ENERGY AND CLIMATE
PANORAMA

GREEN HYDROGEN

As a Fuel in the Energy Transition of Pakistan, Toward a Zero-Carbon, Climate-Resilient Future

ABOUT US

Who we are

We are a dedicated team of researchers and experts who recognize the urgent need for action in addressing climate resilience and energy transition in Pakistan. Our mission is to develop and implement effective policies for cleaner, renewable energy sources like solar and wind, aligning with Pakistan's 2030 goal of 30% renewable energy in its electricity mix. As a multidisciplinary team, we leverage expertise in three key disciplines of study—Energy Systems Engineering, Thermal Energy Engineering, and Electrical Power Engineering—to drive our mission forward. We are united by a shared vision of creating a sustainable and resilient future for Pakistan, where cleaner energy sources play a pivotal role in reducing the nation's vulnerability to climate-related challenges.

What we do

We conduct in-depth, evidence-based research to analyze and improve energy policies in Pakistan. Our focus is on advancing renewable energy solutions and engaging stakeholders to ensure effective policy implementation. Our methodology involves a critical examination of current energy policies to pinpoint areas of improvement and formulate strategies for the widespread adoption of renewable energy sources across various levels.

In line with our commitment to fostering sustainable practices, we have established a fellowship program as part of our broader initiatives that aims to facilitate evidence-based research for promoting energy transition in Pakistan. Through research studies, surveys, and forecasting, we plan to assess various aspects of energy transition, including the adoption of renewable energy technologies and their impact on climate change. Our approach involves active engagement with stakeholders to address their concerns and facilitate the effective implementation of policies, fostering the growth of renewable energy manufacturing and marketing facilities.

CONTACT US

Industry Liaison & Outreach Office

Bilal Mehmood Bhutta
Phone: +92-51-90855274
Fax: +92-51-90851302
Email: ilo@uspcase.nust.edu.pk
USPCAS-E Building, National University of Sciences & Technology, H-12, Islamabad.

Primary Contributors

DR. NASEEM IQBAL
PRINCIPAL INVERSTIGATOR
Professor

DR. MUSTAFA ANWAR
CO-PRINCIPAL INVERSTIGATOR
Assistant Professor

JOSHI LAILA
RESEARCH ASSISTANT
MS in Energy Systems Engineering

Layout Design

SAAD NADEEM
RESEARCH ASSISTANT
MS in Energy Systems Engineering

SANA MEHMOOD
RESEARCH ASSISTANT
MS in Energy Systems Engineering

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Executive Summary

Hydrogen being an energy vector is increasingly becoming a crucial element in the decarbonization of hard-to-abate sectors. Heavy industry sectors include iron and steel, cement, fertilizer production, oil refineries that are carbon intensive and emit large amount of CO2 emissions. To meet paris agreement goal of 1.5 C, it is the need of hour to decrabonize heavy industry sector by introducing zero carbon initiatves. Decarbonizing industrial processes using green hydrogen is very promising and challenging. Pakistan is currently facing challenges with economic growth and energy security. As pakistan is blessed with great potential of wind and solar energy due to its geographical location, which makes pakistan a best candidate for implementing green hydrgen projects. Hydrogen generated through water electrolysis using renewable energy sources is the best proposed solution for decarbonizing industrial processes such as steel production, as considered in this case study. In this process hydrogen is used as a reducing agent that helps to reduce iron ore which is further converted into green steel with the help of electric arc furnace (EAF). This study performed a techno-economical analysis for hydrogen production from wind and solar using Hybrid Optimization of Multiple Energy Resources (HOMER) Pro optimisation software. The study compared off-grid and on-grid hybrid system based on net present cost (NPC), levelized cost of energy and hydrogen. Results depicted that on-grid hybrid system is more feasible as compared to off-grid system. A qualitative analysis was performed through a survey questionnaire that help us to determine social significance of green hydrogen as a fuel in Pakistan. The study outcomes and future recommendations are provided at the end of this study. This study will help policy makers and researcher community to develop an understanding of the green hydrogen technology and make new standarized policy regulations.

