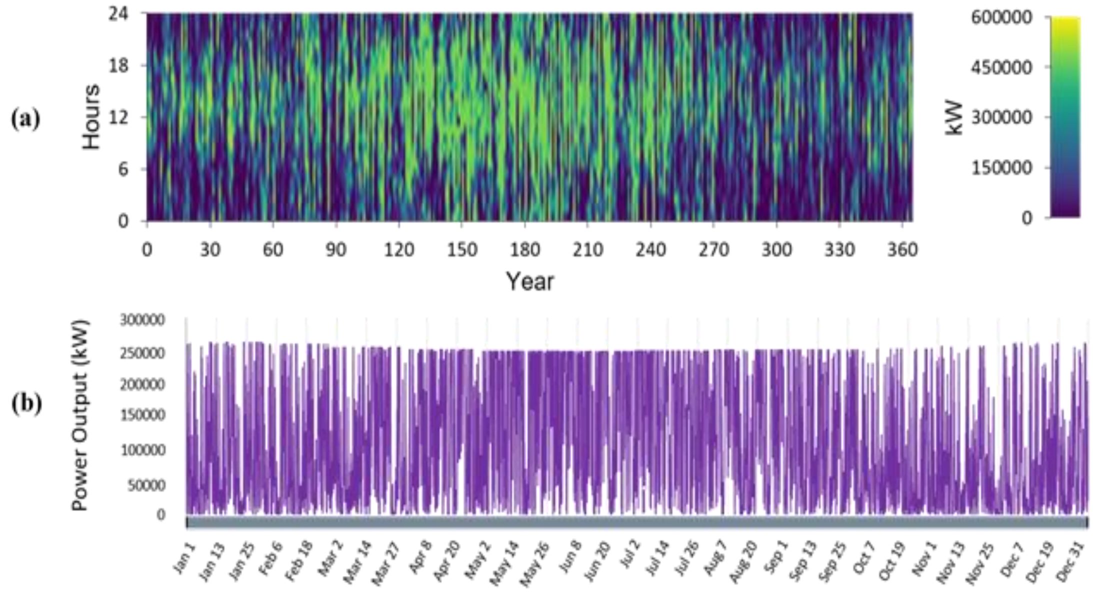

Figure 5.11 - WTG Power Output in PV Exclusive Scenario 3: (a) Power Output on Daily Basis; (b) Power Output on Bi-weekly Basis

5.5.2 Auto-size Genset

Identical to the benchmark scenario, genset was an element of the HES in scenario 3 as well. It was included as a backup in the event of prolonged intermittence. However, the need to take it into service did not arise.

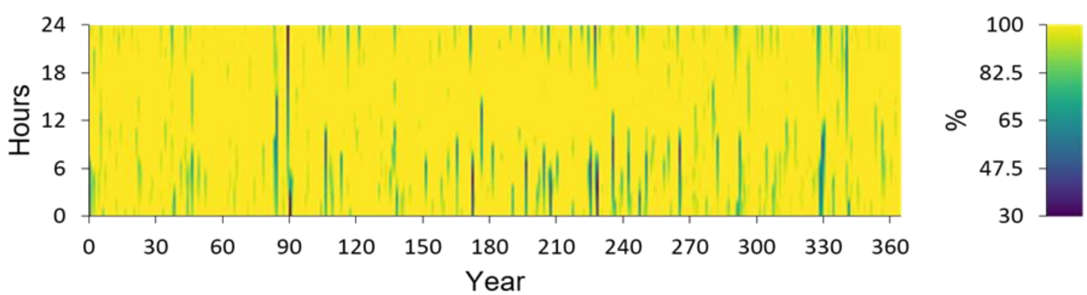

Figure 5.12 - Battery Pack State of Charge in PV Exclusive Scenario 3

5.5.3 Battery Pack

In this scenario, the number of batteries required to be embedded in the HES in absence of a PV system, as per HOMER Pro simulations, is 291, and one battery per string. The autonomy of the batteries is 19.6 hours. The battery pack has an expected lifetime of 15 years. The nominal capacity of the battery pack is 291,000 kWh and the usable nominal capacity is 232,800 kWh. The battery pack has a lifetime thorough output of 137,263,265 kWh. Whereas its annual thorough output is 9,150,884 kWh/year. The state of charge of the battery pack is shown in Figure 5.12.

