Techno Economic Assessment of Green Hydrogen Production from Renewable Energy Sources along CPEC Special Economic Zones in Pakistan

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A thesis submitted to the National University of Sciences and Technology, Islamabad,

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Master of Science in
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Supervisor: Dr. Mustafa Anwar

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

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This thesis is dedicated to first and foremost to my beloved mother ***Saeeda Kanwal, my Late Father*** *and my siblings* **Dr. Goshi Laila** *and* ***Shah Zaman*** *for their love, support, and affection. This achievement is as much yours as it is mine. Thank you all for being my pillars of strength.*

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Nomenclature

CAPEX	Capital Expenditure
CCS	Carbon Capture Storage
CPEC	China Pakistan Economic Corridor
CRF	Capital Recovery Factor
HOMER	Hybrid Optimization of Multiple Energy Resources
IEA	International Energy Agency
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
MCDA	Multiple Criteria Decision Analysis
MOOP	Mult Objective Optimization Problem
NEPRA	National Electric Power Regulatory Authority
NPC	Net Present Cost
PEM	Polymer Electrolyte Membrane
RES	Renewable Energy Sources
RF	Renewable Energy Fraction
ROI	Return on Investment
SEZs	Special Economic Zones
SMR	Steam Methane Reforming
SOC	State of Charge

Symbols

A_{HT}	Hydrogen tank autonomy (hours)
E_{excess}	Total excess electricity [kWh/yr]
E_{prod}	Total electrical production [kWh/yr]
F	Faraday constant (96485.33 C/mol)
f_{PV}	PV derating factor [%]
f_{excess}	Excess electricity fraction
$\bar{G}_T$	Incident radiation on the PV array in the current timestep [kW/m^2]
$\bar{G}_{T,STC}$	Incident radiation at standard test conditions [1 kW/m^2]

I_e	Applied current to one of the Electrolyzer cells (A)
N_c	Number of Electrolyzer cells
P_{WTG}	Wind turbine power output [kW]
$P_{WTG,STP}$	Wind turbine power at standard temperature and pressure [kW]
Q_{H_2}	Hydrogen production rate
T_c	PV cell temperature in the current time step [°C]
$T_{c,STC}$	PV cell temperature under standard test conditions [25°C]
U_{hub}	Wind speed at the hub height of the wind turbine [m/s]
U_{anem}	Wind speed at anemometer height [m/s]
Y_{PV}	Rated capacity of the PV array
Z_0	Surface roughness length [m]
Z_{hub}	Hub height of the wind turbine [m]
Z_{anem}	Anemometer height [m]

Greek Letters

η_f	Faradic efficiency (%)
α_P	Temperature coefficient of power [%/°C]
η_{inv}	Inverter efficiency
ρ_0	Air density at standard temperature and pressure (1.225 kg/m^3)
ρ	Actual air density [kg/m^3]

ABSTRACT

Green hydrogen solutions are getting attention in efforts to achieve low-carbon and net-zero emissions targets. In developing countries, natural gas and coal serve as a primary source for hydrogen production, given their accessibility and cost-effectiveness. The potential decarbonization of the industrial sector through the utilization of green hydrogen emerges as a promising clean energy solution due to its carbon-free nature, versatility, and ability to provide high-energy-density fuel for energy-intensive processes. In this thesis, a techno-economic analysis has been performed for green hydrogen production using wind and solar energy. The analysis is carried out at nine special economic zones (SEZs) and a free zone at Gwadar Sea Port using the Hybrid Optimisation of Multiple Energy Resources (HOMER) Pro software. The proposed hybrid energy system is designed that meet the required industrial electrical and hydrogen demand of 600 MWh/day and 60 tonnes H_2 per day, respectively. A comparative analysis of on grid and off grid systems in all SEZs has been performed. A sensitivity analysis is also performed on different parameters that may influence the levelized cost of hydrogen (LCOH). The study findings indicate that LCOH varies from 3.76 $/kg to 8.18 $/kg for off grid and 1.69 $/kg to 4.19 $/kg for on grid systems which is competitive cost with respect to other countries. The most feasible economic zones for green hydrogen production are found to be Dhabeji and Port Qasim with lowest LCOH of 3.76 $/kg and 3.79 $/kg for off grid, 1.69 $/kg and 1.93 $/kg for grid connected system, respectively. Dhabeji exhibits lowest CO_2 emissions per year making itself the most feasible location for green hydrogen production. Grid connected systems are a great opportunity for Pakistan to produce low-cost green hydrogen for industrial decarbonization and country’s economic growth.

Keywords: Green hydrogen; Techno-economic analysis; Levelized cost of hydrogen; CPEC; special economic zones

CHAPTER 1

Introduction

1.1 Background

Global warming due to climate change is a serious concern that requires widespread shift in energy transition. The major cause of the rise in temperature is the use of fossil fuels such as coal, natural gas, and petroleum oil for many sectors like power generation, transportation, industrial and residential sectors. Fossil fuels emit high amounts of greenhouse gases (GHG) such as carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x) and other particulate matters. Carbon dioxide (CO_2) is considered as the primary contributor in global GHG emissions due to extensive usage of fossil fuels. The Paris Agreement 2015 has set a target to limit the rise of temperature to 1.5 ^oC above pre-industrial levels to achieve net zero carbon emissions target [1]. Coal is the major culprit among all fossil fuels and contributes more than 44% of the total CO_2 emissions and this share will increase up to 47% from 2020-2030; whereas the accumulative share of natural gas and liquid fuels is around 22% of the global GHG emissions [2]. Developed countries' contribution in global GHG emissions is higher as compared to developing countries such as Pakistan which is accountable for only 0.9% share of emissions but is considered in the most vulnerable countries to the climate change impacts [3].

The current energy mix of Pakistan comprises 59% from thermal sources (fossil fuels), 25% from hydroelectric power, 7% from renewables (solar, wind, and biomass), and 9% from nuclear energy as shown in Figure 1-1 Figure 1-1 Share in electricity generation [4][4]. The industrial sector is the second highest energy consuming sector in Pakistan after household sector as shown in Figure 1-2. According to climate transparency report 2020, industry related CO_2 emissions make up to 38% of the total GHG emissions in Pakistan in which 7% are emissions from electricity related industries and 32% are direct emissions. Cement and steel making industries are the most carbon intensive industries in Pakistan [5].

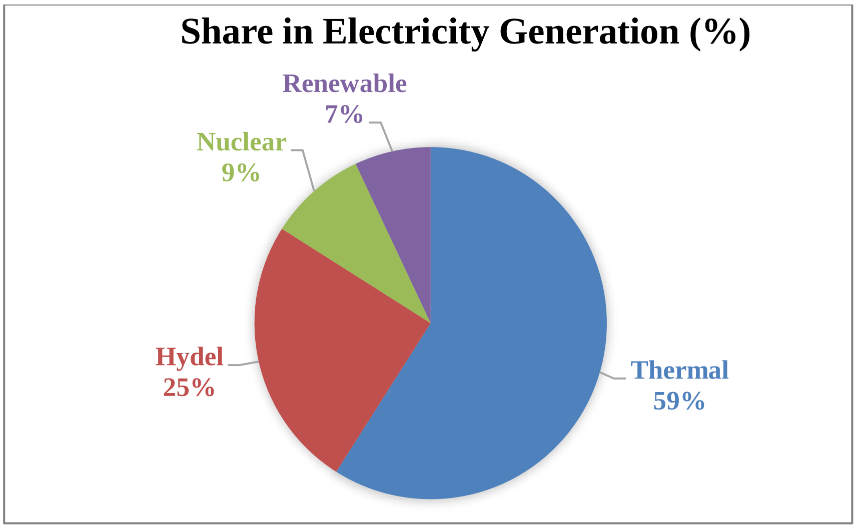


Figure 1-1 Share in electricity generation [4]

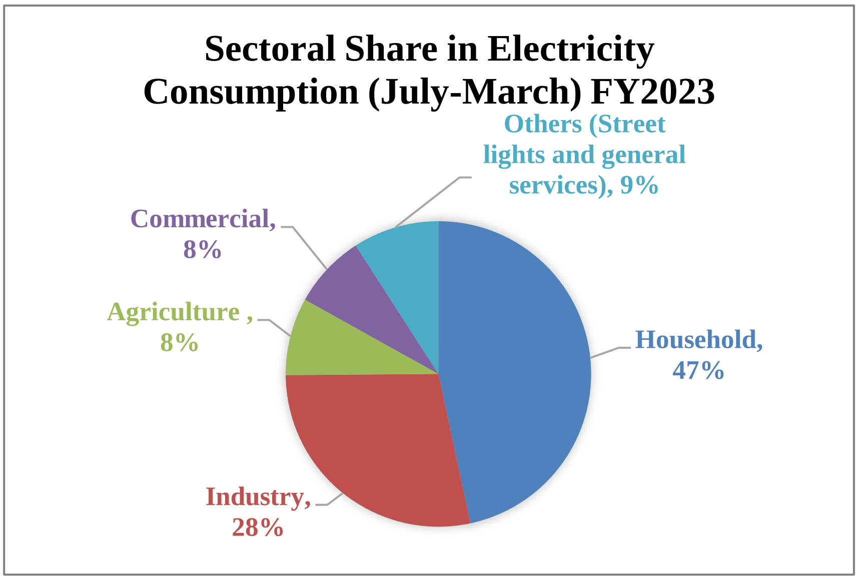


Figure 1-2 Share in electricity consumption [4]

1.2 Problem statement

In Pakistan, industrial sectors such as steel production, oil refineries, chemical manufacturing, food processing, and general manufacturing are heavily reliant on hydrogen produced from coal and natural gas. This reliance results in significant GHG emissions, contributing to environmental degradation and climate change. With volatile fossil fuel prices and a growing energy demand-supply gap, Pakistan faces challenges in achieving energy security and sustainable economic growth. To address these challenges, Pakistan has set a target to produce carbon-free electricity by increasing the share of renewable energy sources to 60% by 2030 [3]. However, this goal cannot be achieved without addressing the industrial sector's carbon footprint. Industrial decarbonization through green hydrogen is a crucial component of this transition. Green hydrogen, produced via water electrolysis using electricity from renewable energy sources, offers a carbon-free alternative that can significantly reduce GHG emissions from industrial processes. The development of a techno-economic model for green hydrogen production from wind and solar energy, specifically tailored for CPEC Special Economic Zones (SEZs), is essential. CPEC SEZs provide a great opportunity for green hydrogen infrastructure development in Pakistan. This model would provide a sustainable and cost-effective solution to meet the growing energy demands of Pakistan's industrial sector while promoting environmental sustainability. Moreover, a comprehensive techno-economic and environmental feasibility study of green hydrogen production is needed to evaluate its potential benefits, cost-effectiveness, and environmental impact.

1.3 Research Objectives

This research study revolves around creating sustainable energy solutions by integrating green hydrogen into the industrial sector to increase the use of RES, predominantly wind and solar energy sources. The current study addresses the following research question:

Which China Pakistan Economic Corridor (CPEC) Special Economic Zones are feasible to produce green hydrogen using wind and solar energy in Pakistan?

The research objectives are divided as follows:

- Develop an optimized techno-economic model of a hybrid PV-Wind-H_2 system with energy storage to meet electrical and hydrogen demand and its feasibility in Pakistan.
- Study the impact of sensitive parameters on the levelized cost of hydrogen production.

1.4 Scope of Research

The scope of this research encompasses a pioneering feasibility study on green hydrogen in Pakistan, representing a novel initiative poised to advance research in this domain. Given the limited existing research on this topic, the study aims to explore the various applications of green hydrogen in industry. Specifically, it will investigate its potential for off grid and grid connected systems in ten CPEC special economic zones in Pakistan. Green hydrogen integration in industries can provide grid support and flexibility, and seasonal hydrogen energy storage. The scope of this research study is limited to Pakistan.

1.5 Limitations

Green hydrogen is a new concept for Pakistan industrial sector and encompasses few limitations. Data collection is based on publicly available information sources such as industry reports, journals, and research studies. HOMER Pro software has limited component libraries which restricts the choice of component selection. Land/area costs of special economic zones are not included in this study

1.6 Thesis organization

This thesis is structured as follows: **Chapter 1** introduces the background of the topic, problem statement and set the subject of the thesis, delimiting research objectives, limitations, and thesis organization. **Chapter 2** provides literature review on the green hydrogen role in energy transition with national and international perspectives. It also explains why there is a need to produce green hydrogen in Pakistan. **Chapter 3** presents assessment of site selection, resource data collection, research methodology and technique used to carry out this research work. **Chapter 4** provides study results for on grid and off grid hydrogen production systems and provides comparative and sensitivity analysis for LCOH. **Chapter 5** summarizes the research work in the conclusion section and provides future directions for the expansion of this study.

Summary

This chapter introduces green hydrogen and its importance and background to the research topic under study with a focus on problem statement. It also describes the main objectives and research questions along with scope of this research work followed by thesis organization. Limitations and assumptions have been discussed in this chapter.

CHAPTER 2

Literature Review

2.1 Green Hydrogen – Global perspective

Green hydrogen (GH_2) plays a crucial role in industrial decarbonization and may lead the world towards a significant energy transition. Significant research is being conducted on green hydrogen around the globe to assess GH_2 potential and feasibility at various sites with respect to its production, storage, transportation, and delivery options. Non-renewable technologies such as steam methane reforming (SMR), pyrolysis and gasification produce hydrogen at low cost but generate significant amount of greenhouse gases [6]. Hydrogen production cost varies based on its production methods and other factors. Natural gas steam reforming is a widely used method due to its lower cost of hydrogen production 2.08 $/kg [7]. Natural gas consists of 95% methane and 3.5% other hydrocarbons [8]. Due to fossil fuel usage in the manufacturing process, high amounts of carbon emissions are generated.

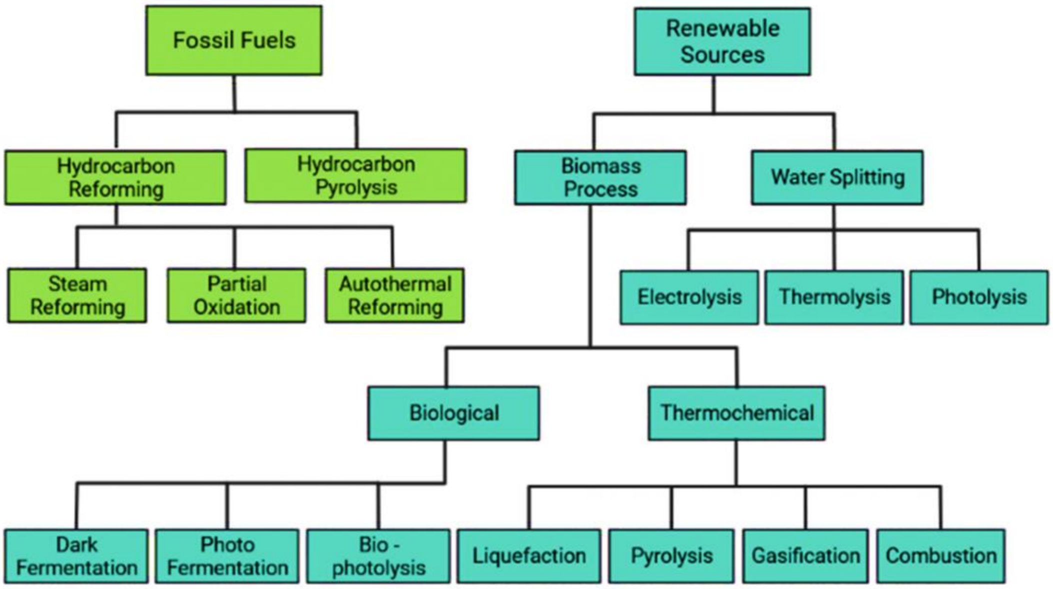


Figure 2-1 H_2 Production routes [9]

Figure 2-1 shows the detailed route map of hydrogen production methods. Partial oxidation and Autothermal reforming processes have around 60 to 70% efficiency and low hydrogen production cost of 1.48 to 2 $/kg [7]. Renewable technologies such as electrolysis, photocatalysis, plasmolysis, bio-hydrogen and thermochemical cycles produce clean and low carbon hydrogen but at high price [10]. An extensive comparative analysis of different H_2 production technologies, assessing them depending on both cost and life cycle assessment metrics is presented in [8], [11], [12]. Variation in hydrogen production methods leads to different costs of hydrogen production and different amount GHG emissions. Review in [13] provides comprehensive insights into the techno-economic feasibility analysis of several H_2 production methods. Key factors which influence H_2 production costs, including feedstock type, capital expenditure (CAPEX), and internal rate of return (IRR), were examined. Natural gas steam reforming has gained significant attention from policymakers and the research community due to its higher efficiency (70-85%) and relatively lower operational cost (0.3 $/kg H_2) and generation cost (1.25 to 3.50 $/kg H_2). However, the process emits a substantial amount of carbon dioxide, highlighting the need for further research to minimize emissions and reduce overall production costs. Another review paper [14] examines modern methods for producing blue and green hydrogen utilizing both conventional and RES, with an emphasis on hydrogen's storage solutions and applications as a fuel. It highlights the potential of intermittent energy sources such as wind and solar for H_2 production and compares them with non-renewable energy systems depending on the efficiency, overall cost, and environmental impact. The review also addresses key challenges and opportunities for commercial-scale hydrogen production, storage, transportation, and distribution. Another study compares wind and solar energy for H_2 production and discusses different Electrolyzer technologies [15]. The cost of H2 production varies depending on RES, electrolysis type, weather conditions, CAPEX, and daily hydrogen productivity. Both PV to H_2 and wind to H_2 systems are optimal for distant areas, as they require less maintenance and do not use a power cycle to generate electricity. In contrast, the concentrated solar power (CSP) to H_2 system requires a power cycle. Wind to H_2 production cost is higher than PV to H_2. Hybrid solar PV and wind energy systems are considered as the most suitable choice for power supply worldwide and have been found to be optimal [16]. Table 2-1 shows the H_2 production technologies, feedstock type, their advantages, disadvantages, energy efficiency, H_2 yield and cost per kg of H_2.