1. Introduction

Pakistan is a developing country and is facing serious energy and economic crisis. COVID'19 and devastating floods in 2022 heavily impacted Pakistan's economic growth. Pakistan is one of the most vulnerable countries to face the impacts of climate change, although contributing only 0.9% share in global greenhouse gas (GHG) emissions [1]. In line with the revised 2021 Nationally Determined Contributions (NDCs), the Pakistani government is dedicated to significantly reducing greenhouse gas emissions. This commitment aims to curtail the temperature rise within the range of 1.5˚C to 2˚C as outlined in the Paris Agreement. The primary objective of Alternative and Renewable Energy Policy (ARE) 2019 is to produce 60% of energy from renewable energy resources including hydropower by the year 2030 [2]. Energy sector is of high importance in terms of socio-economic growth of a developing country like Pakistan. Relying solely on existing energy infrastructure and sources like fossil fuels (natural gas, coal and petroleum oil) for power generation, transportation, and industrial processes may lead to several challenges such as increased load shedding, natural gas shortage, aging infrastructure, high-cost fuel for power generation, high prices of electricity, energy insecurity, grid instability and GHG emissions. Pakistan's total energy consumption is 84,034 GWh, according to the Pakistan Economic Survey 2022-2023.

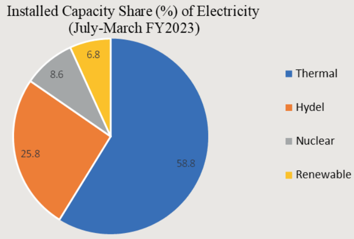


Figure 1. Share of Installed capacity in Pakistan Energy Mix

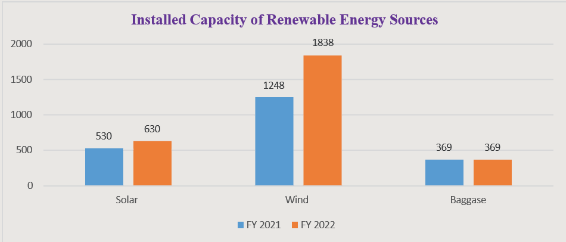


Figure 2. Installed Capacity of Renewable Energy Sources

Figure 3. Power Supply Demand Trend of Pakistan

The industrial sector of Pakistan is the 2nd largest energy consumer with a share of 28.2%. The total installed capacity of electricity is 41,000 MW, out of which renewables have a share of 6.8% only (figure 1)[3]. The installed capacity of renewable energy in Pakistan is 2837 MW. Bifurcation of Renewables for FY 2020-21 and FY 2021-22 is given in figure 2[4]. Power demand growth is increasing 8% to 10% annually that is higher than annual supply growth of 7% (figure 3)[5]. This gap in supply and demand indicates that the current indigenous energy sources are unable to meet the continuously rising electricity demand.

The world is steadfastly exploring pathways toward sustainable, carbon-neutral energy sources capable of fueling their economies without aggravating environmental crises. Industrial decarbonization is one critical step in mitigating climate change and transitioning to a more sustainable and low-carbon economy. The industrial sector is a significant contributor to the GHG emissions due to its energy intensive operations and use of fossil fuels. However, achieving the decarbonization of the global economy is unlikely to occur without significant technological advancements. These advancements need to address both the energy supply aspect, which involves the widespread deployment of renewables on a large scale, and a shift in end-use towards low-carbon energy sources. While electrification plays a central role in this transition, it may not be sufficient to decarbonize challenging sectors. Clean hydrogen could be a critical component of decarbonization, assisting in overcoming the limits of electrification to decarbonize sectors such as industry or heavy-duty transport.

Figure 4: Heavy Industry Carbon Dioxide Emissions

Decarbonization of difficult-to-abate sectors that are highly energy intensive is a far more challenging problem than decarbonization of sectors where merely the use of renewable energy sources is sufficient. These are the industries that contribute around 30% of CO2 emissions from all sectors[6]. Heavy industries such as cement, iron and steel, chemical production falls into this category because of their complex production process and extremely high temperature requirement. Apart from high temperature limitation, the high cost associated with deploying zero-carbon initiative in developing countries is also very promising. This underscores the urgent need for the formulation of innovative policies and strategies to make these initiatives more economically viable and accessible in these regions.