5.5.4 Electrolyzer

The size of the electrolyzer was optimized to be the same as that of the baseline case by HOMER Pro for this. However, the capacity factor of the electrolyzer, in this case, was 77.2%. Mean input for the electrolyzer remained 27,026 kW and total input energy for the electrolyzer was 236,746,726 kWh per year. Mean hourly output also remained 582 kg H_2/per hour. Moreover, the maximum hourly hydrogen generated was unchanged. Total AHP by the electrolyzer was 5,101,725 kg. Figure 5.13 (a) and Figure 5.13 (b) depict the power consumed by the electrolyzer on an hourly basis and hydrogen production (kg/hr) respectively.

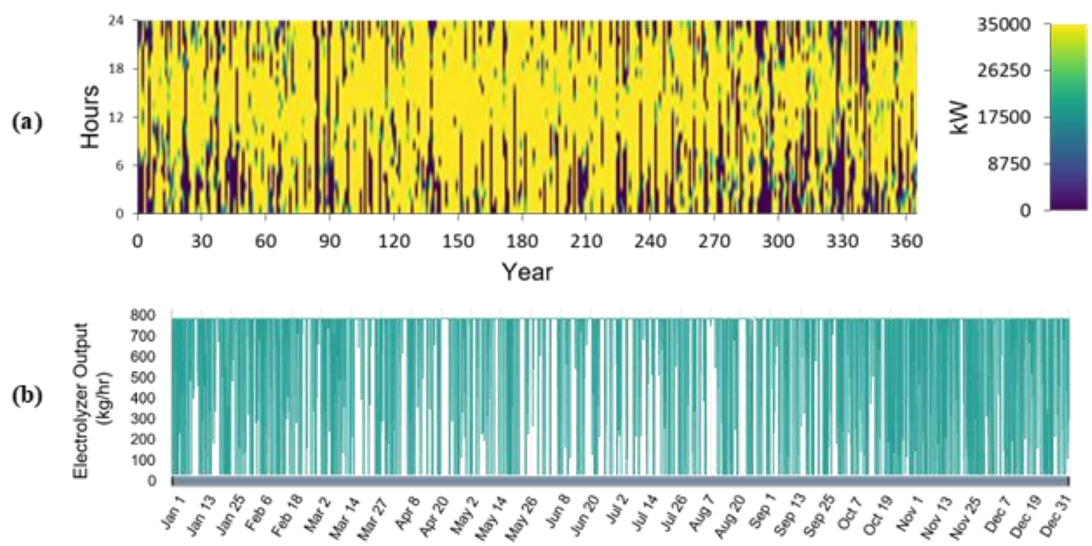

Figure 5.13 - Electrolyzer Power and Output Stats in PV Exclusive Scenario 3: (a) Hourly Power Consumption (kW); (b) Hydrogen Production (kg/hr)

5.5.5 ABB PStore-PCS Convertor

For this PV system exclusive architecture, HOMER Pro optimized the convertor size to 87,786 kW which would be sufficient to convert electrical energy from AC to DC bus in proportion to load demand. The mean output of the convertor rectifier turned out to be 39,040 kW. The capacity factor stood at 44.5% and the convertor operated for 8,663 hours annually. The maximum output from the convertor was 87,786 kW. Figure 5.14 shows the rectifier output for this scenario.