Table 2-1 Different hydrogen production technologies

Feed stock	**Technology**	**Advantages**	**Disadvantages**	**Energy Efficiency (%)**	**H_2 Yield per kg (g/kg feedstock)**	**Cost (\$/kg of H_2)**	**Ref.**
Water	Electrolysis	Simplicity and Low temperature Zero carbon emissions, O_2 as byproduct	Require high pressure, Energy storage issues, Low efficiency, High CAPEX	55−80	111	4.15 - 10.30	[17]
	Thermolysis	Low carbon emissions, Clean and sustainable energy, O_2 as byproduct	Require separation step to prevent recombination of volatile material, High CAPEX	20-50	111	7.98-8.40	[9]
	Photo electrolysis	Low operating temperature and pressure, Sustainable energy supply	Needs photocatalytic material, Less efficient, Surface area required.	0.06−14	111	4.98−10.36	[18]
	Bio photolysis	H_2 production at ambient conditions, CO_2 consumption	Large reactor volume, requires large surface area, Challenging bacteria control process	10-15	111	1.42 - 2.13	[7], [19]
Biomass	Dark fermentation	Continuous H_2 production, Streamlined design & waste recycling	Metabolically restricted H_2 yield, large reactor volume, less efficient system, byproduct generation	60-80	4 - 44	1.68 - 2.57	[18]
	Photo fermentation	Waste recycling, Wide range of substrates (waste streams), High efficiency in removing chemical O_2 demand.	Require controlled environmental conditions, Need large surface area and high reactor volume, Nitrogenase metabolism affects the economic viability of H_2 production	0.1 - 12	9 - 49	2.57 - 2.83	[7], [19]
	Pyrolysis	Abundant and cheap feedstock, established technology, carbon-neutral emissions, product streams are gas, liquid and solid	H_2 production is based upon the feedstock, Tar formation occurs.	35 - 50	25 - 65	1.59 - 2.20	[20]
	Hydrothermal liquefaction+B7	Abundant and cheap feedstocks No need of drying step, high energy efficient, product streams are solid, liquid, gas	H_2 yield is influenced by feedstock type, presence of nitrogenated compounds	85 - 90	0.3 - 2	0.54 - 1.26	[21]
	Gasification	Abundant and cheap feedstocks, Carbon-neutral emissions	Oxidating agents required, tar formation, H_2 production depends upon the feedstock,	30-60	40-190	1.77 - 2.05	[7]
	Steam Reforming	Established technology. Upgrading of bio-oil not necessary	Carbon by-products generation	74 - 85	40-130	1.83 - 2.35	[19]

Grey hydrogen is the hydrogen produced from fossil fuels and it results in a significantly large amount of greenhouse gases footprint [22], such as 153g of CO_2 equivalent are produced per megajoule of heat energy production [23]. GHG Emissions during H_2 production alter significantly based on the source of energy used. For example, geothermal power plants generate hydrogen with emissions that can be double those of solar PV applications [24], [25]. Geothermal technology presents significant technical challenges, including issues related to raw material inputs, energy and exergy efficiency, and process control [26]. In nuclear power plants, over half of the carbon emissions are attributed to the processes involved in fuel mining, preparation, and transportation. The remaining emissions arise from the construction, operation, and maintenance of the plants [12], [27]. The mining and milling of uranium are particularly significant contributors to these emissions, comprising a substantial portion of the front-end of the nuclear fuel cycle [28]. Biomass gasification generates the highest emissions [2], and its global warming potential (GWP) is 4,000 grams of CO_2 per kg of hydrogen [29], [30]. Conversely, wind energy is the most favorable source for H_2 production and has a GWP of less than 1,500 grams of CO_2 per kg of hydrogen [31], [32]. Wind power also has minimal adverse health impacts and can create employment opportunities, though it is not sufficiently cost-effective [33].

Solar PV-driven hydrogen production methods can result in substantial GHG emissions, generating nearly 3,000 grams of CO_2 per kg of H_2 when utilizing solar thermolysis [34]. Technoeconomic analysis of GH_2 production using solar energy has been performed and impact of future improvements in components unit costs have been analyzed in [35]. Research indicates that, across all nations under study, the optimal Electrolyzer size to reduce the levelized cost of hydrogen (LCOH) is about 60% of the capacity of solar energy. Although installing batteries does not improve economic viability, it can boost hydrogen production by utilizing excess electricity during peak periods. The article [36] explores the feasibility of using photovoltaic systems to produce hydrogen in four major Iraqi cities. A 22 kWp stand-alone grid solar system, paired with an 8-kW alkaline Electrolyzer (AEC), a H_2 compressor, and a hydrogen storage cylindrical tank, was modeled for a year using MATLAB/Simulink and hourly weather data from 2021 to 2030. The study found annual H_2 production ranged from 1713.92 to 1891.12 kg, with costs at $3.79 per kilogram. Results suggested that central Iraq and regions with similar high solar radiation are optimal for solar hydrogen production systems. Figure 2-2 shows the CO_2 emissions generated by different sectors in the current scenario and in future after energy transition.

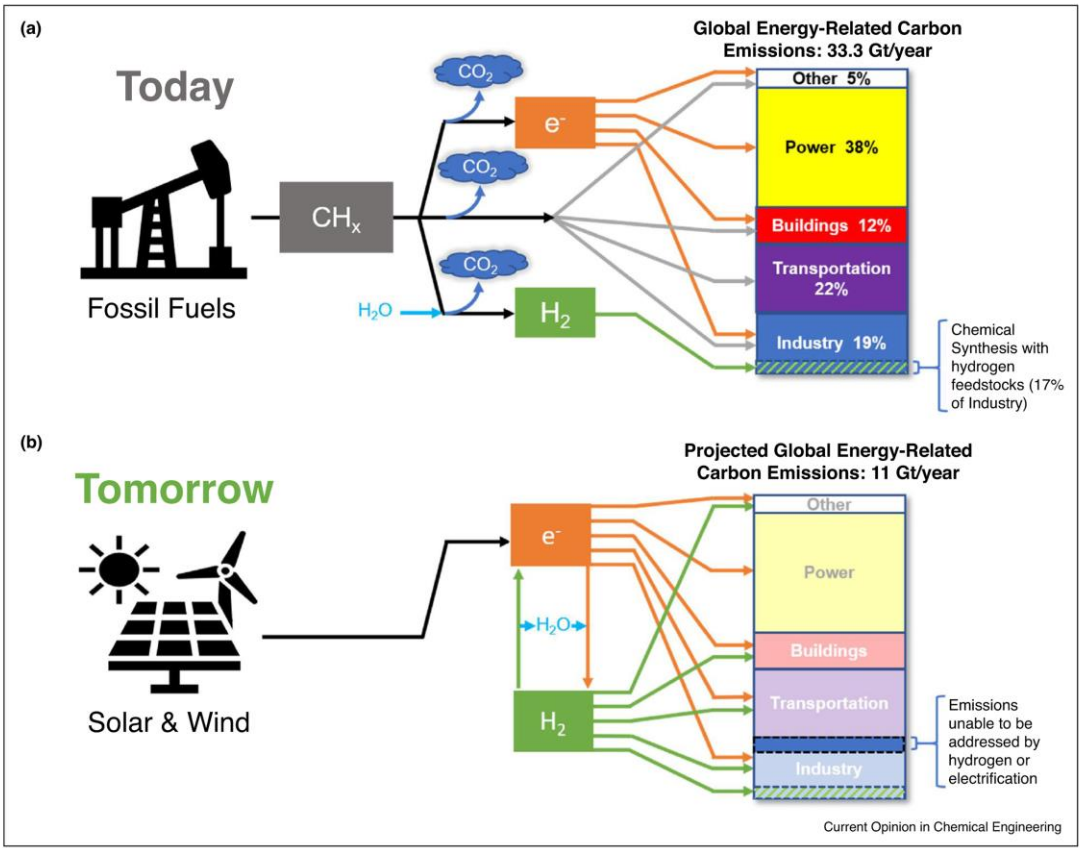


Figure 2-2 Current and Projected Energy sector [37]

A study in [38] presents an optimization model which examines H_2 production in Australia, Germany, Singapore, and Saudi Arabia, highlighting how geospatial solar irradiance impacts facility design. The lowest H_2 production cost, $10.68 per kilogram of hydrogen, is found in Saudi Arabia under current technoeconomic conditions. This research provides a valuable tool for exploring the changing technoeconomic landscape of green hydrogen production. A study projected that globally hydrogen demand can reach up to 2.3 giga tons annually, as compared with the hydrogen demand in 2019 which was 88 million tons [37]. Large scale H_2 production from fossil fuels is the most suitable and economical technology, but it possesses serious environmental impacts although fossil fuels are depleting. Therefore, transition towards a new clean hydrogen energy economy has better prospects. H_2 production at large scale for industrial decarbonization is the only way to support hydrogen economy [39]. Feasibility studies for GH_2 production potential have been conducted around the world. An economic feasibility of GH_2 production from RES in China is presented in [40]. It also discusses the utilization of GH_2 in fuel cell-based EV for road transport. Technical and economic analysis for stand-alone GH_2 production in Uruguay under various H_2 loads has been performed [41]. Cost of GH_2 production is estimated for 2020, 2030 and 2050 by using alkaline and solid oxide Electrolyzer. The cost of GH_2 production using solid oxide Electrolyzer is expected to decrease from 3.47 to 2.06 $/kg by reducing the levelized cost of energy (LCOE) from 65.11 to 32.55 $/MWh by 2050 [42]. Techno-economic analysis is performed in [43] on GH_2 production utilizing various water electrolysis technologies, including proton exchange membrane electrolysis (PEMEC), alkaline water electrolysis (AEC), solid oxide electrolysis with electric heaters (SOEC.EH), and solid oxide electrolysis combined with a waste heat source (SOEC.WH). Their analysis highlighted SOEC.WH as the most competitive option, boasting the lowest LCOH at 7.16 USD per kilogram, attributed to energy savings from sensible heat and enhanced stack efficiency. Many studies compared different water electrolysis technologies based on the types of Electrolyzer and energy source. The research article [44] compares three integrated energy system of hydrogen, power, and desalinated water production using different Electrolyzer: SOEC, PEM, and AEC. The SOEC system achieves the highest exergy efficiency (13.15%) and hydrogen production rate due to its dual use of thermal and electrical energy. Figure 2-3 shows COH with different Electrolyzer types and energy source across various studies [45], [46], [47], [48], [49], [50], [51].

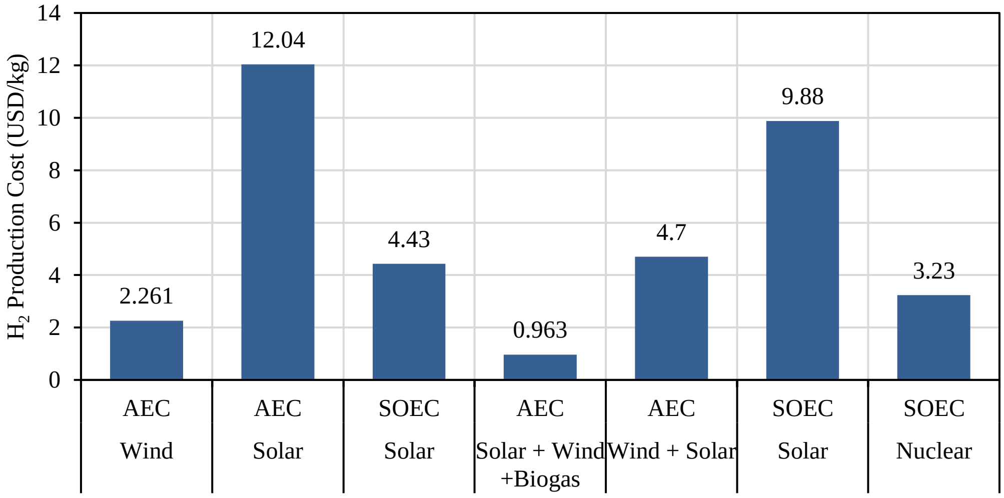


Figure 2-3 H_2 production cost across different studies

Monte Carlo model approach was employed to forecast the LCOH in Poland [52]. The study results reveal that by 2030, a 6 MW PEM Electrolyzer will be able to minimize the COH from solar photovoltaic energy to about €4.12–4.30 per kg. A technical and economic analysis of green hydrogen production by a stand-alone solar PV energy system is performed in the capital city of Iraq in [53]. LCOH range was found to be from 5.39 \$/kg to 3.23 \$/kg. Green hydrogen feasibility is assessed in different sites of Egypt using wind, solar and hybrid energy systems using HOMER Pro software in [54], [55]. Resulted LCOH was in the range of 3.73 \$/kg - 4.13 \$/kg whereas lowest LCOE was in the range of 0.308 \$/kWh - 0.353 \$/kWh. A multi-energy system (MES) designed in [56] is evaluated through a techno-economic analysis to produce GH_2, renewable electricity, and heat while meeting the demand for hydrogen, electrical, and thermal loads respectively. The range of LCOH and LCOE for this hybrid system in Italy are 3.14 - 3.49 \$/kg and 0.048 - 0.054 \$/kWh, respectively. Another study in ref. [57] optimized a Hybrid Renewable Energy System (HRES) to meet the electricity and hydrogen demand of a remote community in Uttarakhand, India, aligning with sustainable development goals (SDGs) 7 & 8. The levelized cost of electricity was determined to be 7.61 Indian rupees (INR)/kWh, while the cost of hydrogen stood at 330 INR/kg. Developing countries like India and China are actively working in the field of GH_2 energy. LCOH from water electrolysis process and from coal coupled with Carbon Capture Storage (CCS) is compared for China as a case study in [58]. Main findings of this study indicate that LCOH for coal to H_2 (C2H) coupled with CCS is around 57.6 to 128.3% higher than C2H process but it is 20 – 60 % than lower than water electrolysis. Another recent study in China compared the cost of H_2 produced from alkaline water Electrolyzer (AWE) and PEM water Electrolyzer [59]. The results showed that LCOH from AWE is 3.18–8.74 USD/kg lower than from PEMWE that ranged from 3.33–10.24 USD/kg. The technical and economic analysis of a system to fulfill the electricity demand of a city in Egypt is performed by using HOMER software [60]. Three distinct scenarios were analyzed, each featuring a PV system integrated into the grid-connected city with different configurations. The findings reveal an optimized scenario where 64.3% of the city's electricity demand can be met through solar energy production, resulting in a net present cost (NPC) of 71.7 million dollars. Table 2-2 shows a comparison of different previous studies conducted.

Table 2-2 Literature review of previous studies

Year	**Country**	**Application**	**Software**	**LCOH ($/kg)**	**LCOE ($/kWh)**	**Optimized Components**							**Ref.**
						Grid	**WT**	**PV**	**BS**	**EL**	**FC**	**HT**	
2024	China	Coal Chemical Industry	MATLAB	3.11 to 3.44	-	×	×	✓	✓	✓	×	✓	[61]
2024	Spain	Industry	TRNSYS	10 to 11.5	-	✓	×	✓	×	✓	×	✓	[62]
2024	India	Residential	HOMER Pro	2.59	0.252	×	✓	✓	✓	✓	×	✓	[63]
2024	Fiji	Fuel Cell buses	HOMER Pro	9.08(on), 13(off)	0.1(on),1.15(off)	✓	✓	✓	✓	✓	×	✓	[64]
2023	Canada	Residential	HOMER Pro	×	0.78	×	×	✓	✓	✓	✓	✓	[65]
2023	Egypt	Small Hotel	HOMER Pro	3.94	0.3085	×	✓	✓	×	✓	✓	✓	[54]
2023	Egypt	Hotel	HOMER Pro	3.73-4.13	0.308- 0.353	×	✓	✓	✓	✓	✓	✓	[55]
2023	Morocco		HOMER Pro	2.54-7		×	✓	✓	✓	✓		✓	[66]
2023	Turkey	University	MATLAB/ Simulink	×	0.223(on), 0.416(off)	✓	✓	✓	✓	✓	✓	✓	[67]
2022	Iraq	Four cities	MATLAB/ Simulink	3.79-4.19	×	×	×	✓	×	✓	×	✓	[68]
2022	Sweden	Refuelling stations		6.93-14.94(off), 3.83-7.89 (on)	×	✓	✓	✓	✓	✓	×	✓	[69]
2021	Morocco	Heavy-duty trucks	MATLAB/ Simulink	3.49-5.96	0.23-0.41		×	✓	×	✓	×	✓	[70]
Current	Pakistan	Industry	HOMER Pro	3.76 (off), 1.69 (on)	0.876 (off), 0.645 (on)	✓	✓	✓	✓	✓	×	✓	

*WT: Wind Turbine; PV: Photovoltaic; BS: Battery Storage; EL: Electrolyzer; FC: Fuel Cell; LCOH: Levelized Cost of Hydrogen; LCOE: Levelized Cost of Energy

2.2 In the context of Pakistan

Pakistan is blessed with great RES potential that should be utilized for low carbon hydrogen production [71]. Solar and wind are the two most efficient energy sources for GH_2 production in Pakistan [72], [73], [74]. In [75] investigated H_2 /production potential using agricultural biomass feedstock in Punjab, Pakistan. Estimated H_2 potential was 26.2 million tons per year which can be used by industrial and transportation sector. Iqbal [76] studied wind energy potential for green H_2 production in Sindh province. This province exhibits great wind energy potential with high wind speed at different sites [77], [78], [79], [80]. A study conducted techno economic feasibility analysis on producing H_2 from RES using Power to Gas (P-t-G) concept and using this H_2 into fuel cells to generate electricity [81]. It was found that HES without a diesel generator was the most feasible configuration with the lowest CAPEX of 669.44 M$ and LCOE of 0.465 $/kWh. China–Pakistan Economic Corridor (CPEC) offers extraordinary significance to the economic growth of Pakistan through industrialization and infrastructure development. Special Economic Zones (SEZs) are the key pillars of CPEC and offer significant incentives to both Chinese and Pakistani government. Nine proposed SEZs will boost foreign investment, industrial growth, and economic activity [82]. The initial phase of establishing these SEZs presents a significant opportunity to assess the feasibility of green hydrogen-based energy systems potentially contributing to the achievement of global SDGs [83]. Pakistan's hydrogen generation capacity was assessed on a national level using spatial multi-criteria analysis and density-based clustering in a GIS framework [84].

The study found areas with the potential to produce GH_2, with a capacity of around 7 MT per year using solar PV energy. Key possible sites include the Quetta-to-D-I-Khan alignment, the Surab-Gwadar alignment, and the N-25 national highway all of which are close to water resources and national energy transmission networks. The study recommends that many optimal sites for H_2 generation are located near the Gwadar economic zone, a key area within the Belt and Road Initiative (BRI) CPEC. Our current study is focused on the sustainable development of SEZs utilizing renewable energy resources such as green hydrogen. Techno-economic analysis of hybrid (wind/solar) energy system is performed to fulfill electrical load along CPEC central route in Gilgit-Baltistan, Pakistan [85]. Hydrogen, as an energy carrier, holds the potential to play a substantial role in achieving carbon neutrality for a nation. Conducting a feasibility study on the production of GH_2 will assist policymakers in formulating hybrid energy policies that contribute to the development of a hydrogen economy roadmap. This study serves as a foundational step for industries aiming to integrate hydrogen technologies into their operations. Furthermore, it unlocks economic opportunities such as job creation, attracting investment, and stimulating growth in related industries, enhancing Pakistan's global competitiveness in the clean energy sector. Ultimately, the feasibility study serves as a critical step towards building sustainable and resilient energy systems, ensuring a prosperous and environmentally conscious future for Pakistan.

Summary

This chapter provides an overview of existing studies conducted on the feasibility of GH_2 production. It highlights different technologies of hydrogen production, their cost of H_2 production and GHG emissions from conventional methods. The cost of H_2 production is influenced by several factors, including the production method, energy source, location, scale of production, and associated capital and operational costs. Techno-economic analysis for green hydrogen feasibility through different energy sources has been discussed on a global level. Additionally, the chapter discusses the research conducted on green hydrogen in Pakistan, which emphasizes that there is scarcity of available literature and further research is required for a sustainable development of Pakistan economy. Literature review has been supported by incorporating tables, graphs, and figures of existing research findings.

CHAPTER 3

Research Methodology

3.1 Site selection

The China-Pakistan Economic Corridor (CPEC) holds significant potential to bolster the economic growth of Pakistan through industrialization within its Special Economic Zones (SEZs). The early stages of SEZ development present an opportune moment to formulate policies related to green energy. Currently, there are several proposed SEZs under the CPEC umbrella in Pakistan poised to serve as industrial hubs and foster economic sustainability. This study also includes the Gwadar Port Free Zone due to its strategic economic importance. Figure 3-1 illustrates the selected sites, while Table 3-1 provides details on all ten economic zones considered in this analysis.