1.1 Renewable Energy Potential in Pakistan

Pakistan is blessed with great potential of renewable energy resources such as solar, wind, biomass and geothermal due to its geographic location. Baluchistan and Sindh province show the highest feasibility for developing a large infrastructure project of wind and solar[7]. Pakistan has average global solar horizontal irradiance of 5-7 kWh/m2/day and average peak sun hours are 8 to 10 hours per day [8]. Muhammad M. Rafique et al. performed assessment of solar energy potential in Pakistan [9]. A study conducted by National Renewable Energy Laboratory (NREL), USA and USAID estimated that

2900 GW solar energy potential exists in Pakistan[10]. According to world bank study report, by utilizing only 0.071% of the land of Pakistan can fulfill the country's demand[11] Figure 5 shows GHI solar resource map of Pakistan[12].

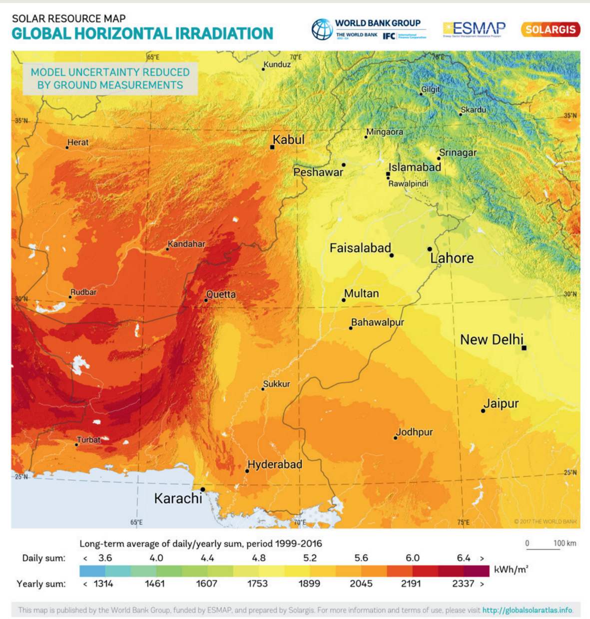


Figure 5. Solar Resource Map of Pakistan

Li Xu et al. showed that levelized cost of electricity for off grid PV system is found to be PKR 6.87/kWh that is cheaper than conventional energy sources [13]. Mazhar H. Baloch et al. findings show that Sindh province is an excellent location to install wind power plants for power generation. This coastal zone shows maximum and minimum wind speed of 13.9 m/s and 5 m/s at the height of 50 meter having maximum capacity factor[14]. Feasibility studies estimated that if 3% of Pakistan land is used for wind power plants then, it can produce 132 GW power with 5 MW installed capacity per km2 [15]. Many researchers have worked on feasibility of wind power generation in different areas of Sindh province [16]-[18]. Shahnawaz Farhan Khahro et al. investigated the wind potential at Gharo, Sindh. He found that average wind speed in summer and winter is 7.63 m/s and 3.61 m/s, respectively. Gharo location was found to be favorable location for wind power generation plants [19]. Figure 6 shows the wind resource map of Pakistan. It can be observed that Sindh coastal area has higher wind speeds at 50m height of wind turbines [20].