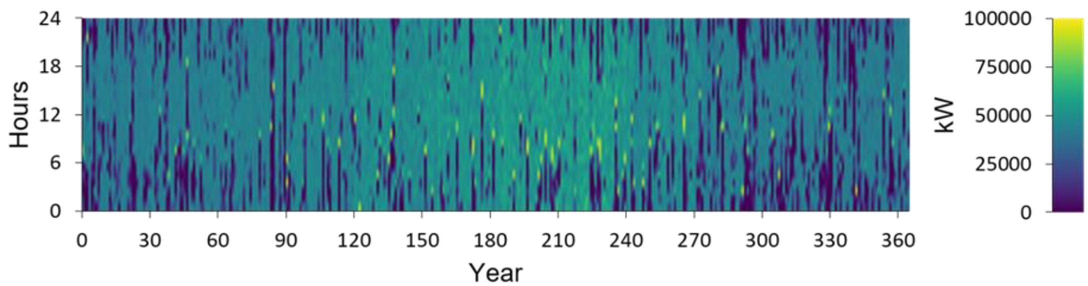

Figure 5.14 - Rectifier Output in PV Exclusive Scenario 3

Table 5.2 below compares the major economic parameters of all the four cases including the baseline case.

Table 5.2 - Economic Highlights of Simulated Architectures of HES

Economic Parameter (USD)	**Baseline Case** (All Components Inclusive)	**Scenario 1** (Batteries Excluded)	**Scenario 2** (Genset Excluded)	**Scenario 3** (PV System Excluded)
Total NPC	819.330288 million	3.027835 million	778.1371 million	1358.604 million
CAPEX	734.445 million	2632.63636 million	669.445 million	1188.284 million
Fixed Expense (OM + OPEX)	130.085324 million	511.226896 million	131.49607 million	229.50072 million
LCOE	0.49	1.8	0.465	0.7732
Salvage Value	42.527774 million	93.367138 million	18.720981 million	57.848530 million

Convertor size in baseline case was enhanced due to genset inclusion. Thus, the converter was sized up beforehand so that in case of genset taken into service, AC electricity may be converted into DC electricity promptly for batteries to store and for electrolyzer to use. Contrary, in scenario 1, the size of the converter was reduced by HOMER Pro because the system was exclusive of major components demanding DC electricity. Only electrolyzer was the DC load and hence, lesser AC electricity was required to be converted to DC. In scenario 3, when the PV system was terminated from the HES architecture, convertor size, as per HOMER Pro simulation, escalated to 87,786 kW. The reason behind this is the exclusion of major DC power contributors i.e., the PVs.

Summary

This particular chapter of the study has brought under detailed discussion the results of the simulations of all the four scenarios including the baseline case as produced by HOMER Pro. Technical results, as well as the economic results, have been presented and in-depth comparative analysis has been drawn between all the four configuration scenarios of HES architecture. Technical parameters like AEP, AHP, electrolyzer output, energy consumption, PV system size, WTGs size, rectifier outputs, etc., and economic parameters like NPC, LCOE, salvage value, etc. were discussed too to choose the most feasible HES configuration out of the four architectures.

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Chapter 6

Conclusion and Recommendations

6.1 Conclusion

Principally, the grail of this research was to conduct a techno-economic suitability study of H_2 production using PtG route and generate electricity from this hydrogen i.e., gas-to-power (GtP). Four cases with varying architecture were built and evaluated for the best techno-economic parameters in HOMER Pro. To draw contiguity, key system variables were modified for all scenarios. So, power class, location, and electrical and hydrogen loads were regulated to identical levels in every case. The electrolyzer produced 583 kg/hr of hydrogen in every case. Excess electricity after fulfilling the DSP and electrolyzer package demands were evaluated for sale to nearby areas. HES with the genset exclusive scenario, 2 is found to be the most feasible. The share of wind and solar energy in total AEP kept varying in all the scenarios. But, in scenario 2, it is 1,175,015,675 kWh/year with a solar share of 18.9% and wind share of 81.1%. CAPEX and LCOE of this system are the lowest i.e., 669,445,000 USD and 0.465 USD/kWh. Moreover, the payback period and IRR are also feasible being 2.45 years and 17.3% respectively against a discount rate of 12%, inflation rate of 9%, and debt to equity ratio of 70:30. Among all the cases, the payback period was the longest as well as CAPEX and LCOE were the highest in the baseline case. Highest CAPEX is discovered in scenario 1 followed by scenario 3. Nevertheless, payback periods in scenarios 1 and 3 are negligibly lower than that in winning scenario 2. The dominant feasibility of scenario 1 can be justified by its lowest LCOE and CAPEX.