Figure 3-1 Selected SEZs on the map of Pakistan

Table 3-1 Special Economic Zones details

Sr.no.	Economic Zones	Covered Area	Focused sectors	Status
1	Rashakai Economic Zone, M-1, Nowshera	Over 1000 acre	Processing and Manufacturing, Pharmaceutical & Automobile, Wholesale Market/ Specialty mills	Under Construction
2	China Special Economic Zone - Dhabeji, Thatta	1530-acre land	Automotive, Textile, Garments, Chemical, Pharmaceuticals, Steel-Foundries, Consumer Electronics, Building Material & Warehousing	Under Construction
3	Allama Iqbal Industrial City (M3), Faisalabad	3,217-acre Approx.	Textiles, Automobiles, Chemical & Paints, Food Processing, Pharmaceuticals, Building Material & Packaging	Under construction
4	Bostan Industrial Zone, Quetta	1000 acres	Pharmaceutical, Food Industry, Agriculture machinery, Electric Appliance & Motor Bikes Assembly, Chromite & Ceramic industries	Under construction
5	ICT Model Industrial Zone, Islamabad	200 – 500 acres	Steel industry, Food processing, Textile industry	In-Pipeline
6	Industrial Park on PSM land in Port Qasim	1500 acres	Steel industry, Garments industry, Automobile manufacturing	In-Pipeline
7	Special Economic Zone, Mirpur	1078 acres	Mixed industries	In-Pipeline
8	Mohmand Marble City, FATA	To be allocated	To be decided	In-Pipeline
9	Moqpondass SEZ, Gilgit-Baltistan	250 acres	Iron ore Industries, Marble/granite industry, Leather industry	In-Pipeline
10	Gwadar Sea Port Authority Free Zone, Baluchistan	2281 acres	Mixed industrial hub	Under construction

3.2 Resource data

3.2.1 Solar Resource

Pakistan is blessed with great renewable energy potential. Pakistan has high solar radiations in Sindh, Baluchistan, and southern Punjab as shown in solar map of Pakistan in Figure 3-2. Average solar radiations in Pakistan ranges from 5 to 7 kWh/m^2/day [86].

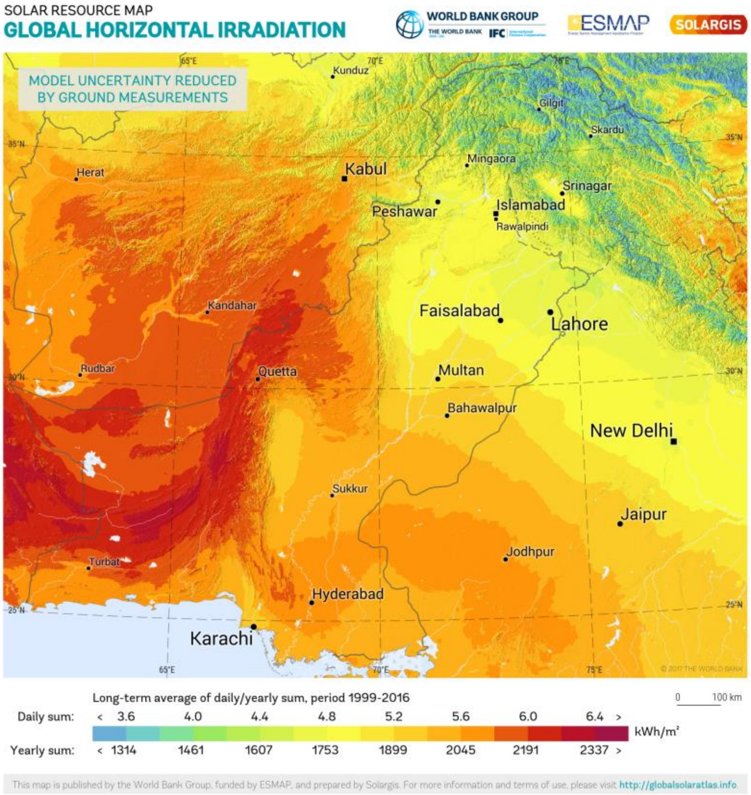


Figure 3-2 Solar map of Pakistan

Special economic zones are spread across all provinces of Pakistan and each SEZ faces different climatic conditions. Solar profile of selected locations throughout the year obtained from NASA POWER database is given in Figure 3-3. It is observed that Thatta and Port Qasim showed the highest average solar radiations of 5.45 kWh/m^2/day whereas lowest solar radiations of 4.45 kWh/m^2/day were observed in Moqpondass.

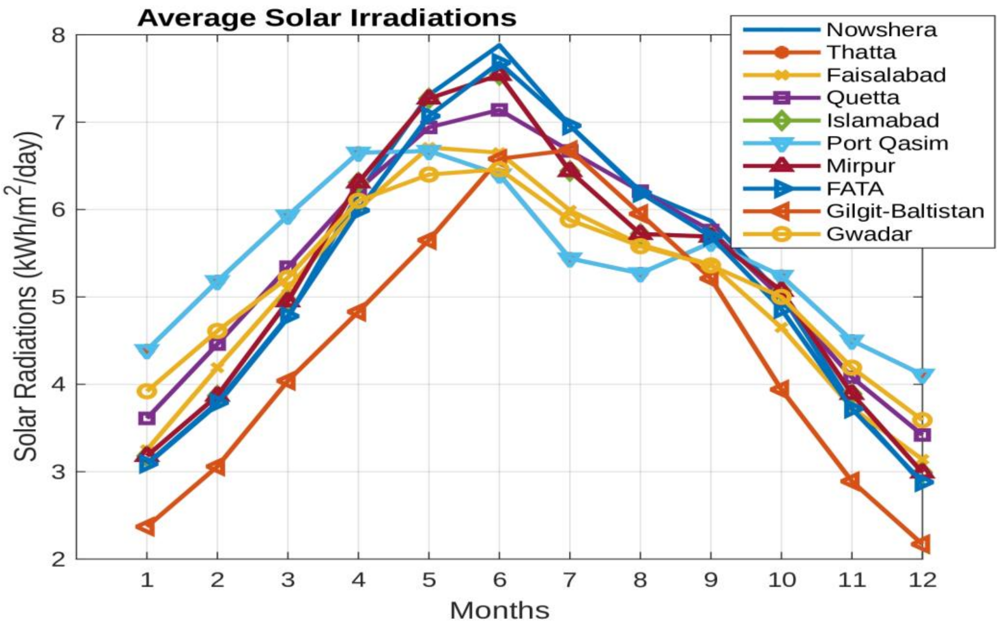


Figure 3-3 Solar profiles of selected sites

3.2.2 Wind Resource

Pakistan's extensive coastal line presents a significant opportunity for the large-scale installation of wind turbines, given the region's higher wind speeds. With an average wind speed in Pakistan 3 to 5 ms^{-1}, the coastal areas offer particularly favorable conditions for harnessing wind energy efficiently as shown in Figure 3-4.

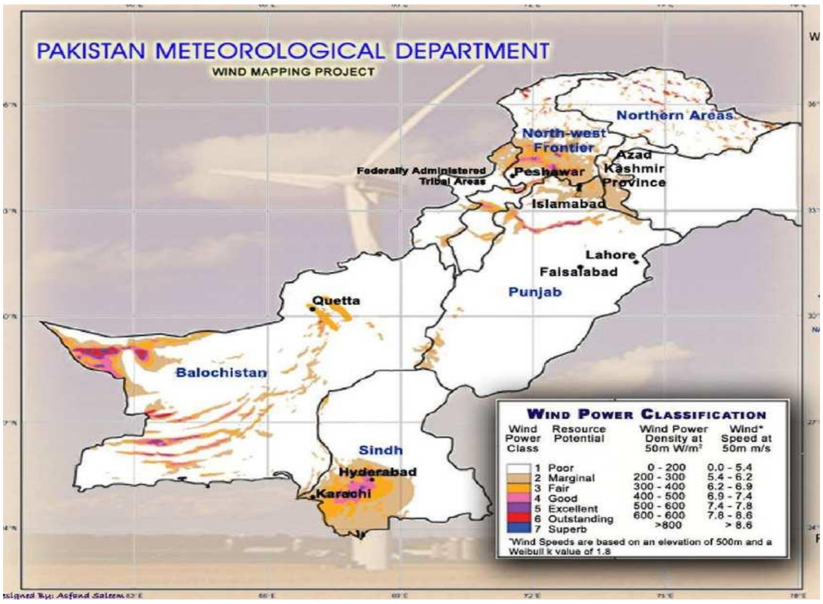


Figure 3-4 Wind map of Pakistan

Wind profile data of selected sites obtained from NASA POWER database are shown in Figure 3-5. The monthly average wind speed data is calculated at 50 m above the surface of earth. It can be observed that Port Qasim, Thatta and Gwadar exhibit high wind speeds throughout the year due to their location.

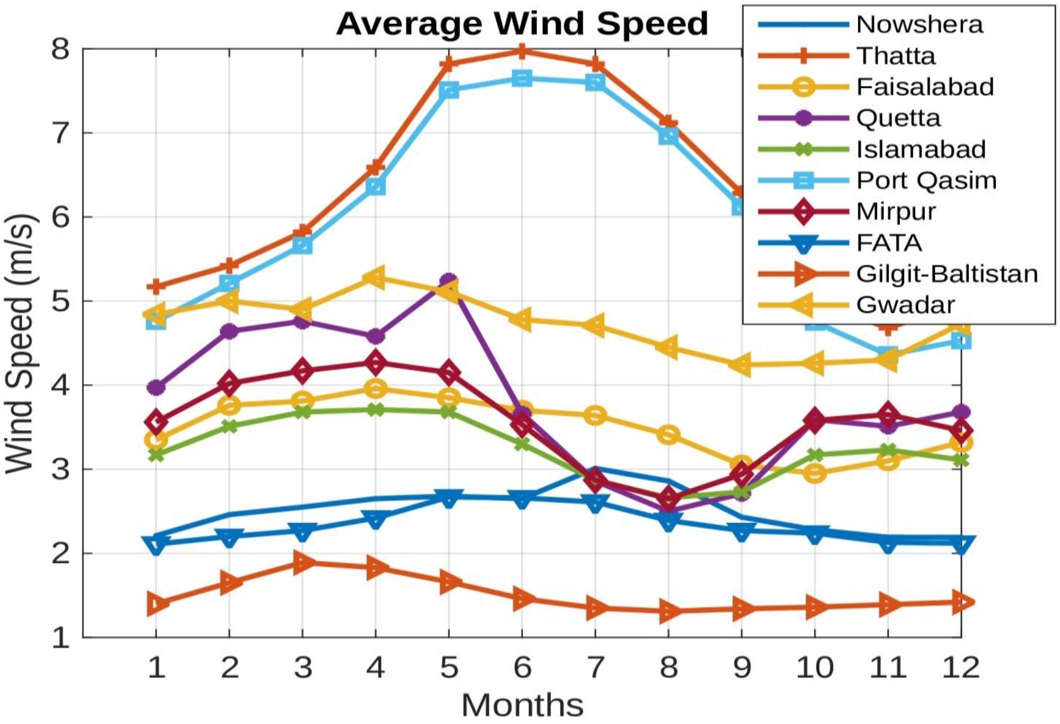


Figure 3-5 Wind speed profiles of selected sites

3.2.3 Ambient temperature

Monthly ambient temperature is downloaded from NASA POWER database for the period of over 30 years for the specific location. Maximum average temperature is observed in Thatta (26.86 ^{o}C), Gwadar (26.4 ^{o}C) and Port Qasim (26.3 ^{o}C) as shown in Figure 3-6. Temperature significantly affects power production from wind and solar energy sources. For wind energy, colder temperatures increase air density, resulting in higher power output, whereas warmer temperatures decrease air density, reducing efficiency of power generation.

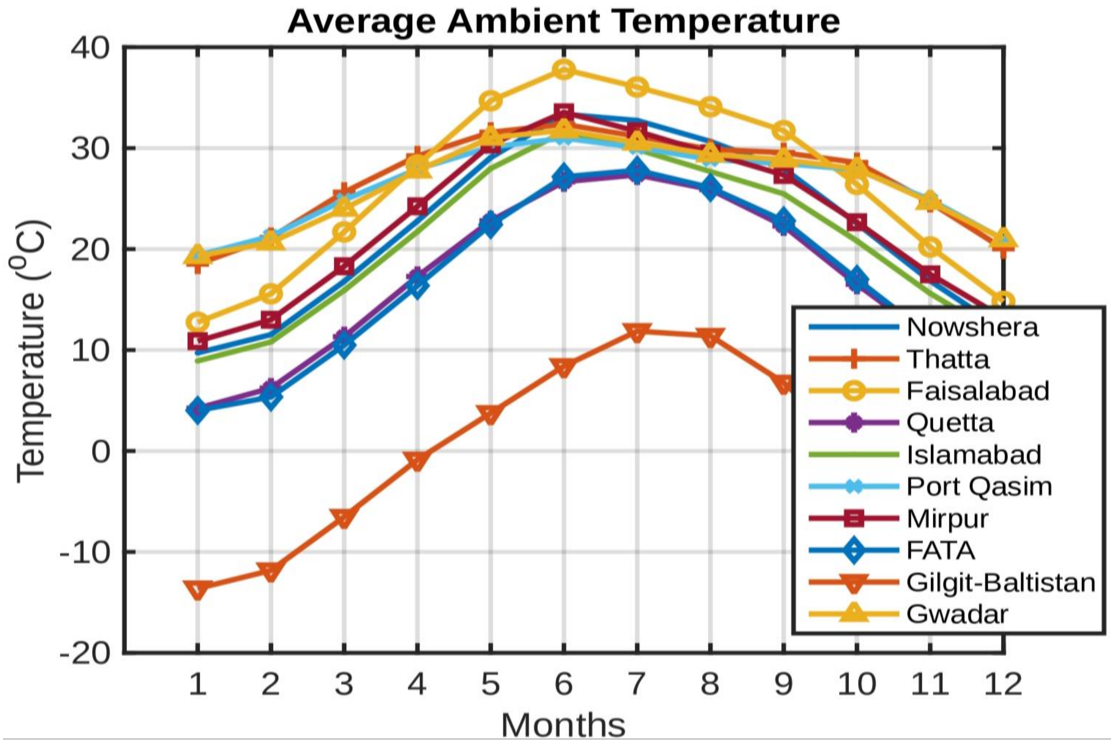


Figure 3-6 Average ambient temperature profile of selected SEZs

3.2.4 Load modelling.

The electrical load requirements for a steel industry located in Karachi, Sindh, with an annual melting capacity of 450,000 metric tonnes (MT) and a rolling capacity of 250,000 MT per annum, have been estimated. H_2 is used in iron making process to for iron ore reduction which is usually done by natural gas or coal. Decarbonization of steel industry by using green hydrogen in steel making process can help achieve near zero CO_2 emissions. Hydrogen-based direct reduction (H2-DRI) process is the most viable option in the near future [87]. The peak power of the estimated electrical load is 45.83 MW, with an annual average energy consumption of 600 MWh/day and a load factor of 0.55. Daily random variability is accounted for at 10% with a timestep of 20% for both electrical and hydrogen load. Additionally, the estimated hydrogen demand is set at 60 tonnes of H_2 per day, with a peak load of 4.5 tonnes per hour. The maximum permissible unmet hydrogen load is 5%, which translates to a maximum of 3 tonnes of hydrogen per day. Any hydrogen demand that exceeds this threshold incurs a penalty of $40 per kilogram of unmet hydrogen load. This penalty mechanism is likely in place to incentivize maintaining a high level of reliability and ensuring that the hydrogen demand is met as consistently as possible. Figure 3-7 shows H_2 and electrical load of a steel industry.

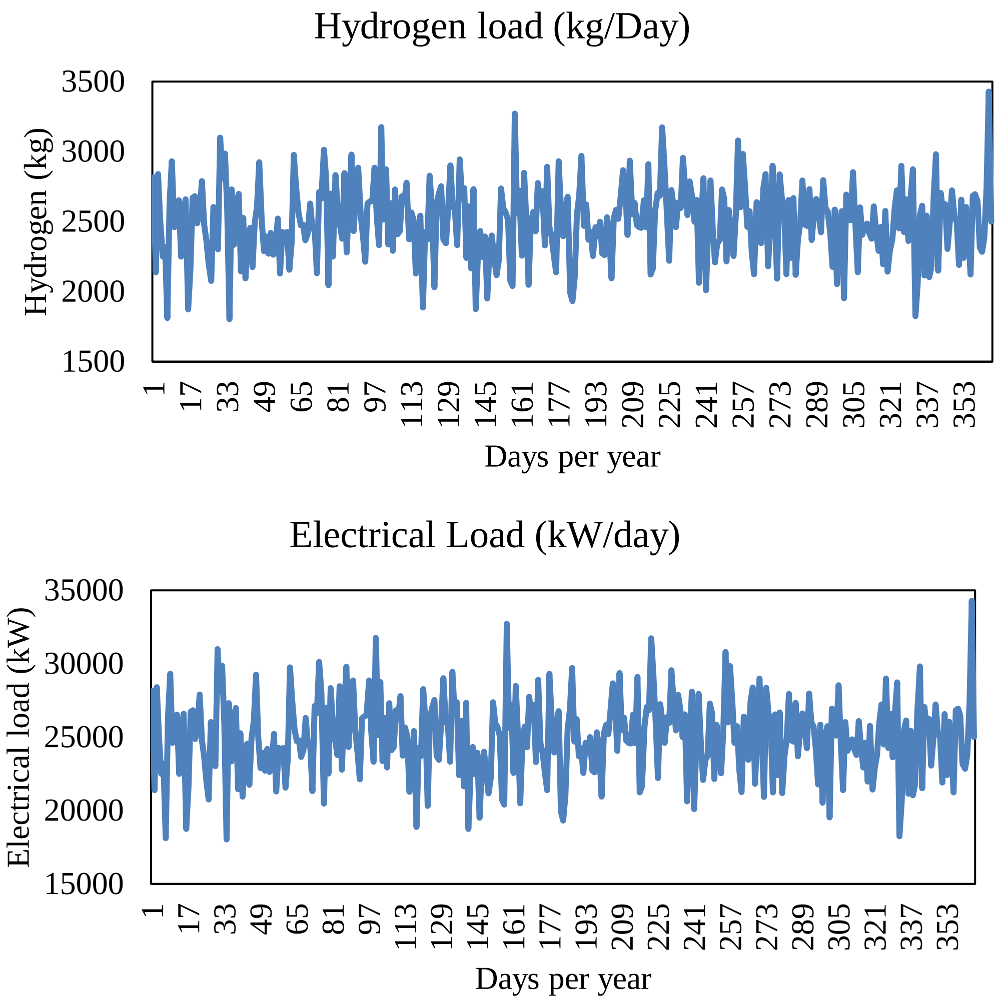


Figure 3-7 Electrical and H_2 load profile of steel industry

3.3 Optimisation Framework

In this study, off grid and grid connected hybrid energy systems are designed and comparatively analyzed based on green H_2 production technical and economical parameters. Schematic diagrams of the proposed systems are shown in Figure 3-8. The energy management strategy of the proposed system is as follows: In off-grid systems, wind and solar power plants are sized to generate electricity to meet the electrical load demand and supply the Electrolyzer for hydrogen production. Excess electricity produced is used to charge lithium-ion batteries for later use. The hydrogen storage system is also sized according to the hydrogen load demand and total hydrogen production. The on-grid strategy is similar, with the main difference being the addition of the national grid, which supplies electricity during periods when renewable energy generation is insufficient. HOMER Pro software employs two optimization algorithms: the original grid search algorithm, which uses search space to determine the most feasible system configuration, and an additional optimization algorithm for enhanced accuracy and efficiency. HOMER Pro optimizer uses propriety derivative-free algorithm to look for an optimal system with lowest NPC. HOMER Pro conducts system simulations by computing energy balances during each time interval throughout the year and predict annual operation of the system in the time steps of 1hour by analyzing different system configurations. It assesses the electrical and hydrogen demands against the system's energy supply for every interval, determining the energy flow to and from each system component accordingly.