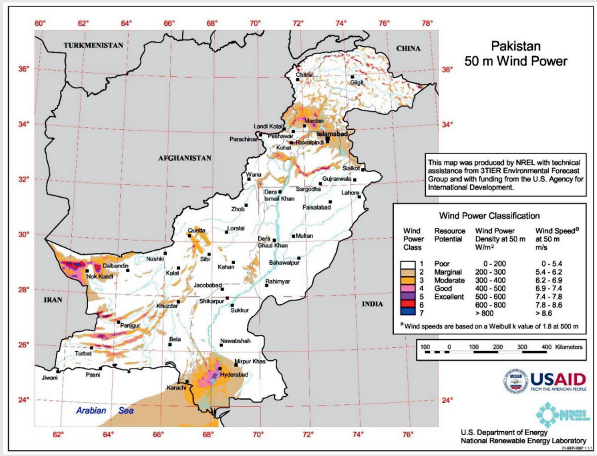


Figure 6. Wind Resource Map of Pakistan

1.2 Green Hydrogen

Hydrogen is an incredibly versatile molecule, and it happens to be the most abundant element in the universe. Energy content in Hydrogen is higher than gasoline as low heat value (LHV) of H2 and gasoline is 120 MJ/kg and 44.5 MJ/kg respectively [21]. Globally, the total hydrogen production stands at approximately 120 million metric tonnes, with a noteworthy observation that a substantial 95% of this hydrogen originates from steam reforming of natural gas and water gas-shift reaction, and the rest of hydrogen is produced from renewable energy sources through water elecrolysis [22][23].

Steam Methane Reforming

$$CH4+H2O \rightarrow CO+3H2\ \Delta H295=-206 kJ/mol$$

Water gas-shift reaction

$$CO+3H2O \rightarrow CO2+H2\ \Delta H298=-41 kJ/mol$$

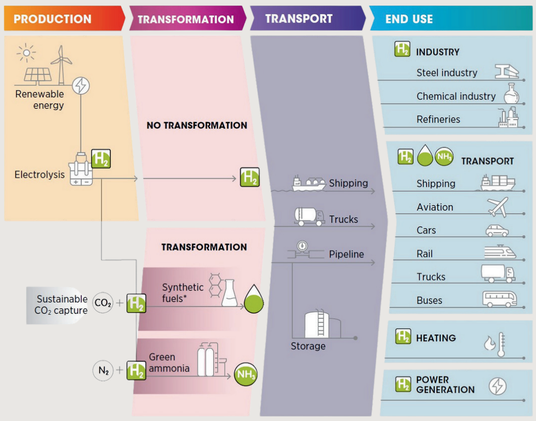


Figure 7. Production, conversion, transportation, and end uses of green hydrogen

Green hydrogen can serve dual roles as both a feedstock and an energy source across a wide range of applications. Hydrogen finds its primary use in industrial processes, encompassing activities like oil refining, iron ore reduction, and the production of ammonia and methanol. Additionally, it plays a crucial role in various other applications, including electricity generation, energy storage, mobility solutions, and heating, serving both industrial and residential needs. Notably, when sourced from clean and sustainable origins, hydrogen has the potential to significantly contribute to overall decarbonization efforts, particularly in those challenging sectors where emissions reduction is complex. In Figure 7, we can observe the various stages in the green hydrogen supply chain, encompassing production, transformation, and its ultimate applications within the energy system[24][25].

Hydrogen is classified into various colors such as grey, blue, and green hydrogen.

Grey Hydrogen is produced using carbon-intensive processes that do not include carbon capture and storage (CCS) or other emissions-reducing technology. Grey hydrogen is typically produced using methods such as natural gas steam methane reforming (SMR) or coal gasification, both of which emit carbon dioxide (CO2) into the environment.

Blue Hydrogen is a type of hydrogen produced through processes such as natural gas or coal gasification combined with carbon capture and storage (CCS) technology. It promises to drastically reduce carbon emissions compared to standard grey hydrogen production methods by including CCS or CCU, making it a more ecologically friendly option.

Green Hydrogen is produced through an electrolysis process in which water is split into hydrogen and oxygen using electricity. What distinguishes green hydrogen is that the electricity used in the process is generated exclusively from renewable energy sources such as wind, solar, geothermal etc. PEM and alkaline electrolyzer are commercially available electrolyzer.