6.2 Future Prospects

The concept and technology implemented are novel but regional as well as global potential is tremendous. The capital costs are high at present but will decline with advancements in technologies. If galvanized by the international governments and bodies, this technology can offer lasting, steady, and affordable electricity to the global populace and reverse the environmental deterioration. Future studies should focus on in-depth simulations and analysis of H_2 cryocooling for storage and transportation purposes, and gas turbines that will run on 100% hydrogen. Also, policies should be devised to integrate all the existing wind farms to produce hydrogen enabling sector coupling and leading the regional transformation into a hydrogen hub.

Acknowledgment

Foremostly, I bow down to Allah S.W.T, The Mightiest and The Most Merciful, for His countless blessings on me and for providing me with the backup in the form of indefatigable resolve to stand firm in the face of every challenge and surf the rough and high tides of my life till to date. The resilience, knowledge, window of this opportunity, and energy to ace this endeavor are some of His infinite favors upon me without which all of this would have remained unattainable.

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Moreover, I am grateful to my GEC members, Dr. Kafaitullah (ESE, USPCASE) and, Dr. Sarah Farrukh (SCME) for being on my supervisory committee.

Lastly, and most eminently, I am indebted to all four of my grandparents (late) especially my respected Nana Abbu and my beloved Nani Amma for their lifelong sacrifices for us and for making us their topmost priority (I anticipate that you both will be proud of me while sitting together up there in heavens); my respected parents for their duas, sacrifices, and affection for me; the love and purpose of my life A.E for her supplications for me and her unshaken faith in me; my nephews and nieces (Syeda Zainab Fawad, Muhammad Ahmed, Daiyan, Syeda Inayah Fatima, Muhammad Mateen, Syeda Bareeha Fatima, and Syeda Irha Fatima) for bringing hope and joys to my life; Zumar; all of my beloved siblings for putting their faith in me and supporting me all along and, respected bhabis and brothers in law for remembering me in their duas. I dedicate my success to all of you as I was emboldened to keep going by the unremitting motivation from the whole family.

Appendix

A.1 Publication 1

Techno-economic Feasibility Analysis of Hydrogen Production by PtG Concept and Feeding it into a Combined Cycle Power Plant Leading to Sector Coupling in Future

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Abstract

World has embarked on a journey of unleashing the untapped potential of hybrid energy systems to quench the ever-growing thirst for green energy. Being still in its formative stages, Power-to-Gas offers an efficient opportunity to turn renewable energy into "green" hydrogen, establishing an inevitably remunerative spectrum of end-uses. A zesty episode of initiatives announced across the globe that are more yearning, awe-inspiring, and mammoth in size, reflect that it has accomplished substantial inroads in the energy revolution. However, utilizing the produced hydrogen for electricity production is yet ignored. In this spirit, the current paper intends to contribute to the worldwide scientific community by evaluating, from a techno-economic perspective, a hybrid model for sizing hydrogen generation by water electrolysis from renewable energy and using it for electricity production in Pakistan. Modeling of this hybrid system is done using HOMER Pro. Hydrogen is produced using a hybrid energy system and then fed into a hypothetical combined cycle power plant to produce electricity. Hydrogen has economic dominance over batteries in terms of energy storage and cost of energy, as per results. The economic analysis is constructed on economic parameters like payback period, internal rate of return, and cost of energy, and multiple configurations of the system. Four scenarios including baseline case have been simulated. The most feasible configuration yielded levelized cost of energy being 0.465 USD/kWh, internal rate of return being 17.3**%,** and payback period of 2.3 years. Renewable energy sources are thoroughly assessed for coupling with the desalination plant and electrolyzer array. This system can further be expanded on a larger scale to transform the region into a hydrogen hub to produce green, high-energy-density hydrogen to be supplied to and utilized by multiple sectors.

Keywords: Power-to-Gas, Hydrogen hub, Hybrid energy system, Sector coupling, Techno-economic feasibility, Windfarm

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