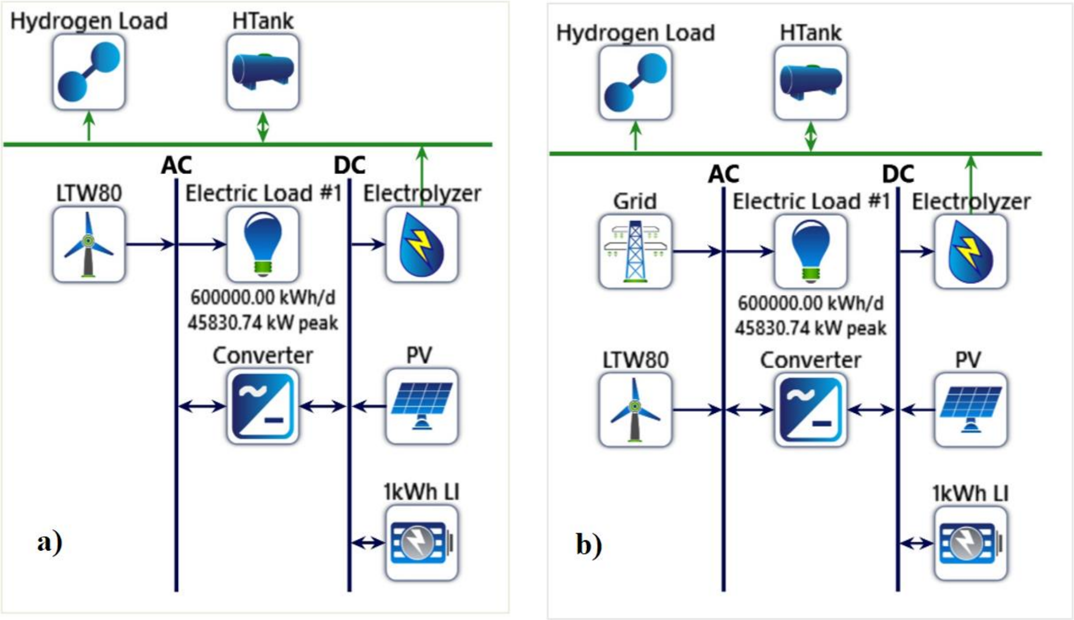


Figure 3-8 a) Off grid b) On grid hybrid system under study

Figure 3-9 shows a flowchart methodology of HOMER Pro to evaluate the hybrid energy system. The proposed hybrid energy system uses a combined dispatch strategy in which HOMER Pro algorithm decides that system will use cycle charging or load following strategy. In current study, optimal off grid HES is based on load following strategy while grid connected system uses cycle charging strategy.

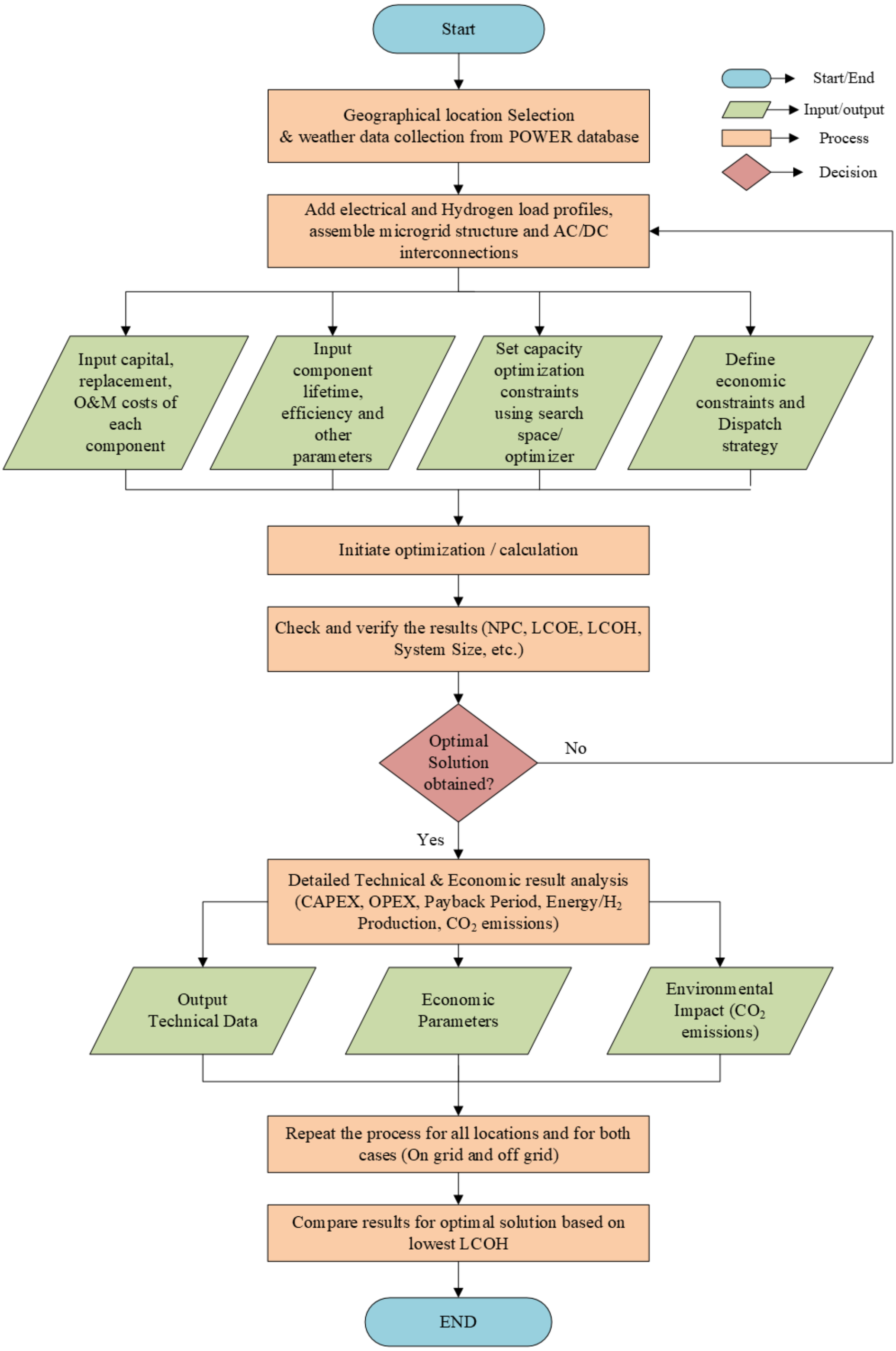


Figure 3-9 Flow chart of proposed methodology

3.4 Techno-economic Model

Solar panels and wind turbines generate renewable electricity that is used to meet the electrical load. Excess electricity is directed towards a PEM Electrolyzer which generates H_2 and O_2 gases as byproducts. These gases are then stored in designated cylindrical tanks. The system incorporates both battery storage and grid electricity as supplementary power sources as shown in schematic diagram in Figure 3-10. Within this research study, off-grid and on-grid configurations are examined to ascertain the optimal system setup. The projected lifespan span is set to 25 years, with a nominal discount rate of 10%, inflation rate of 6% which makes the real discount rate of 3.77%. Annual capacity shortage assumed is zero in this study. Techno-economic analysis is performed using HOMER Pro software for all selected locations.

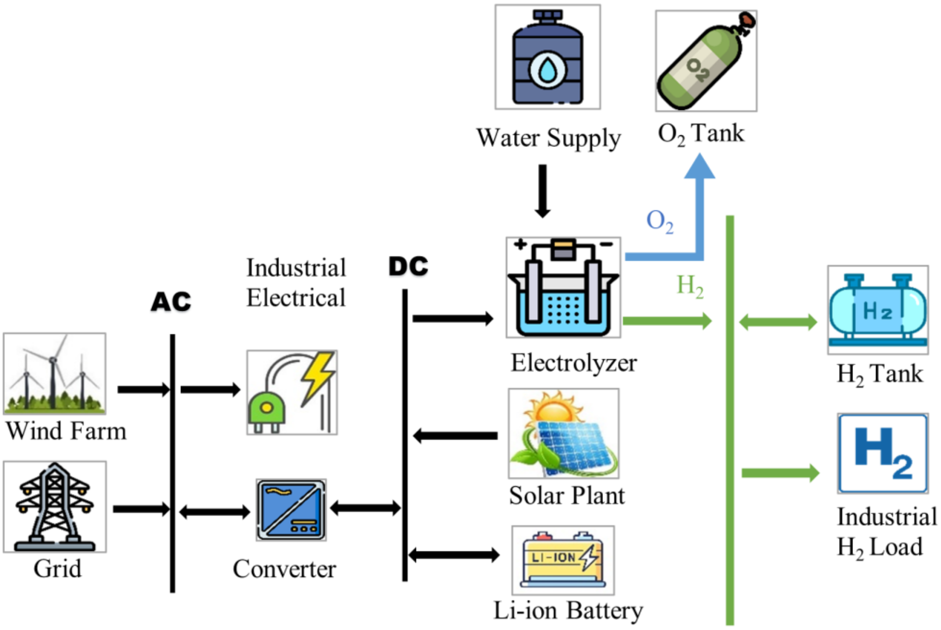


Figure 3-10 Schematic diagram of the proposed hybrid system

3.4.1 System Architecture

Solar Panel

Peimar SG325P flat plate solar panel is considered in this hybrid energy system (HES) which has efficiency of 16.7%. A derating factor of 0.8 incorporates different factors of solar panels soiling, shading, wiring losses and aging throughout the panel lifetime. The output of solar panels is based on the total amount of solar irradiations, humidity, ambient temperature, and other environmental factors. Solar PV panels output power can be calculated as follows:

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

The initial capital cost includes PV panel unit cost, hardware mounting structure, wiring, labor cost and installation cost. PV panel rated output power and other parameters are obtained on standard testing conditions (STC) which are a radiation of 1 kW/m^2, a cell temperature of 25°C, and no wind. The Solar panel specifications and cost data is presented in Table 3-2.

Table 3-2 Solar panel specifications

PV Panel Model	**Peimar SG325P**
Panel Type	Flat Plate
Derating factor (%)	80
Temperature Coefficient	-0.43
Operating Temperature (^{o}C)	25
Efficiency (%)	16.7
Capital Cost ($/KW)	560
Replacement Cost ($)	430
O & M Cost ($/year)	56
Lifetime (years)	25

Wind Turbine

The Leitwind 80 1MW wind turbine model was selected for the proposed model because it is ideal for high windy areas and has guaranteed average technical availability of up to 97%. The hub height for wind turbine is 80 m and its power curve is shown in Figure 3-11.

Wind turbines calculate wind speed at hub height U_{hub} at standard atmospheric conditions using equation (2).

$$U_{hub} = U_{anem} \left(\frac{ln\left({}^{Z_{hub}}/_{Z_0} \right)}{ln\left({}^{Z_{anem}}/_{Z_0} \right)} \right) \tag{2}$$

Wind turbine power output (kW) is calculated by equation (3)

$$P_{WTG} = \left(\frac{\rho}{\rho_0} \right) \times P_{WTG,STP} \tag{3}$$

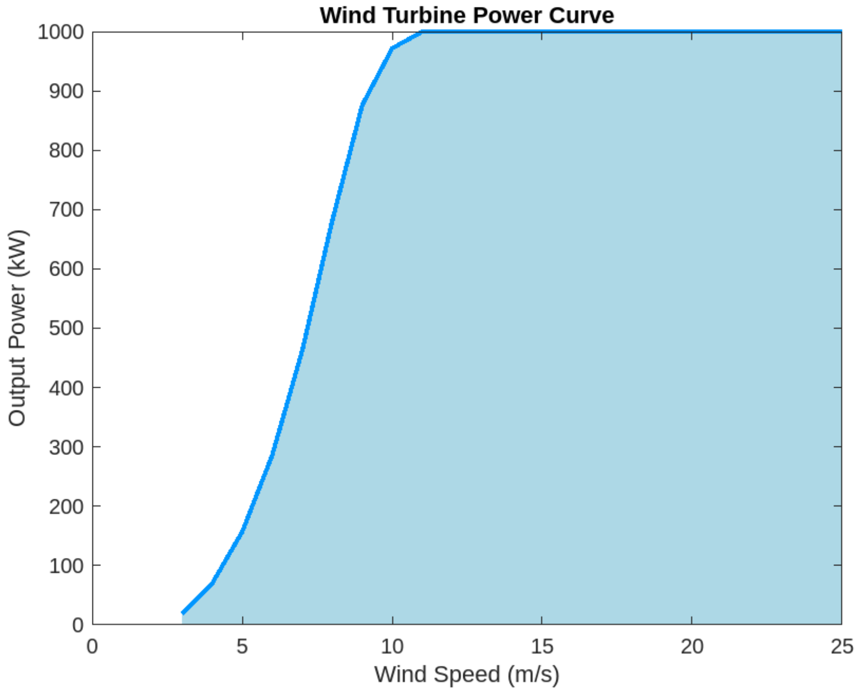


Figure 3-11 Wind turbine power curve

Wind turbine specifications are presented in the Table 3-3 below. The capital cost of wind turbine includes cost related to wind turbine tower, rotor, wiring, control system and installation cost.

Table 3-3 Wind turbine model specifications

Wind Turbine Model	**Leitwind 80 1000kW**
Hub heights (m)	65, 80
Cut in speed (m/s)	3
Cut out speed (m/s)	25
Wind class (IEC)	IA/IIA
Rotor diameter (m)	80.3
Capital Cost ($/MW)	1,500,000
Replacement Cost ($)	1,050,000
O & M Cost ($/year)	150,000
Lifetime (years)	25

PEM Electrolyzer

A Proton Exchange Membrane (PEM) Electrolyzer is a device that splits water into hydrogen and oxygen gases through an electrochemical process. This technology is highly efficient and can operate at low temperatures and pressures. It utilizes a proton exchange membrane to separate the gases produced during electrolysis which also prevents the regeneration of water during the reaction.

$$H_2O \xrightarrow{Electricity} H_2 + O_2$$

The total PEM Electrolyzer stack capacity is 400 MW. Cost analysis of PEM Electrolyzer shows that per unit cost of an Electrolyzer is 430 \$/kW [88], [89], [90] . The specific energy consumption of Electrolyzer is 46.4 kWh per kg of H_2. Hydrogen production rate can be calculated with the equation no. (4) as follows [53], [91]:

$$Q_{H_2} = n_f \times \left(\frac{N_c I_e}{2F}\right) \qquad (4)$$

shows Electrolyzer specifications and costs. Efficiency of Electrolyzer can be determined by equation no. 5, where higher heating value (HHV) of H_2 is 39.4 kWh/kg [92]:

$$\eta_{electrolyzer} = \frac{Higher\ heating\ value\ of\ H_2}{Specific\ energy\ consumption\ of\ H_2} \qquad (5)$$

Table 3-4 Electrolyzer specifications

PEM Electrolyzer	**Generic Electrolyzer**
Efficiency (%)	85
Specific energy consumption	46.4 kWh/kg
Capital Cost ($/5KW)	6000
Replacement Cost ($)	4200
O & M Cost ($/year)	600
Lifetime (years)	25

Hydrogen storage tank

A hydrogen storage tank plays a crucial role in storing the hydrogen (H_2) produced at a large-scale industrial plant. H_2 generated from a PEM Electrolyzer is stored directly in these tanks in its gaseous form, typically at a pressure of 30 bars. The expected lifespan of the hydrogen tank in this system is set at 25 years, aligning with the project's lifetime. The cost of the hydrogen tank varies depending on its capacity size. Hydrogen tank autonomy (A_{HT}) can be calculated with the following equation no. (6):

$$A_{HT} = \frac{Y_{HT}\, LHV_{H_2} (24\ hours/day)}{L_{avg,Prim}\ (3.6\ MJ/kWh)} \qquad (6)$$

Where lower heating value (LHV) of hydrogen is 120 MJ/kg [93], Y_{HT} is hydrogen tank capacity in kg and $L_{avg,Prim}$ is average daily primary load in kWh/day. H_2 tank specifications and costs are presented in Table 3-5.

Table 3-5 H_2 tank specifications

H_2 storage tank	**Generic H_2 storage tank**
Tank size	10 kg
Relative to tank size	10 %
Capital Cost ($/10 kg)	3500
Replacement Cost ($)	2450
O & M Cost ($/year)	350
Lifetime (years)	25

Lithium-ion battery storage

1 kWh Lithium-ion battery is selected as a backup power supply to store excess electricity produced by RE sources and power the system at the time of need. The idealized Li-ion battery model has a nominal capacity of 167 Ah, nominal voltage of 6V and has 90% round-trip efficiency. Battery throughput is another essential parameter used to calculate the life of battery storage bank which can be calculated using the following equation (7).

$$R_{batt} = \begin{cases} \frac{N_{batt} \cdot Q_{lifetime}}{Q_{thrpt}} & if\ limited\ by\ throughput \\ R_{batt,f} & if\ limited\ by\ time \\ Min\left(\frac{N_{batt} \cdot Q_{lifetime}}{Q_{thrpt}}, R_{batt,f}\right) & if\ limited\ by\ throughput\ and\ time \end{cases} \qquad (7)$$

Battery bank autonomy is the ratio of the storage bank size to the electric load and can be calculated using the following equation (8).

$$A_{batt} = \frac{N_{batt}V_{nom}Q_{nom}\left(1 - {}^{q_{min}}/_{100}\right)(24\ h/day)}{L_{prim,ave}(1000\ Wh/kWh)} \quad (\ 8)$$

Where N_{batt} is number of batteries in storage bank, V_{nom} is the voltage of single storage (V), Q_{nom} is the nominal capacity (Ah), q_{min} is the minimum state of charge of storage bank (%), $L_{prim,ave}$ is average primary load in kWh/day.

Table 3-6 Li-ion battery specifications

Battery storage type	**Generic 1 kWh Li-Ion**
Nominal voltage (V)	6
Nominal Capacity (Ah)	167
Round trip efficiency (%)	90
Initial State of Charge (SoC)	100 %
Minimum State of Charge (SoC)	20%
Throughput (kWh)	3000
Capital Cost ($/kWh)	250
Replacement Cost ($)	175
O & M Cost ($/year)	25
Lifetime (years)	15

Converter

A generic system converter considered in the system can act as inverter as well as rectifier to sustain the flow of electricity between AC and DC.

Table 3-7 Converter specifications

Converter type	**Generic system converter**
Inverter & rectifier efficiency	95%
Rectifier relative capacity	100%
Capital Cost ($/kW)	200
Replacement Cost ($)	200
O & M Cost ($/year)	0
Lifetime (years)	15

Converter power rating P_{inv} can be calculated with the following equation [94].

$$P_{inv} = \frac{P_{peak}}{\eta_{inv}} \quad (\ 9)$$

Where P_{peak} is peak load demand and η_{inv} is efficiency of inverter that is 95 %. Inverter is parallel with AC generator having lifetime of 15 years as shown in Table 3-7.