1.3 Water Electrolysis

Electrolyzer require electricity to split water molecules into hydrogen and oxygen. If the electricity supplied to electrolyzer is generated from natural renewable energy sources, then this route is entirely environmentally benign and a zero-carbon emission solution. Basic electrochemical reactions of this process are:

$$Anode: H_2O \rightarrow 1/2\ O_2 + 2H^+ + 2e^-$$

$$Cathode: 2H^+ + 2e^- \rightarrow H_2$$

$$Overall: H_2O \rightarrow H_2 + 1/2\ O_2$$

Hydrogen produced from water electrolysis shows 99.99% high purity as compared to other methods that can be used in many industrial processes as a feedstock and reducing agent[26][27]. Depending on the electrolyte type, separator materials, operating temperature and pressure, electrolyzer are classified into 3 main types: Proton exchange membrane (PEM) electrolyzer, Alkaline water electrolyzer (AWE), Solid oxide electrolyzer (SOEC). PEM and alkaline electrolyzer operate under low temperature (50-80oC) and are widely available for large-scale commercial applications. PEM electrolyzer is more expensive as compared to alkaline electrolyzer but it has some operational advantages. PEM electrolyzer can operate under high pressure, which reduces the amount of Hydrogen compression required for storage and transport. PEM electrolyzer has high current density with small footprint and its efficiency ranges from 67- 82% [28]. A comparison graph between PEM, Alkaline and SOE electrolyzer is shown in figure 6. United States of America (USA) National Renewable Energy Laboratory (NREL) evaluated that PEM electrolyzer is best suitable technology for wind and solar energy conversion into hydrogen [29].

Different capacity size electrolyzer are being commercialized and used in different industries. The largest green hydrogen production initiative is a 150 MW alkaline electrolyzer operationalized by a Chinese chemical manufacturer in late 2021 [30].

In parallel, the largest PEM electrolyzer, boasting a capacity of 20 MW, is situated in Canada [31]. Several leaders in electrolyzer manufacturing such as Cummins Inc., ThyssenKrupp, NEL, ITM Power, and Plug Power Inc. planned to expand electrolyzer capacity size [32].

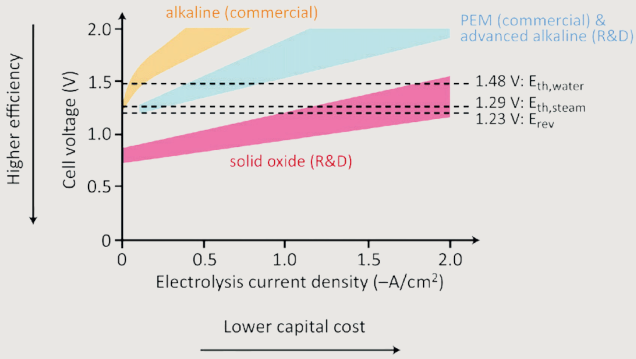


Figure 8. Polarization curves for different water electrolysis cells

Irfan Ahmad Gondal et al. presented the hydrogen economy roadmap for other countries and suggested that Pakistan should also focus on developing hydrogen economy roadmap. Their study estimated the potential of renewable energy sources along with hydrogen production potential [37]. Hydrogen being an energy vector has wide applications in different sectors such as electricity generation, transportation, energy storage systems, fertilizer production, oil refinery, methanol production and as a reducing agent for metal (steel or aluminum) ore processing [38]. Yi He et al. investigated a techno economic feasibility of coal fired power plant decarbonization by retrofitting 100% renewable energy and green hydrogen that is produced by curtailed energy in China [39]. Alessandro Mati et al. investigated the techno-economic feasibility for decarbonization of a paper industry through retrofitting of existing cogeneration system with hydrogen produced from solar energy. The study concluded that with minimal investment traditional cogeneration plants can be retrofitted into a low carbon, net zero emission plant. The optimal system configuration shows € 6.41/kg levelized cost of hydrogen (LCOH) [40].

1.4 Decarbonization of Steel Industry

The steel industry is one of the most energy and carbon intensive industries. The steel making process involves three main stages: raw material preparation (using coal, iron ore, lime, and scrap), ironmaking, and steelmaking. The dominant method for global steel production is the blast furnace and basic oxygen furnace (BF-BOF) process, which uses coke and iron ore in a blast furnace to produce molten iron, followed by the basic oxygen furnace to reduce carbon and create crude steel. This process is energy-intensive, emitting CO2 at an intensity of 2.2 t CO2 per ton of crude steel, with a cost range of $340-$460 per ton of crude steel [41]. An alternative process, the Direct Reduced Iron and Electric Arc Furnace (DRI-EAF) pathway, involves using natural gas or coal to produce directly reduced iron, which is then converted into steel in an electric arc furnace (EAF). This method has an energy intensity of 17 GJ/t crude steel and emits 1.4 t CO2 per ton of crude steel, costing around $400-$600 per ton [42].