Electrical Grid

The proposed hybrid energy system is connected with the national electrical grid to provide backup electricity when renewable energy sources are not sufficient to meet the electricity needs. National Electric Power Regulatory Authority (NEPRA) is responsible for regulating electricity supply in Pakistan. It is also responsible to set tariff, rates, and electricity charges for electric power services on generation, transmission, and distribution. In this study, electricity purchase price is taken as 0.13 \$/kWh (off peak) and 0.15 \$/kWh (on peak), while electricity sellback price is considered as 0.1 \$/kWh. Electricity sales capacity is the maximum capacity that can be sold to the grid and has been specified as 20 MW in each case. Excess electricity fraction can be calculated by the following equation:

$$f_{excess} = \frac{E_{excess}\,[kWh/yr]}{E_{prod}\,[kWh/yr]} \qquad (10)$$

Table 3-8 Advanced grid specifications

Advanced grid type	**Grid with scheduled rates**
Sale capacity	20 MW
Net metering	On
Sellback price (\$/kWh)	0.1
Interconnection charges (\$)	1000
Standby charges (\$/year)	100
Off peak purchase price (\$/kWh)	0.13
On peak purchase price (\$/kWh)	0.15
Mean outage frequency (1/year)	20
Mean repair time (h)	2
Repair time variability (%)	10
Carbon dioxide emissions (g/kWh)	350
Sulfur dioxide emissions (g/kWh)	2.74
Nitrogen oxides emissions (g/kWh)	1.34

3.4.2 Mathematical modelling

The proposed hybrid system for green hydrogen production technical and economic analysis is performed using HOMER Pro software. In this section, mathematical equations are presented to determine each technical and economical parameter. Capital, replacement, and economic costs are defined in the system after a thorough literature review and market research. Hydrogen transportation costs from supply side to its demand sites have been included in the system's yearly fixed O&M cost.

The location factor serves as a highly valuable criterion in determining the most viable site for industrial operations, particularly in power generation projects. Key considerations within location factors encompass labor productivity, as well as material and labor costs. It can be estimated by the following equation:

$$Location\ factor = Labor\ productivity\ factor \times Material\ cost\ factor \times Labor\ cost\ factor \quad (11)$$

The total NPC ($) can be measured as follows:

Where $CF_{t,equip,earned}$ is the nominal cash flow in that is earned from the equipment throughout the project lifetime, $CF_{t,equip,incurred}$ is the nominal cashflow out associated with costs incurred during the project lifetime. $C_{NPC,tot}$ is total net present cost of the project over its lifetime where m is the total equipment number and n is the project lifetime of 25 years.

$$C_{equip,tot} = CF_{t,equip,earned} - CF_{t,equip,incurred} \quad (12)$$

Total annualized cost of project ($C_{ann,tot}$) can be calculated as:

$$C_{ann,tot} = CRF\left(i, R_{proj}\right) \cdot C_{NPC,tot} \quad (13)$$

Where capital recovery factor (CRF) is a function of real discount rate (i) and project lifetime (R_{proj}) which can be calculated with equation as follows:

$$CRF(i, R_{proj}) = \frac{i \times (1+i)^N}{(1+i)^N - 1} \quad (144)$$

Where N is number of years and i is annual real discount rate considered as 3.77% in current study. It is a function of nominal discount rate i' and expected inflation rate f and can be obtained by the following equation:

$$i = \frac{i' - f}{1+f} \quad (155)$$

Levelized cost of energy (LCOE) is an important parameter which depicts the average cost of energy per kWh of useful electricity generated by the HES. LCOE can be obtained by the following equation:

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \tag{166}$$

Where E_{served} is total served electrical load in kWh/yr.

Levelized cost of hydrogen (LCOH) is a crucial parameter measured in \$/kgH$_2$ can be calculated with the following equation [40]:

$$LCOH = \frac{C_{ann,tot} - C_{electricity}}{M_{hydrogen}}$$

(177)

Where $C_{electricity}$(\$/year) is the revenue generated from electricity sales to the grid, $M_{hydrogen}$(kg/year) is the total H$_2$ produced per year. For off grid system, $C_{electricity}$ is zero because of zero electricity sales, while for on grid electricity is sold to the national grid.

Another detailed formula to calculate LCOH as presented in [95] is as follows:

$$LCOH_{r,j,t} = \frac{Capital\ cost_{j,t} + \sum_{n=1}^{t} \frac{(O\&M\ Cost_{j,t} + C_{carbon,t} + C_{fuel,j})}{(1+i)^t}}{\sum_{n=1}^{t} \frac{8760 \times Capacity\ Factor_{j,t} \times Capacity_{j,t}}{(1+i)^t}}$$

(188)

Payback period is an important term in economic analysis of a system. It is the time in number of years that the system will take to recover all initial investments. It can be calculated with the following equation:

$$Payback\ period = \frac{Initial\ investment}{Annual\ cash\ inflow} \tag{19}$$

The Return on Investment (ROI) represents the annual cost savings compared to the initial investment. HOMER computes ROI using this formula:

$$ROI = \frac{\sum_{i=0}^{R_{proj}} C_{i,ref} - C_i}{R_{proj}(C_{cap} - C_{cap,ref})} \tag{19}$$

Where, $C_{i,ref}$ is base system's nominal annual cash flow, C_i is current system's nominal annual cash flow, C_{cap} is current system's capital cost and $C_{cap,ref}$ is base system's capital cost.

Oxygen processing

Oxygen gas produced during the H$_2$ production process is stored in an oxygen storage tank to further utilize it during a time of need. Oxygen (O$_2$) produced along with hydrogen during the process can calculated by using H$_2$:O$_2$ ratio in water molecule by mass [96]. Oxygen is typically stored as a gas in high-pressure O$_2$ cylinders. However, the current approach does not factor in the energy expended during the oxygen capture and purification process. Oxygen can also be distributed to various sectors, including industries and hospitals. In the steel industry, oxygen plays a crucial role in blast oxygen furnaces (BOF), where it accelerates the melting rate by raising the furnace temperature and enhancing ferromanganese production. Additionally, oxygen serves as a valuable tool in electric arc furnaces, particularly in processing stainless steel scrap and refining high-alloy content steels [97].

Summary

In this chapter, weather resource data of wind, solar and temperature is provided at each special economic zone of CPEC. Research design methodology is explained with a schematic diagram of the proposed system. Flow chart of working methodology of HOMER Pro software and its energy management strategy has been presented. Components specifications including their parameters and cost input data is presented in tabular form. Mathematical modelling equations of each component is also provided in this chapter followed by the processing of oxygen during the hydrogen production method.

CHAPTER 4

Results and Discussion

The proposed system methodology designed in the previous section is validated in this section through HOMER Pro simulation results. The study is carried out on ten economic zones to determine optimal system component sizing that will allow industry to get 60 tonnes of H_2 per day as well as 600 MWh of electricity per day. Solar PV and wind energy sources were chosen as main renewable energy sources based on their availability at each location. The following discussion is focused on technical and economic aspects of off grid and grid connected systems.

4.1 Off Grid

Off grid system is based on wind and solar with lithium-ion battery stack to provide backup power supply. Table 4-1 shows calculated installed capacities of PV panels, Wind turbines, battery stack and converter for off grid system at each location. All sites showed great feasibility based on solar PV panels only, while Dhabeji, Port Qasim and Gwadar port showed good feasibility on hybrid system of wind and solar. Solar panels capacities ranged from 523 MW to 1342 MW while wind turbines capacity ranged from 32 MW to 92 MW in off grid system scenarios across all locations. Required capacities of Li-ion batteries and system converter are also provided in the table. Moqpondass, Rashakai, Faisalabad and Mirpur SEZs required high solar panel capacity and large number of batteries due to low weather condition. PEM Electrolyzer size capacity is set to 400 MW to produce the targeted amount of hydrogen gas with specific energy consumption of 46.4 kWh/kg and 85% efficiency. Excess H_2 produced is stored in hydrogen tank with capacity of 300 tonnes and storage tank autonomy of 400 hours. Figure 4-1a shows yearly H_2 production across each economic zone. Dhabeji, Port Qasim and Gwadar port produce enough amount of H_2 that can meet the industry demand, hence producing excess amount of hydrogen. Rashakai, Faisalabad, Quetta and Islamabad also fulfil hydrogen demand at higher costs.

Table 4-1 Required capacities for off grid systems at each location.

Locations	**PV Panels (MW)**	**Wind Turbines (MW)**	**Battery (MWh)**	**Converter (MW)**
Rashakai	864	0	656	54.57
Dhabeji	523	92	466	57.398
Faisalabad	873	0	624	49.119
Quetta	686	0	592	48.49
Islamabad	774	0	652	67.802
Port Qasim	591	63	497	48.278
Mirpur	806	0	646	57.882
FATA	795	0	646	83.664
Moqpondass	1342	0	722	113.637
Gwadar Sea Port	787	32	511	50.382

Whereas Moqpondass, FATA and Mirpur produced lowest amount of H_2. Dhabeji produced maximum hydrogen of 21,916,168 kg at 3.76 $/kg LCOH with lowest COE of 0.876 $/kWh as shown in Figure 4-1. LCOH value ranges from 3.76 $/kg to 8.18 $/kg while COE ranges from 0.876 $/kWh to 1.29 $/kWh. Cost of hydrogen is calculated when maximum unmet hydrogen load is set to 5% with unmet load penalty of 40 $/kg at each site. SEZ at Moqpondass has shown the highest LCOH and COE in comparison to other sites because of its cold climatic conditions. Port Qasim, Quetta and Gwadar port showed low levelized cost of hydrogen as 3.79, 4.06 and 4.41 $/kg and cost of energy as 0.879, 0.900 and 0.937 $/kWh, respectively.

The overall net present cost tends to increase in off-grid systems due to the supplementary capital expense incurred by integrating a battery stack. Wind and solar power, being intermittent energy sources, often trigger voltage fluctuations that could potentially damage the system's equipment. This instability can adversely affect the Electrolyzer operational efficiency leading towards degradation of Electrolyzer and influencing hydrogen production cost. Consequently, battery stack in the system plays a key role in protecting the system’s equipment and reducing operational complexities. Capital cost of Electrolyzer and PV panels have high share in the total cost of the system. Dhabeji has the lowest NPC of 3069 M$ followed by Port Qasim (3079 M$), Quetta (3155 M$) and Gwadar (3284 M$).

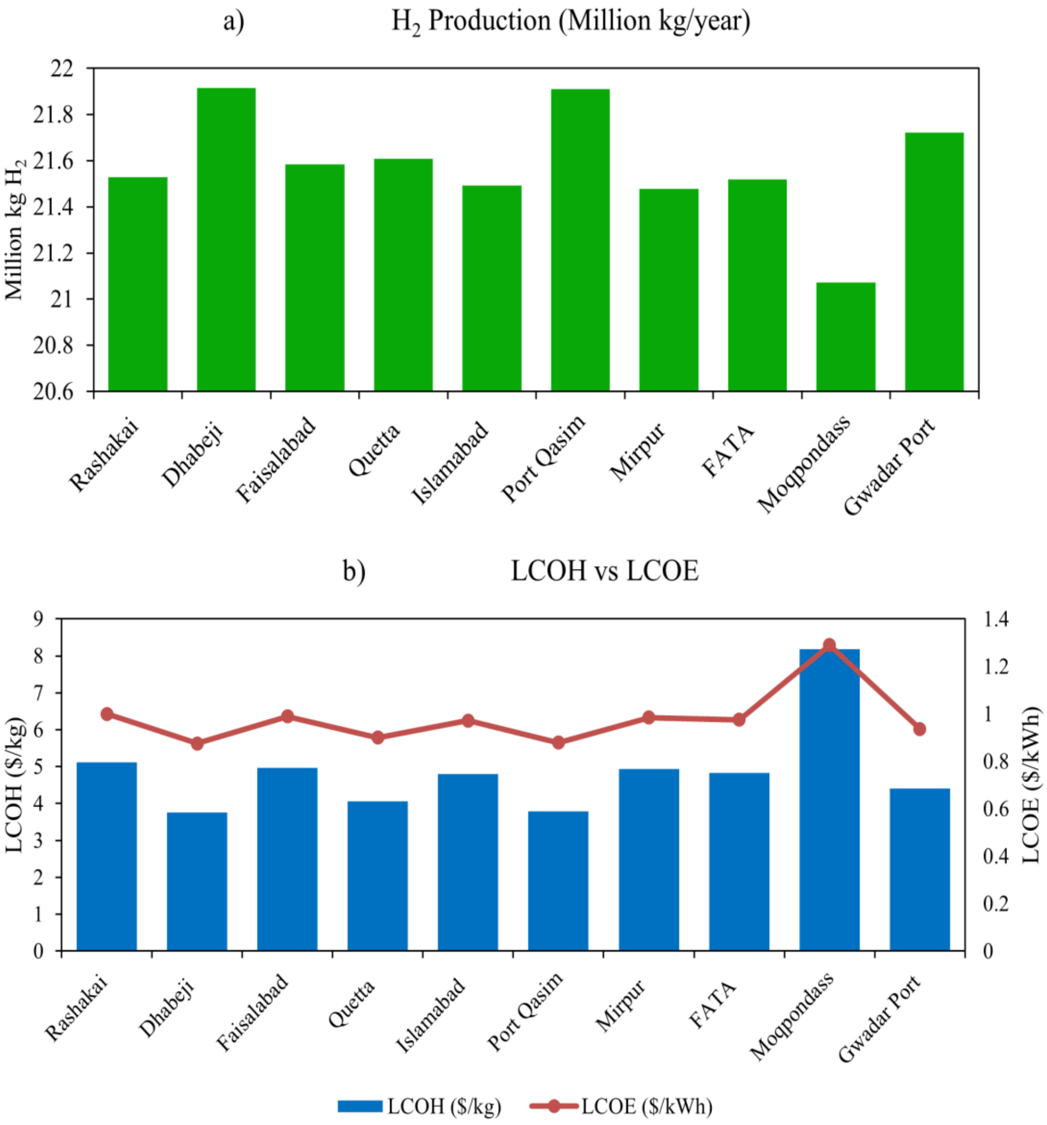


Figure 4-1 Off Grid a) Hydrogen Production (kg/year) b) LCOH vs LCOE

Initial capital cost is the total cost of all components at the beginning of the project, it has low variation across all locations. Operating cost varies across all sites depending on the operation and maintenance required by each component. Table 4-2 and Figure 4-2 shows the detailed breakdown of NPC, initial capital cost, operating costs. Table 4-3 shows the H_2 and O_2 production and total water consumption during the process across each SEZ.

Table 4-2 Costs across all SEZs for off grid system

Location	LCOH ($/kg)	LCOE ($/kWh)	NPC (M$)	Initial Capital (M$)	Operating Cost (M$/year)
Rashakai	5.11	1.000	3512	1240	142
Dhabeji	3.76	0.876	3069	1140	120
Faisalabad	4.96	0.989	3465	1240	139
Quetta	4.06	0.900	3155	1130	127
Islamabad	4.8	0.972	3400	1190	138
Port Qasim	3.79	0.879	3079	1140	121
Mirpur	4.94	0.985	3550	1210	140
FATA	4.83	0.975	3410	1210	138
Moqpondass	8.18	1.290	4513	1530	186
Gwadar Sea Port	4.41	0.937	3284	1210	130

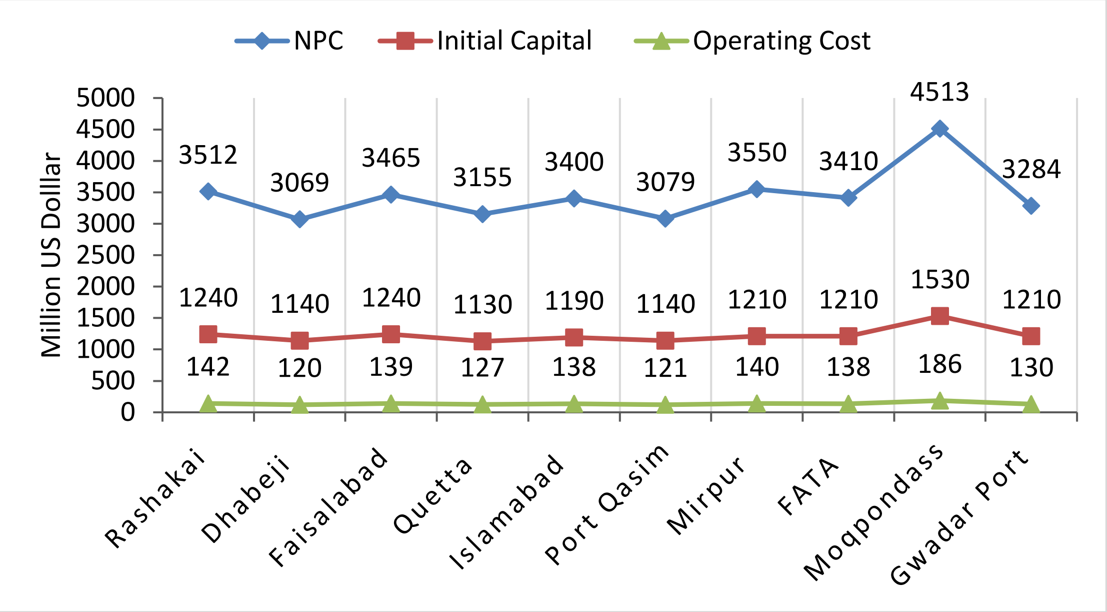


Figure 4-2 NPC, Initial and Operating Cost for off grid systems

Dhabeji special economic zone shows a lowest payback period of 3.7 years with 30% internal rate of return (IRR) and 38% return on investment (ROI). The payback period ranged from 3.7 to 6.6 years; IRR ranged from 15.4 to 30% while ROI range is from 12 to 41.2%.

Table 4-3 H_2, O_2 production and water consumption

Location	H_2 Production (kg/yr)	O_2 Production (kg/yr)	Water consumption (kg/yr)
Rashakai	21529528	172236224	193765752
Dhabeji	21916168	175329344	197245512
Faisalabad	21583347	172666776	194250123
Quetta	21608234	172865872	194474106
Islamabad	21491906	171935248	193427154
Port Qasim	21909411	175275288	197184699
Mirpur	21478570	171828560	193307130
FATA	21519046	172152368	193671414
Moqpondass	21073276	168586208	189659484
Gwadar Sea Port	21722134	173777072	195499206

Table 4-4 shows simple payback period, IRR, and ROI for each site from which we can observe that Rashakai, Islamabad, Mirpur, FATA and Moqpondass demonstrate Payback period exceeding 5 years as shown in Figure 4-3. Conversely, Dhabeji, Faisalabad, Quetta, Port Qasim, and Gwadar port exhibit payback period less than 5 years, from which we can indicate that these sites show greater feasibility for the green hydrogen production system.

Table 4-4 Off grid system's IRR, payback period and ROI across all SEZs

Location	IRR (%)	Payback Period (years)	ROI (%)
Rashakai	19.5	5.2	16
Dhabeji	30	3.7	38
Faisalabad	19.6	4.8	15
Quetta	22	4.6	15.5
Islamabad	20	5.3	17
Port Qasim	27.5	4.43	41.2
Mirpur	15.4	6.2	12
FATA	18.1	5.3	14
Moqpondass	17.3	6.6	16
Gwadar Port	30	3.8	34.2

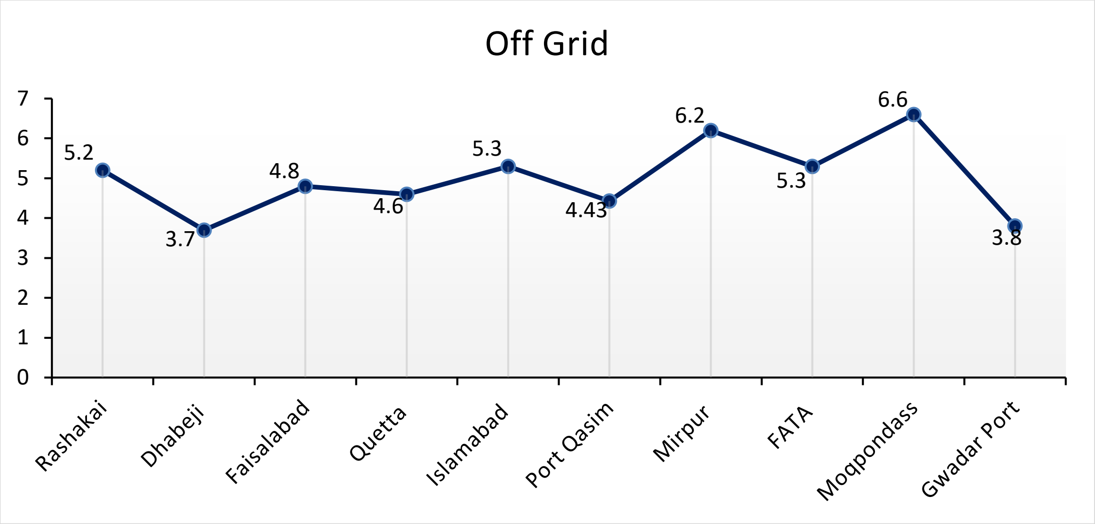


Figure 4-3 Payback Period for Off Grid System

4.2 On Grid system

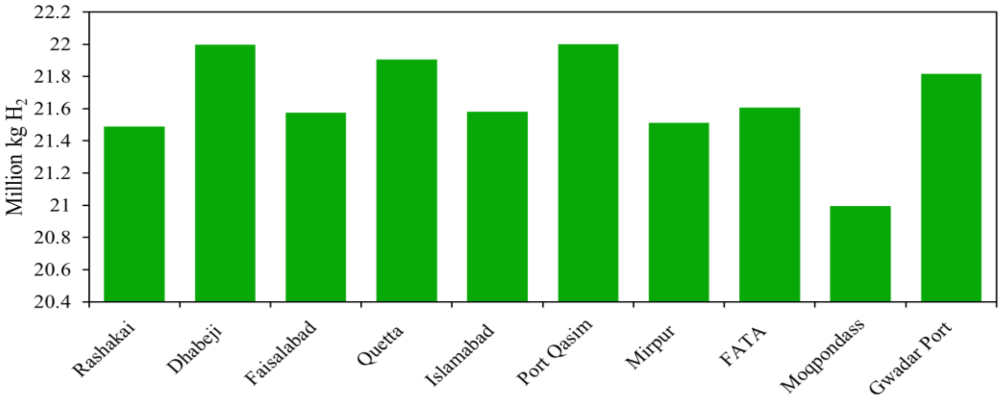
The data in Figure 4-5 depicts the required installed capacity of PV panels, wind turbines, converter and battery stack for grid connected system. PV panels' capacity size range is 491 MW to 855 MW, smaller than the size required for off grid system. The calculated size capacity for PV panels and wind turbine in Dhabeji is 491 MW and 75 MW respectively with 31 MW of converter. The capacity size of PV panels is smaller at Dhabeji as compared to other sites because of high solar radiation. In contrast to relying solely on batteries for backup power in off-grid scenarios, the grid serves as an additional power source during times of varying demand or when renewable energy supply is insufficient, reducing the number of batteries required to meet the load demand. Only Dhabeji and Port Qasim gives optimal solution based on hybrid (PV/Wind) system while other sites show high feasibility with only grid connected solar PV system. The installed capacities for PEM Electrolyzer and Hydrogen tank are same for each site to meet the targeted amount of H_2 production.

Figure 4-4a shows that the total hydrogen production in Dhabeji, Port Qasim, Gwadar and Quetta is nearly 22 million kg per year. Moqpondass generated lowest amount of hydrogen barely meeting the hydrogen load demand. Moqpondass showed highest LCOH, COE, NPC, and payback period from which we can indicate that Moqpondass is infeasible for a green hydrogen production facility.

Table 4-5 Required installed capacities for on grid system.

Locations	**PV Panels (MW)**	**Wind Turbines (MW)**	**Battery (MWh)**	**Converter (MW)**
Rashakai	608	0	40	56
Dhabeji	491	75	0	31
Faisalabad	626	0	51	50
Quetta	580	0	40	52
Islamabad	588	0	40	51
Port Qasim	551	41	19	55
Mirpur	590	0	41	50
FATA	600	0	44	54
Moqpondass	855	0	41	54
Gwadar Sea Port	659	0	44	59

a) H_2 production (Mkg/yr)



b) LCOH vs LCOE

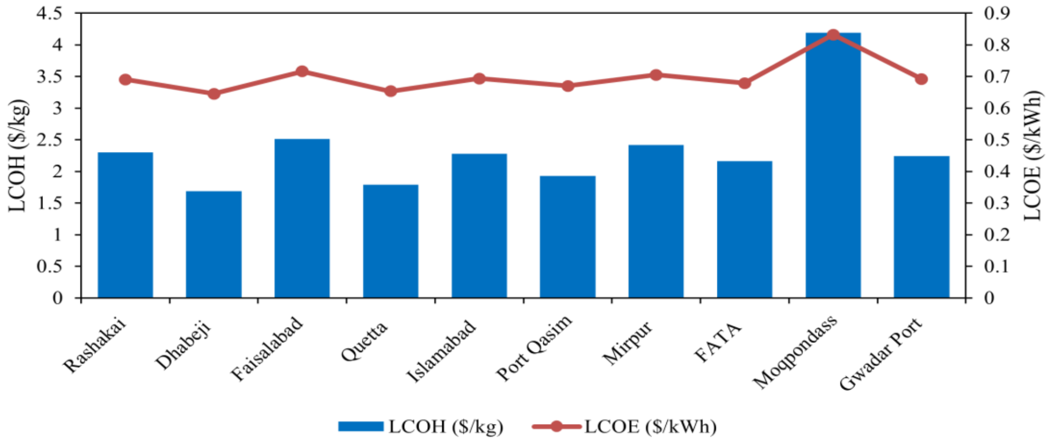


Figure 4-4 On Grid a) Hydrogen production (kg/year) b) LCOH vs LCOE

The calculated cost of hydrogen ranges from 1.69 $/kg to 4.19 $/kg while COE ranges from 0.645 $/kWh to 0.832 $/kWh as shown in Figure 4-4b. It is observed that Dhabeji, with the highest renewable fraction of 77.7% has lowest cost of hydrogen and energy as 1.69$/kg and 0.645 $/kWh respectively, making it the most feasible location for green hydrogen production. Overall net present cost in grid connected system has decreased by an average of 17% from the standalone system. The total net present cost for Dhabeji and Port Qasim is calculated as 2.64 and 2.67 billion US dollars. Moqpondass, Mirpur and Rashakai showed highest net present costs. Initial capital and operating costs associated with the hybrid system are also reduced when grid is connected to the system as shown in Table 4-6.

Table 4-6 Costs across all SEZs for on grid system

Location	**LCOH ($/kg)**	**LCOE ($/kWh)**	**NPC (M$)**	**Initial Capital (M$)**	**Operating Cost (M$/year)**
Rashakai	2.3	0.69	2868	947	120
Dhabeji	1.69	0.645	2645	979	104
Faisalabad	2.51	0.716	2870	958	119
Quetta	1.79	0.653	2672	930	109
Islamabad	2.28	0.693	2824	935	118
Port Qasim	1.93	0.67	2671	971	106
Mirpur	2.42	0.705	2857	936	120
FATA	2.16	0.679	2820	943	117
Moqpondass	4.19	0.832	3530	1080	153
Gwadar Port	2.24	0.692	2820	977	115

Table 4-7 H_2, O_2 production and water consumption

Location	**H_2 production (tonne/yr.)**	**O_2 production (tonne/yr.)**	**Water consumption (tonne/yr.)**
Rashakai	21489.8	171918.7	193408.6
Dhabeji	21996.3	175970.6	197967
Faisalabad	21575.5	172604.1	194179.6
Quetta	21906.7	175253.8	197160.5
Islamabad	21582	172656.5	194238.6
Port Qasim	21999.9	175999.4	197999.4
Mirpur	21510.9	172087.2	193598.1
FATA	21605.6	172844.8	194450.4
Moqpondass	20995	167960	188955
Gwadar Port	21815.6	174525.3	196340.9

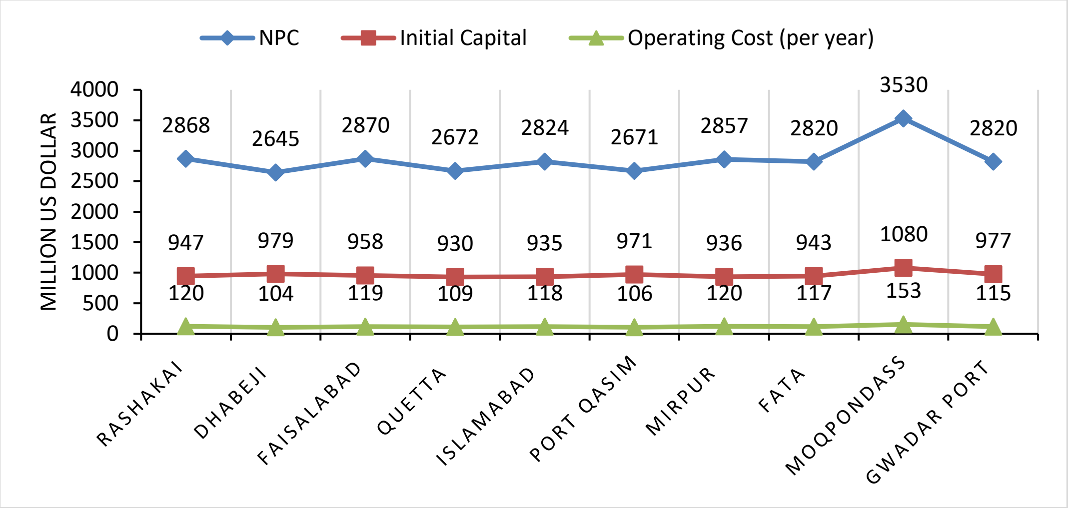


Figure 4-5 NPC, initial and operating costs of on-grid systems

On average approximately, 51 million gallons of water is required for the optimum system at each location. Detailed H_2 and O_2 production across each site along with water consumption is provided in Table 4-7. It is obvious that with large amount of hydrogen production, a significant amount of oxygen is also generated which can be stored in cylinders to utilize it in other industrial processes. Table 4-8shows the share of grid purchases and sales with share of excess electricity. It can be observed that on average only 7% electricity is purchased from the grid and 3% electricity is sold back to the grid in all locations. This small change in renewable energy fraction due to grid purchases significantly reduced the levelized cost of hydrogen. Excess electricity produced by renewable energy sources is sold back to the grid which may offset the initial investment costs and operational expenses, making the production of green hydrogen more economically viable.

Table 4-8 Grid sales and purchases

Location	**Grid purchase (%)**	**Grid sale (%)**	**Excess electricity (%)**
Rashakai	7.13	3.25	18.9
Dhabeji	4.08	2.94	8.44
Faisalabad	7.73	2.5	13.4
Quetta	7.38	2.89	15.6
Islamabad	7.4	2.85	16.1
Port Qasim	5.08	2.35	11.2
Mirpur	7.51	2.73	15.3
FATA	7.14	3.2	18.6
Moqpondass	5.9	3.7	34.6
Gwadar Port	7.46	2.81	15

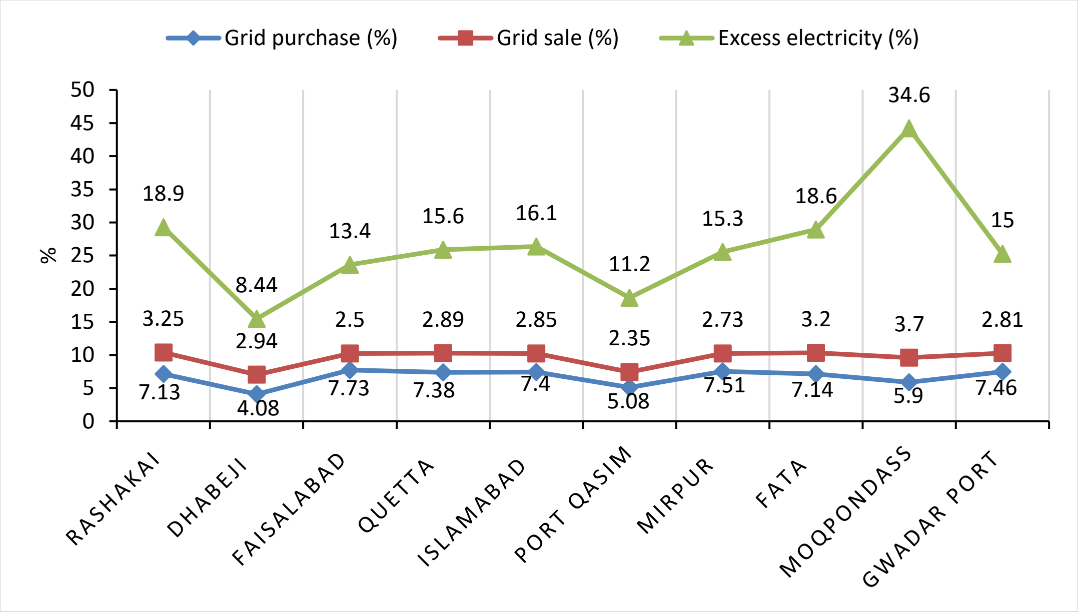


Figure 4-6 Grid purchases and sales vs excess electricity produced

Table 4-9 IRR, Payback period and ROI for on grid system

Location	**IRR (%)**	**Payback Period (years)**	**ROI (%)**
Rashakai	17.3	5.2	20
Dhabeji	27	3.7	25
Faisalabad	23	4.4	19
Quetta	25	4.1	22
Islamabad	19	5.2	15
Port Qasim	23	4.3	20
Mirpur	24	4.1	21
FATA	19	5.2	15
Moqpondass	15	6.5	11
Gwadar Port	23	4.4	19

The payback period is directly influenced by both ROI and IRR as presented in Table 4-9. It can be observed that Dhabeji has the highest ROI, it means it will generally generate higher returns in a shorter period, potentially reducing the payback period which is 3.7 years for Dhabeji. This means the initial investment is recovered faster, making the project more attractive. Conversely, lower ROI extends the payback period as the returns are not substantial enough to quickly recoup the initial investment. A project with a high ROI and IRR typically has a shorter payback period because it generates higher and faster returns as shown in Figure 4-7.

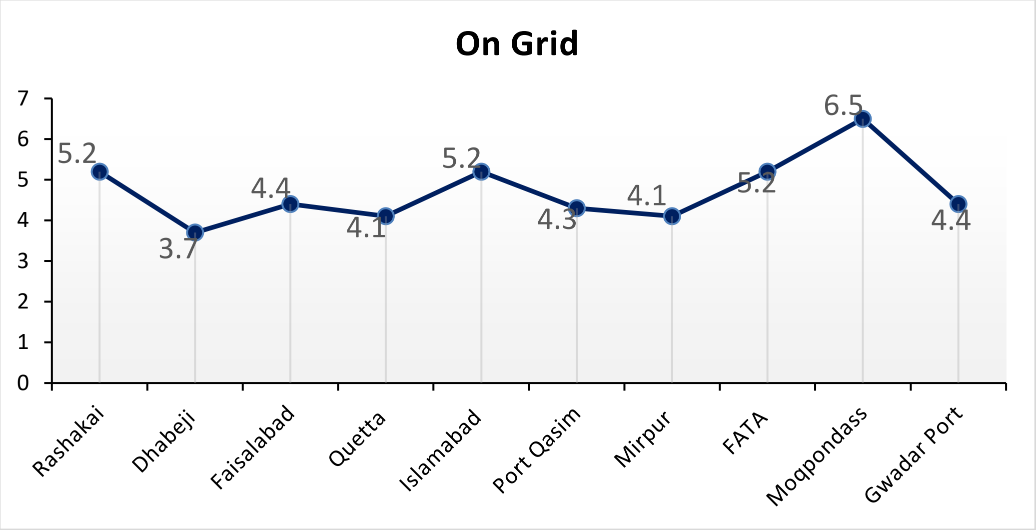


Figure 4-7 Payback Period for on grid system

4.3 Greenhouse gas emissions

Conventional steelmaking processes, such as blast furnace-basic oxygen furnace (BF-BOF), rely heavily on coal and coke, resulting in significant CO_2 emissions. In fact, the steel sector accounts for approximately 7-9% of global CO_2 emissions, making it a critical target for decarbonization efforts [98]. In this study, techno-economic analysis of green hydrogen production for the steel industry has been performed. GHG emissions from H_2 production have only been discussed in this section. The renewable energy fraction (RF) was 100% in the case of off grid systems, it means that off grid systems are clean energy systems with zero greenhouse gas emissions.

Table 4-10 RF (%) and greenhouse gas emissions

Location	**RF (%)**	**Solar (%)**	**Wind (%)**	**CO_2 Emissions (tonne /year)**
Rashakai	57.2	92.9	0	40,255
Dhabeji	77.7	78.9	17	16,126
Faisalabad	55.1	92.3	0	40,938
Quetta	56.2	92.6	0	40,710
Islamabad	56.2	92.6	0	40,435
Port Qasim	70.7	86.5	8.39	26,067
Mirpur	55.9	92.5	0	40,569
FATA	57	92.9	0	40,377
Moqpondass	57.5	94.1	0	41,018
Gwadar Port	56	92.5	0	40,721

Whereas addition of the national grid into the system brings certain GHG emissions such as CO_2 (350 g/kWh), SO_2 (2.74 g/kWh) and NO_x (1.34 g/kWh). Due to these emissions, renewable energy fraction of the energy system reduced to around 55% to 78%. Therefore, grid connected systems do not produce 100% clean and green hydrogen. By increasing the share of renewable energy sources in grid electricity can also reduce GHG emissions. CO_2 emissions for on grid system at each special economic zone are presented in Table 4-10. It can be observed that Dhabeji has the lowest CO_2 emissions because of the high RF of 77.7% with lowest share of grid electricity purchased also shown in Figure 4-8. To achieve zero carbon emission targets, 100% RES are preferred for green hydrogen production.

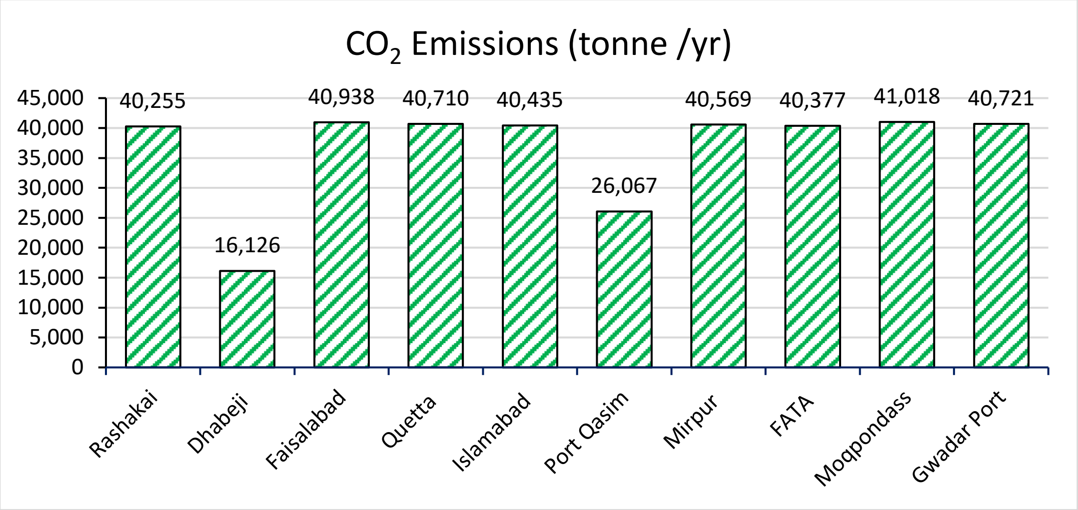


Figure 4-8 CO_2 emissions during grid connected system

4.4 Comparative analysis

The study on optimizing energy systems for both off-grid and on-grid settings across ten different locations highlighted variations in electricity and hydrogen generation based on available resources. Regions with high wind speeds and solar radiation tended to produce more renewable electricity. Feasibility assessments at each location considered technical and economic factors such as LCOH, COE, NPC, IRR, and payback period. A comparison between on-grid and off-grid scenarios has been made based on technical and economical parameters. Figure 4-9 shows the hydrogen production in both case scenarios, which reveals that except Rashakai and Moqpondass SEZs, more hydrogen is produced in all SEZs with an on-grid case scenario as compared to off grid case scenario. Dhabeji, Quetta, Port Qasim and Gwadar Sea port authority produced maximum amount of green hydrogen. Moqpondass could not meet the hydrogen load demand.