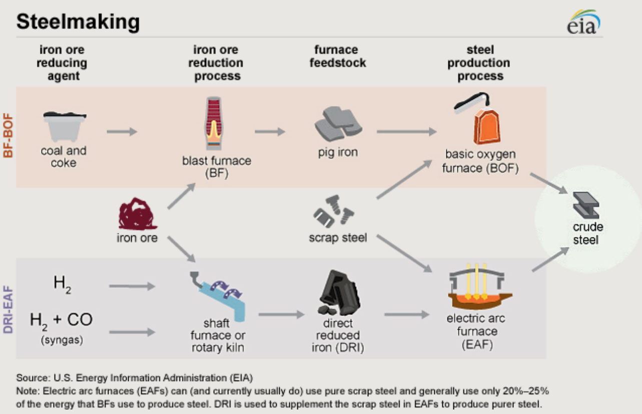


Figure 9. Steel Making Process

The Electric Arc Furnace (EAF) method accounts for 29% of global steel production and utilizes scrap steel, additives, and electricity to melt and produce steel [42]. Emissions from EAF processes vary but average around 0.3 t CO2 per ton of crude steel. This method is more energy-efficient (2-6 GJ/t crude steel) and costs around $340-$490 per ton [41]. After these production processes, further steps like rolling are required to shape the crude steel into the final steel product, with finishing processes tailored to its intended use.

Otto Hebeda et al. presented pathways to decarbonize Brazilian iron and steel industry. Hydrogen assisted direct reduction of iron ore can reduce 88% CO2 emissions from steel sector [43]. Jinsoo Kim et al. presented a comprehensive review on technology innovation and policy barriers related to decarbonizing steel industry [44]. Abhinav Bhaskar et al. presented the technical and economical assessment of a steel plant based on hydrogen in Norway. The levelized cost of steel production was found to vary from $622 to $722/t of steel [45].Anissa Nurdiawati et al. studied the life cycle assessment of iron ore direct reduction process based on bio-syngas. The proposed system climate impact was 70-85% less than conventional process [46].

1.5 Study Scope and Objectives

Different studies have worked on green hydrogen feasibility and determining its potential. In Pakistan, very limited work has been done in this domain. This would be the first study in Pakistan that deals with the technical and economic feasibility of hydrogen production from wind and solar at Gharo, Sindh province Pakistan and produced hydrogen will be fed into iron and steel industry. The scope of this study deals with iron and steel industry decarbonization scenario. Only wind and solar renewable energy sources are used in this work.

The main objectives of this study include:

- Resource estimation of renewables preferably wind and solar for hydrogen production in industrial sector of Pakistan.
- Determine the techno-economic and environmental feasibility of green hydrogen production by renewable energy source for the potential site.
- Determine the social viability for the deployment of the green hydrogen in industry.

1.6 Assumptions and Limitations

Economic constraints that are assumed in this study are discount rate 12%, inflation rate 10%, system's fixed capital cost $10,000, system fixed O&M cost $90/year and 25-year project lifetime. Fixed capital cost and operation and maintenance costs are assumed for electricity transmission from the location where wind and solar plant is installed to the location where electrolyzer and hydrogen storage system is deployed. It is assumed that traditional method of hydrogen production is inefficient and emit hug amount of CO2. Renewable energy sources are reliable and clean source for hydrogen production.

There are some limitations for this study that include limited data availability and some software limitations. Data collection is based on publicly available information sources such as industry reports, journals, and other research publications. Homer software required accurate cost data to accurately measure economic viability of the proposed system. Homer pro software has some limitations such as it has limited library for some components.

2. Methodology

Green hydrogen production feasibility is determined using Hybrid Optimization of Multiple Energy Resources (HOMER) Pro software. This section explains the steps taken to conduct this study. Figure 10 shows the modelling steps for optimization simulation in HOMER Pro.