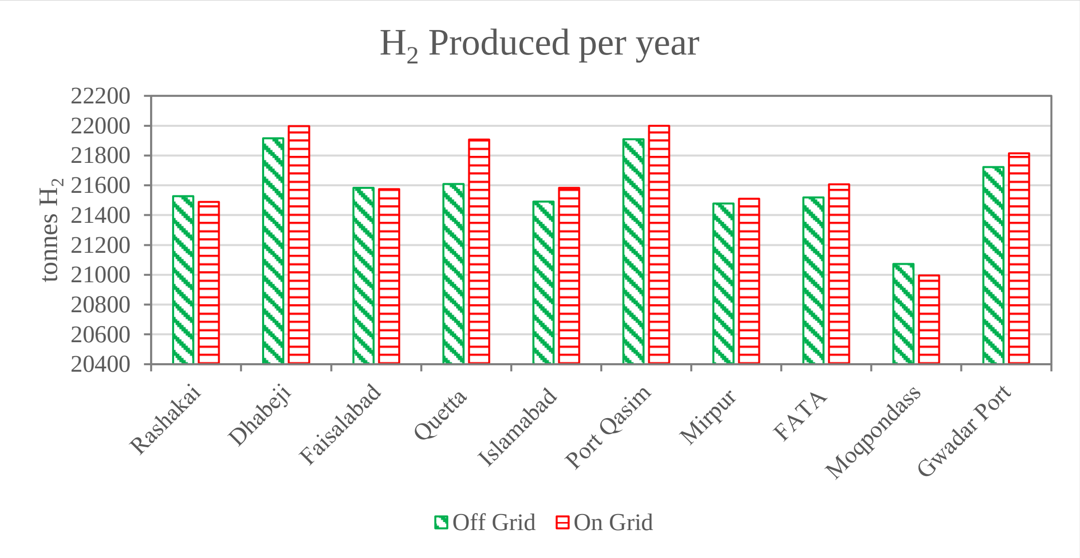


Figure 4-9 H$_2$ production in on and off grid systems across each SEZ

It revealed that Rashakai, FATA, and Moqpondass showed poor feasibility in both scenarios, while Faisalabad, Islamabad, and Mirpur exhibited average feasibility. Conversely, Dhabeji, Port Qasim, Quetta, and Gwadar displayed promising potential for hydrogen production. Despite the substantial initial investment required for green hydrogen production, the payback period typically ranged from 3 to 6 years. Additionally, on-grid systems generally exhibited lower LCOH and LCOE compared to off-grid systems.

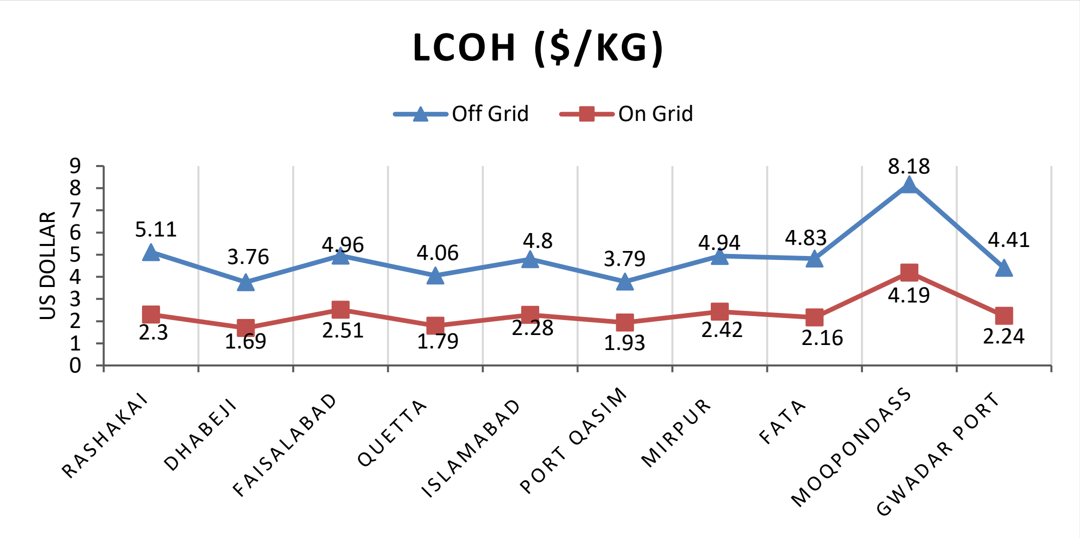


Figure 4-10 LCOH for on and off grid systems

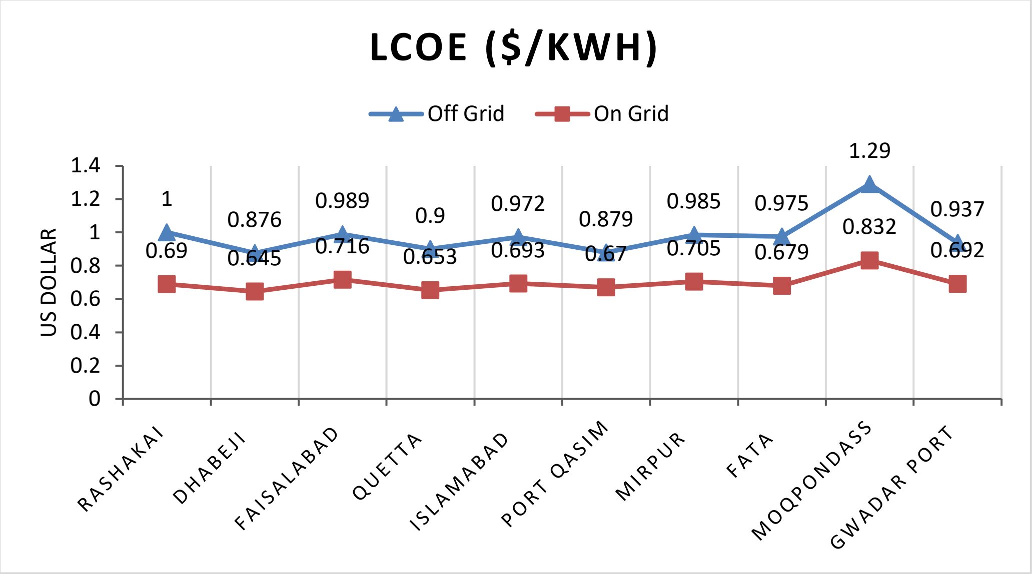


Figure 4-11 LCOE for on grid and off grid systems

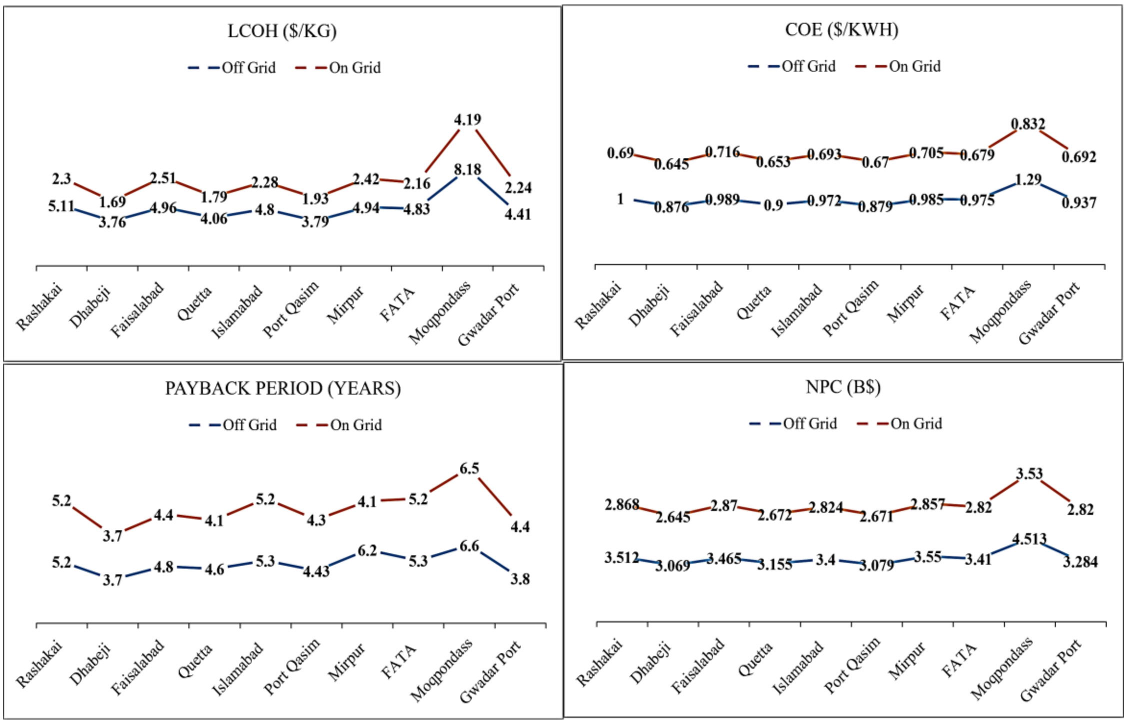


Figure 4-12 Comparison of grid connected and off grid results

4.5 Sensitivity analysis

To assess the impact of key factors on hydrogen production costs, a sensitivity analysis was conducted. The parameters under scrutiny include the discount rate, Electrolyzer efficiency, PV panel derating factor, hub height, and grid sales. These parameters were systematically varied to evaluate the resilience of the optimal system configuration across different locations. Analysis using HOMER Pro highlighted the significant influence of Electrolyzer efficiency on LCOH, primarily due to its direct correlation with the required PV panel capacity. The base value for **discount rate** was 10%, when it was increased to 15%, we can observe from the graphs in Figure 4-14 and Figure 4-13 that it has a significant impact on the LCOH, as it directly influences the present value of future costs associated with hydrogen production. A higher discount rate increases the LCOH, making hydrogen production more expensive, while a lower discount rate reduces the LCOH, making it more cost-effective.

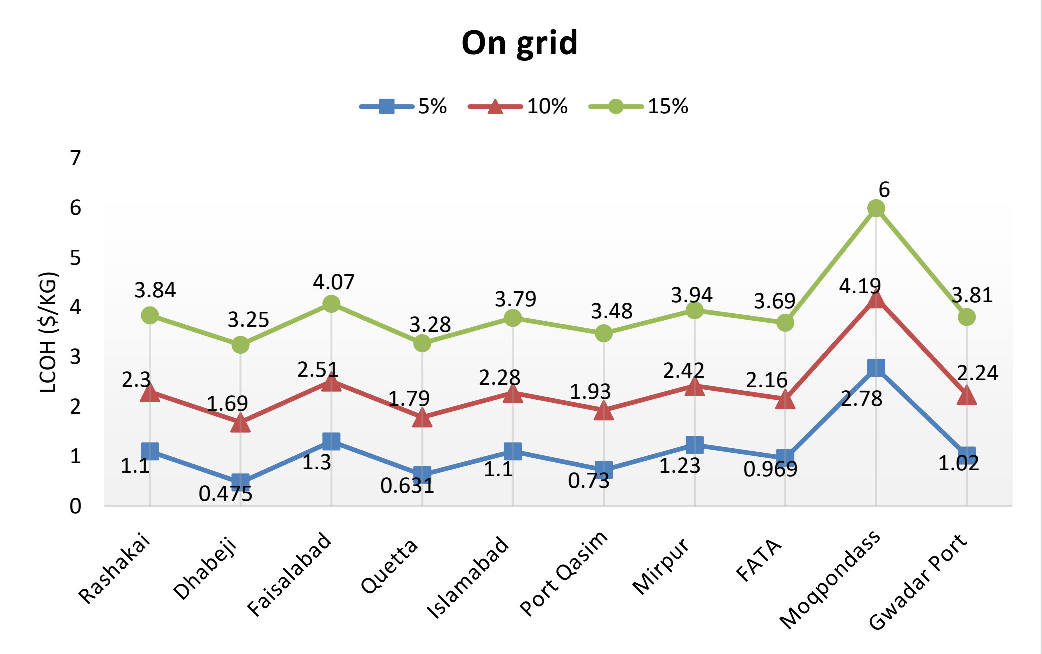


Figure 4-13 Discount Rate vs LCOH for on grid

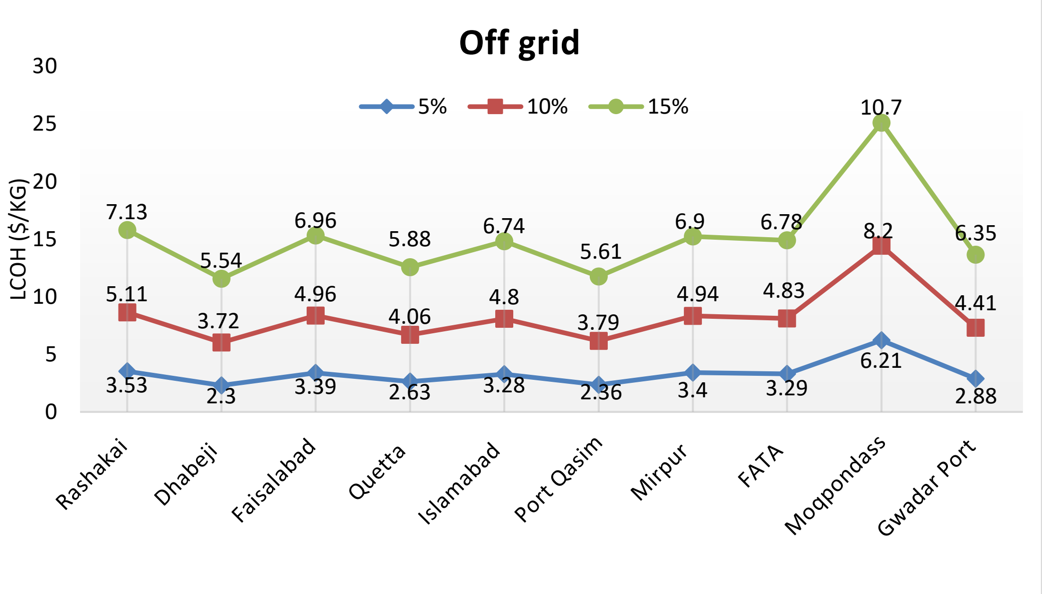


Figure 4-14 Discount Rate vs LCOH for off grid

The base value of **Electrolyzer efficiency** was 85%, when it was decreased to 75%, LCOH significantly increased due to high-capacity factor of Electrolyzer. For grid connected systems, LCOH increased from 1.69 to 3.85 $/kg for Dhabeji and 1.93 to 3.27 $/kg for Port Qasim as shown in Figure 4-15. For off grid systems LCOH increased to 6.49 for Dhabeji by decreasing the electrolyzer efficiency as shown in Figure 4-16.

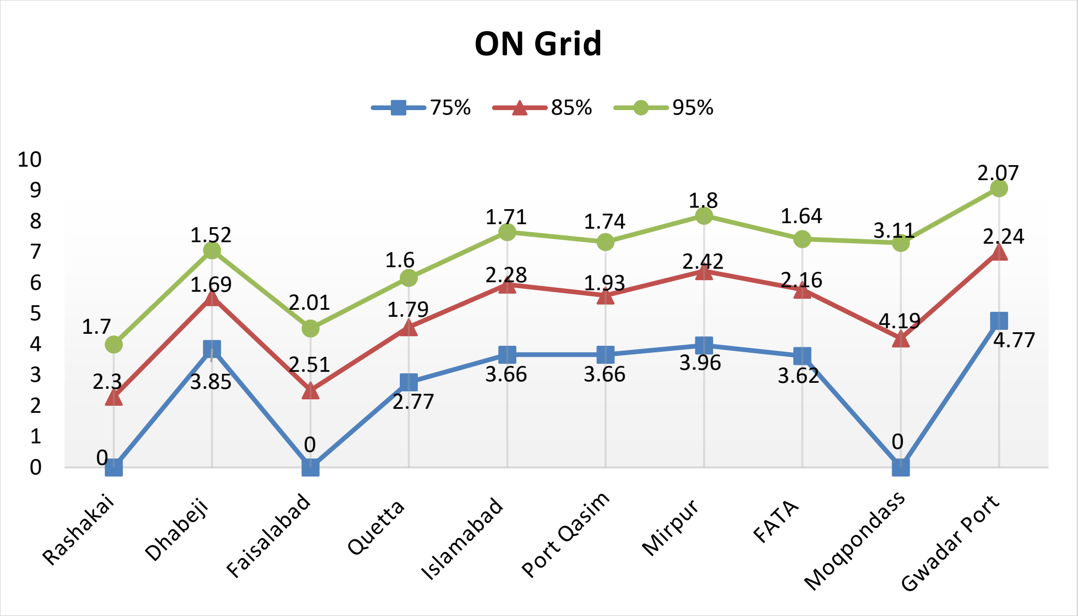


Figure 4-15 Electrolyzer efficiency vs LCOH for on grid

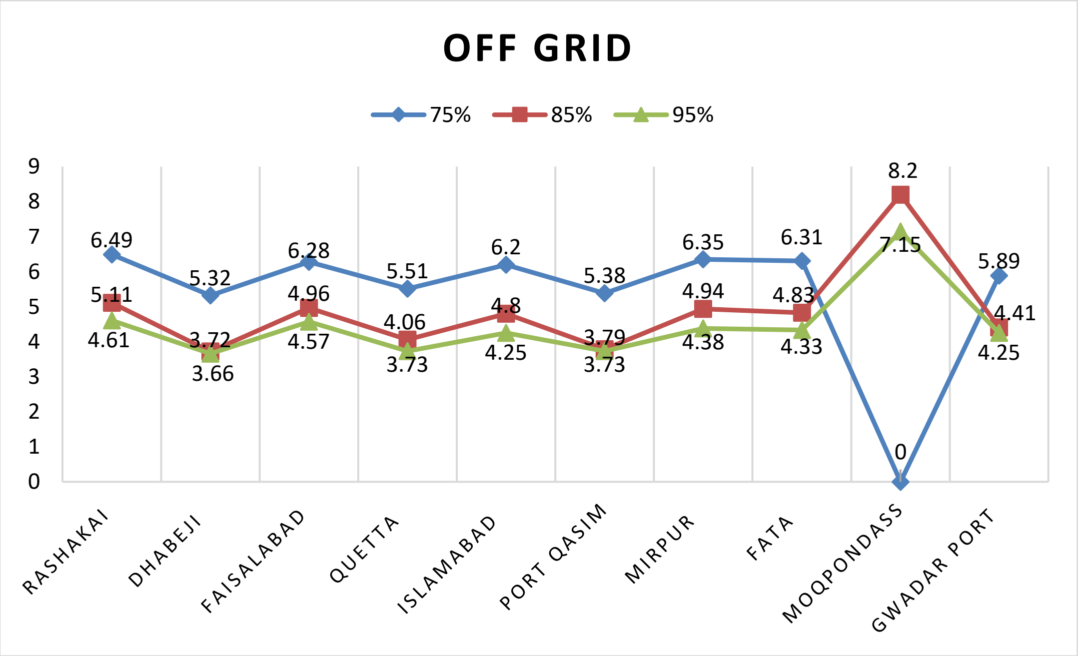


Figure 4-16 Electrolyzer efficiency vs LCOH for off grid system

The impact of **PV derating factor** on LCOH was also checked for both on and off grid systems at each location as shown in Figure 4-17 and Figure 4-18. As PV derating factor reduced, the cost of hydrogen increased because of higher required size of solar panels to meet the load demand.