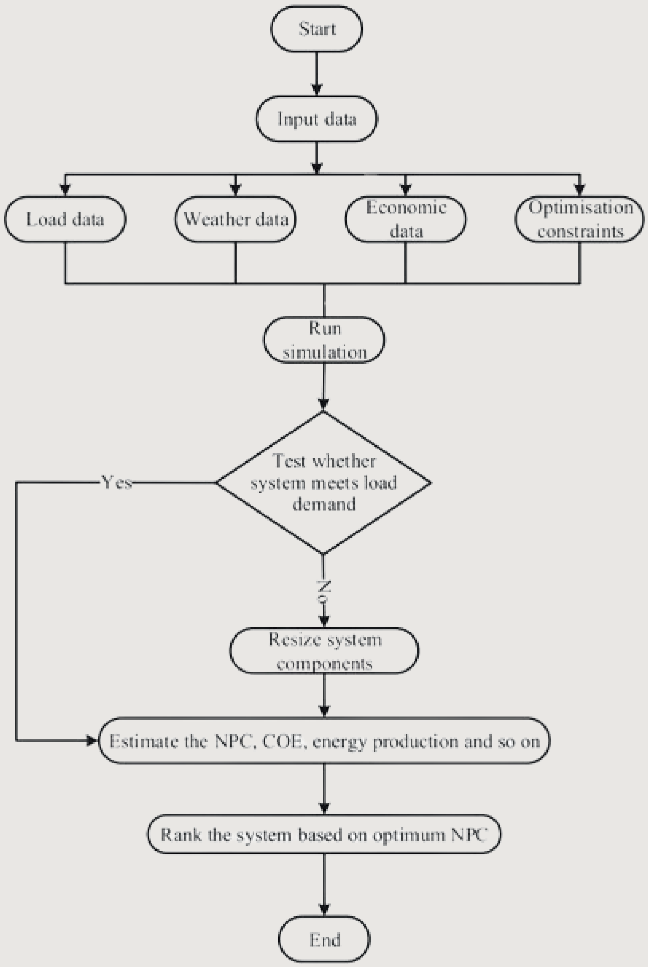


Figure 10. Optimization flowchart of HOMER Pro

2.1 Data Collection

The resource data was collected with the help of market research and literature. The weather data for wind and solar at has been obtained from NASA Prediction of worldwide energy resource (POWER) Database shown in figure 11 and 12. The hydrogen demand was calculated using total steel production capacity of Agha steel mill, Karachi. 51 kg Hydrogen is required to produce one tonne of liquid steel using Electric Arc Furnace (EAF) when burden is only hydrogen - direct reduced iron (H-DRI) with no hydrogen losses considered [47]. Total Hydrogen load demand was calculated as 74000 kg/day and electrical load was taken as 600,000 kWh/day.

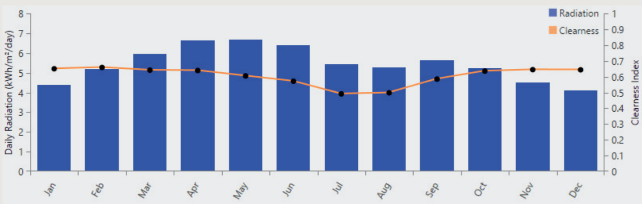


Figure 11. Monthly average solar radiations

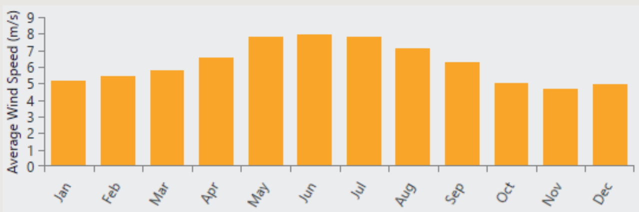
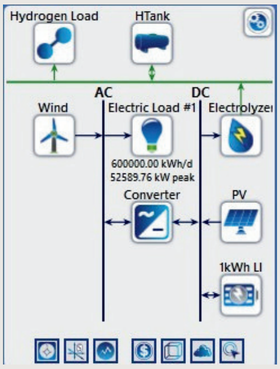