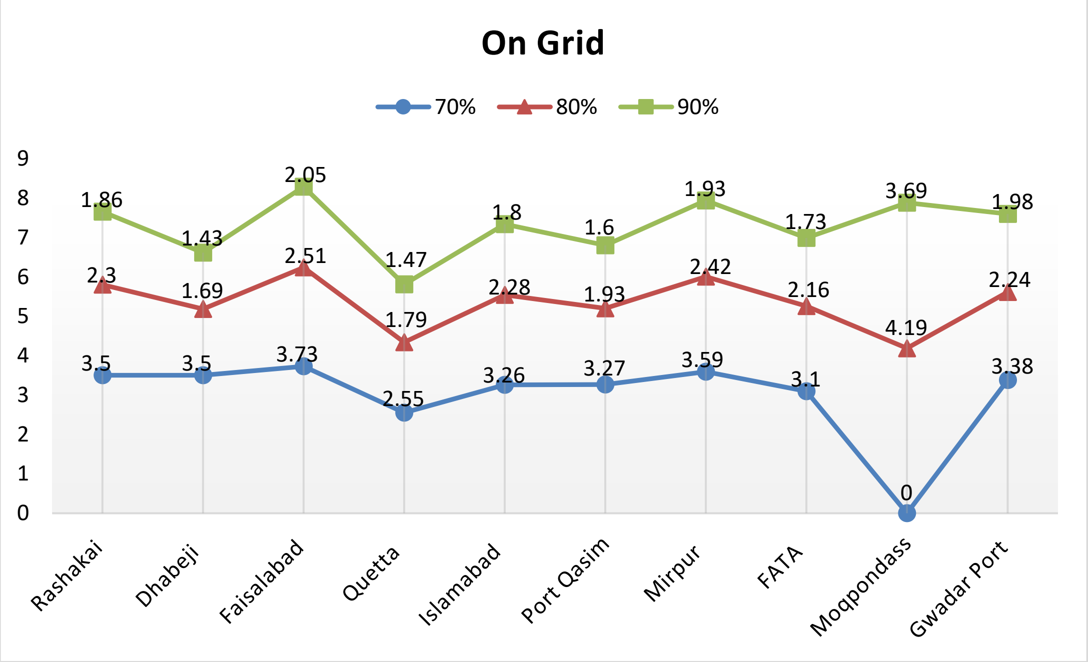


Figure 4-17 PV derating factor vs LCOH for on grid system

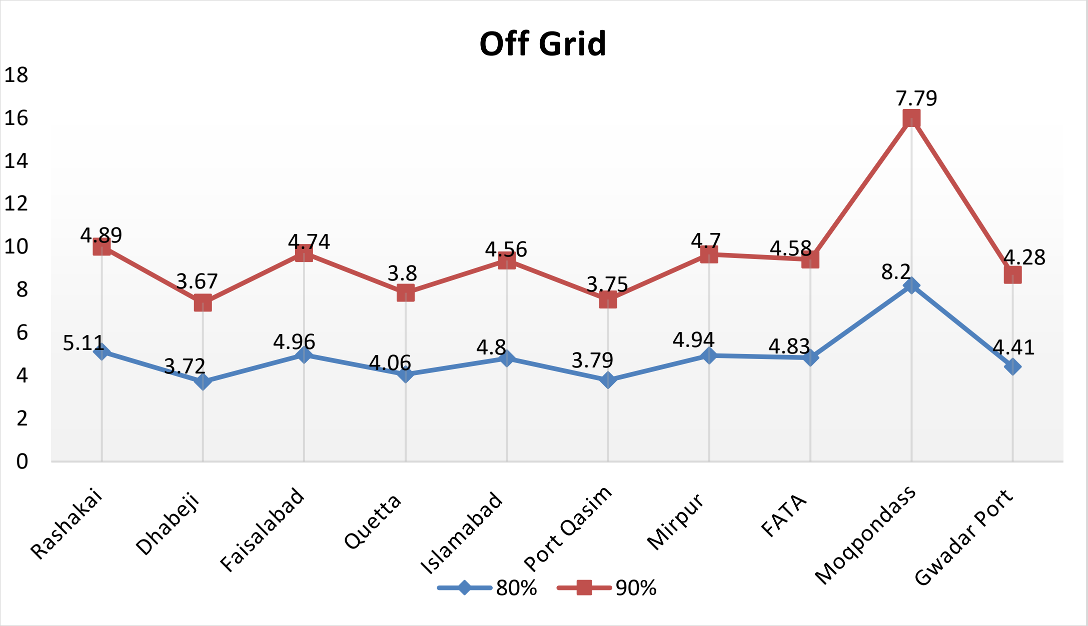


Figure 4-18 PV derating factor vs LCOH for off grid system

The **sales of electricity to the grid** can also impact the cost of hydrogen production as shown in Figure 4-19. When there are no grid sales, LCOH is higher as compared to when 20MW electricity is sold back to the national grid.

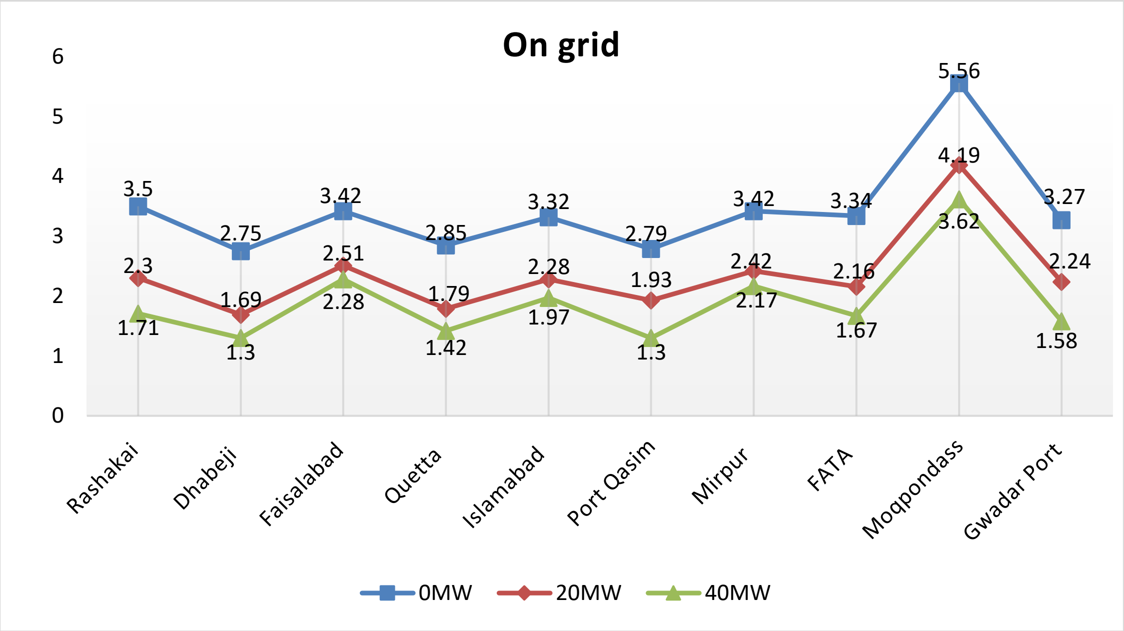


Figure 4-19 Grid sales vs LCOH

LCOE and net present cost are also increased due to high operating cost at low efficiency. Whereas in Moqpondass, electrolyzer with low efficiency did not provide feasible results due to capacity shortage and unmet hydrogen load as shown in Table A-1. To operate Electrolyzer at 75% efficiency, Moqpondass require larger PV capacity size of 1.12 GW. Whereas by increasing electrolyzer efficiency to 90%, LCOH decreases from 3.76 $/kg to 3.70 $/kg for Dhabeji and 1.93 to 1.74 $/kg due to low operational hours and operational cost of Electrolyzer. LCOH cost variation against Electrolyzer efficiency on all economic zones is also presented in Table A-1.

Discount rate is a critical factor in a techno economic analysis of a hybrid energy system. However, it might not have significant impact on improving LCOH. When the discount rate is increased from its base value of 10% to 15%, LCOH increased from 1.69 to 3.25 $/kg for Dhabeji and 1.93 to 3.48 $/kg for Port Qasim, and when it is decreased to 5%, LCOH reduced to 0.475 $/kg and 0.73 $/kg respectively. PV derating factor (DF) is also a crucial factor that scales the output power of PV array. When DF is increased from 80% to 90%, output power of solar panels increases which increases the capacity factor of PV panels. This reduces the cost of hydrogen production from 1.69 to 1.43 $/kg for Dhabeji and 1.93 to 1.6 $/kg for Port Qasim. When DF decreased to 70%, LCOH significantly increased to 3.5 $/kg and 3.27 $/kg for Dhabeji and Port Qasim respectively. Hub height impact on LCOH was checked only in Dhabeji and port Qasim because they have shown optimal results based on wind and solar. By increasing hub height from 80 m to 100 m, it has been observed that LCOH reduced to 1.59 $/kg for Dhabeji and 1.9 $/kg for Port Qasim. Whereas, at a low hub height of 60 m, the system did not provide results due to capacity shortage. To run the wind turbines at this hub height, more wind turbines will be required to generate the required amount of electricity. In grid connected scenario, selling excess electricity back to the grid also plays an important role in determining LCOH. LCOH is increased to 2.75 $/kg for Dhabeji and 2.79 $/kg for Port Qasim when there are zero grid sales. By selling 40 MW electricity to the national grid, LCOH value reduced to 1.3 $/kg for both zones.

In off grid systems, the LCOH variation trend is almost similar to the grid connected systems as shown in Table A-2. The LCOH varies between 3 to 6 $/kg in Dhabeji and Port Qasim when sensitivity parameters are changed. Despite their high LCOH, off grid systems produce carbon free hydrogen. Areas with high renewable energy potential are good locations to produce carbon free green hydrogen to achieve carbon neutrality and net zero emission targets.

Summary

This chapter provides a comprehensive presentation of the HOMER Pro simulation results for both on-grid and off-grid systems deployed across ten special economic zones within Pakistan. The analysis includes a detailed examination of technical and economic parameters to facilitate a comparative assessment between on-grid and off-grid configurations. Through this comparative analysis, the chapter aims to offer insights into the performance and viability of these systems within the context of Pakistan's special economic zones, thereby informing decision-making processes regarding energy infrastructure development and deployment strategies.

CHAPTER 5

Conclusion and Future Recommendations

This paper investigated green hydrogen production feasibility along CPEC special economic zones in Pakistan. A technical and economic analysis has been performed using HOMER pro software by assuming two different scenarios off grid and on grid. CPEC has a strong potential to contribute to green hydrogen production projects in Pakistan. Leveraging grid electricity price, hourly solar radiation, and wind speed at ten locations, this study analyzes the cost factors and sensitive parameters involved in green hydrogen production. The study results show that LCOH varies across different locations based on technical and economic parameters.

- For off grid systems, results reveal that LCOH varies from 3.76 $/kg to 8.18 $/kg and these results align with the study results of [54], [99]. LCOE ranged from 0.876 $/kWh to 1.29 $/kWh. Dhabeji, Port Qasim, Gwadar, and Quetta have good potential for green hydrogen production due to their location factors. Faisalabad, Islamabad, and Mirpur economic zones show average feasibility. Moqpondass, FATA and Rashakai show poor feasibility because of higher LCOH and high payback period for green hydrogen production system.
- For grid connected systems, location factor trend is same as standalone systems with lower hydrogen production costs and costs of energy. LCOH for on grid systems varies across locations from 1.69 $/kg to 4.19 $/kg whereas COE varies from 0.645 $/kWh to 0.832 $/kWh. Dhabeji and Port Qasim are the most feasible sites for hydrogen production in Pakistan. The results can be validated with the results of [69], [100].
- Sensitivity analysis shows that electrolyzer efficiency has a significant impact on the cost of hydrogen production. By increasing electrolyzer efficiency, LCOH can be greatly reduced. Other sensitive parameters that influence green hydrogen production cost are discount rate and PV derating factor.

- As wind is an intermittent source of energy and solar energy is also weather dependent, therefore hydrogen storage needs great attention for a sensible LCOH. Hydrogen storage tanks also add significant cost to the initial capital cost. In this study, Li-ion batteries were used to stabilize and store electricity. Further research can be carried out in hydrogen storage and transport, as it is also a great area of research that is untouched in Pakistan.

Grid connected systems are a promising option to reduce the cost of hydrogen production through renewable energy sources. For areas with low solar radiation or wind speed, grid connectivity is a sensible option to achieve the targeted LCOH. In areas with high solar radiation or wind speed such as Dhabeji, port Qasim and Gwadar, grid connected systems are better than off grid systems because there is a great opportunity to sell excess electricity produced at these locations to the national grid. This is the best-case scenario for producing more renewable electricity and cheap green hydrogen. Purchasing electricity from a grid that is nonrenewable can be offset by selling back the excess electricity to the grid. Future directions of this study are to work on hydrogen storage and delivery options in Pakistan. The study can also be enhanced by integrating hydropower at the optimum locations for green hydrogen production as this is also a renewable energy source.

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APPENDIX A. SENSITIVITY ANALYSIS

A.1 ON GRID SENSITIVITY RESULTS

Table A-1 On grid sensitivity results

ON Grid	Discount Rate (%)			PV Derating Factor (%)			Electrolyzer Efficiency (%)			Grid sales (MW)			Hub Height (m)		
	5	**10**	**15**	**70**	**80**	**90**	**75**	**85**	**95**	**0**	**20**	**40**	**60**	**80**	**100**
Rashakai	1.1	2.3	3.84	3.5	2.3	1.86	inf*	2.3	1.7	3.5	2.3	1.71			
Dhabeji	0.47	1.69	3.25	3.5	1.69	1.43	3.85	1.69	1.52	2.75	1.69	1.3	inf*	1.69	1.59
Faisalabad	1.3	2.51	4.07	3.73	2.51	2.05	inf*	2.51	2.01	3.42	2.51	2.28			
Quetta	0.63	1.79	3.28	2.55	1.79	1.47	2.77	1.79	1.6	2.85	1.79	1.42			
Islamabad	1.1	2.28	3.79	3.26	2.28	1.8	3.66	2.28	1.71	3.32	2.28	1.97			
Port Qasim	0.73	1.93	3.48	3.27	1.93	1.6	3.66	1.93	1.74	2.79	1.93	1.3	inf*	1.93	1.9
Mirpur	1.23	2.42	3.94	3.59	2.42	1.93	3.96	2.42	1.8	3.42	2.42	2.17			
FATA	0.96	2.16	3.69	3.1	2.16	1.73	3.62	2.16	1.64	3.34	2.16	1.67			
Moqpondass	2.78	4.19	6	inf*	4.19	3.69	inf*	4.19	3.11	5.56	4.19	3.62			
Gwadar Port	1.02	2.24	3.81	3.38	2.24	1.98	4.77	2.24	2.07	3.27	2.24	1.58			

A.2 OFF GRID SENSITIVITY RESULTS

Table A-2 Off grid sensitivity results

Off Grid	**Discount Rate (%)**		**PV Derating Factor (%)**			**Electrolyzer Efficiency (%)**				**Hub Height (m)**		
	5	**10**	**15**	**70**	**80**	**90**	**75**	**85**	**95**	**60**	**80**	**100**
Rashakai	3.53	5.11	7.13	inf*	5.11	4.89	6.49	5.11	4.61			
Dhabeji	2.3	3.72	5.54	4.5	3.72	3.67	5.32	3.72	3.66	3.76	3.72	3.66
Faisalabad	3.39	4.96	6.96	inf*	4.96	4.74	6.28	4.96	4.57			
Quetta	2.63	4.06	5.88	inf*	4.06	3.8	5.51	4.06	3.73			
Islamabad	3.28	4.8	6.74	inf*	4.8	4.56	6.2	4.8	4.25			
Port Qasim	2.36	3.79	5.61	4.35	3.79	3.75	5.38	3.79	3.73	3.8	3.79	3.78
Mirpur	3.4	4.94	6.9	inf*	4.94	4.7	6.35	4.94	4.38			
FATA	3.29	4.83	6.78	inf*	4.83	4.58	6.31	4.83	4.33			
Moqpondass	6.21	8.2	10.7	inf*	8.2	7.79	inf*	8.2	7.15			
Gwadar Port	2.88	4.41	6.35	inf*	4.41	4.28	5.89	4.41	4.25	inf*	4.41	4.25

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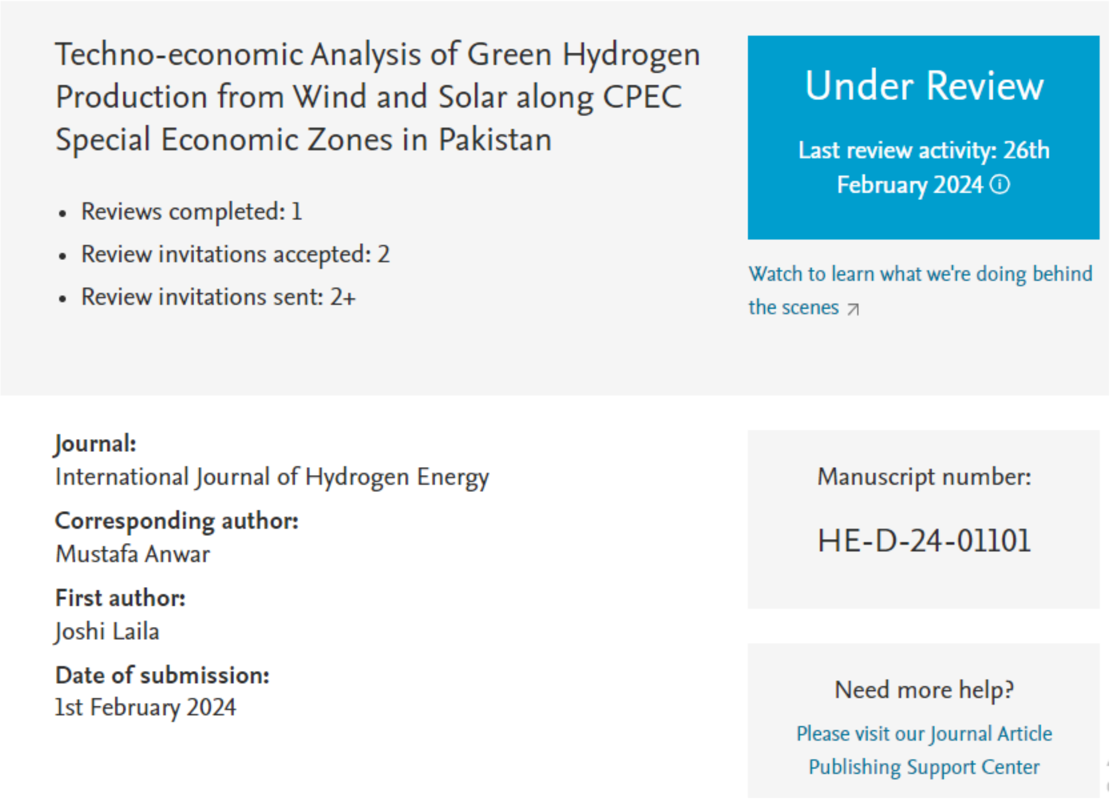

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