Figure 12. Monthly average wind speed at 50m above the earth surface

2.2 Techno-economic System Model

To model a system for green hydrogen production, inputs are weather and location data, electrical and hydrogen load, capital expenditure (CAPEX) and operating expenditure (OPEX) of different components and external economic constraints. Table 1 shows each component cost used in the system. HOMER Pro software calculates the optimized size of the system components and results optimum system configuration based on lowest net present cost (NPC). HOMER Pro optimizer® uses proprietary derivative-free algorithm to look for the least-cost system. While original grid search algorithm simulates all possible system configurations defined by the user in the search space section. Off-grid and on-grid system configurations are simulated shown in figure 12 and 13, and their comparison was made based on lowest levelized cost of electricity and hydrogen. Sensitivity analysis is performed by varying different parameters to analyze the change in NPC, LCOE and Levelized hydrogen cost (LCOH).



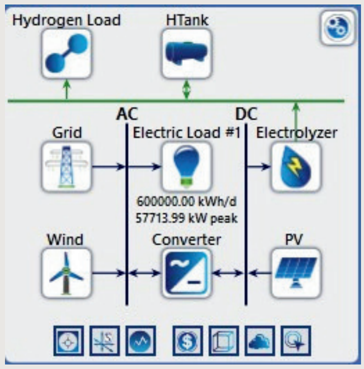


Figure 13 (Left). Off-Grid System and
Figure 14 (Right). On-Grid System

2.3 Social Analysis through Survey

Data for social acceptance of green hydrogen was gathered by survey questionnaire that was designed for researcher community, academia, industry professionals and government officials to get their opinion on development of green hydrogen projects in Pakistan. There are three types of factors, on which based the survey questionnaire assumptions are made: personal, place and project-based factors[48]. Personal factors include demographic factors such as gender, age, education, and occupation.

Table 1. Component Costs

Component	Initial Capital Cost ($)	Replacement Cost ($)	O&M Cost ($/year)	Capacity Size
Generic Wind Turbine	30000	20000	100	1.5 MW
PV Peimar SG325P	400	200	2	1 kW
Converter	200	200	0	1 kW
Generic 1kWh Li-Ion	151	100	1.51	1 kWh
Generic Electrolyzer	450	450	4.5	1 kW
Hydrogen Tank	3000	3000	4	10 kg

It is assumed that men with higher education are more supportive than women. Place based factors include place of residence on which basis we assume that people already living nearby an industry are indifferent and usually do not accept large infrastructure industrial project near their home. While the project-based factors include stakeholders in the project domain. People who are already working on net zero emissions initiatives or projects are more supportive than other.

An online survey questionnaire was circulated among university students, industry professionals and government official in the month of June 2023. Information was gathered pertaining to the widespread acceptance of green hydrogen technology, the approval of protocols and involvement of stakeholders, acceptance of large-scale infrastructure and insights into perspectives and principles concerning environmental and energy matters.

3. Results and Findings

Based on the study assumption and input data in table 1, the simulation was performed on HOMER Pro software. The proposed optimal system can meet high scale electrical load of 600,000 kWh/day as well as hydrogen demand of 74000 kg/day. Electrolyzer stack used in the system has specific energy consumption of 46.4 kWh/kg and rated capacity is 300 MW that can generate 27 million kg hydrogen per year with capacity factor of 47.7%. Hydrogen storage tank is required to store hydrogen. H2 can be stored in the form of Compressed Hydrogen Gas, liquid hydrogen, chemical compound (NH3) storage, metal hydrides, Liquefied Organic Hydrogen Carriers (LOHCs). A total of 100-ton hydrogen storage tank is considered in the simulation. There are two case scenarios: Off-grid and On-Grid hybrid system. The simulation results are based on lowest net present cost of the system.

3.1 Off-Grid Hybrid System

Off grid hybrid system consists of solar panel, wind turbine, converter, Lithium-ion battery, electrolyzer, hydrogen storage tank. Energy analysis simulation shows the optimal off grid configuration with 830 MW solar PV plant and 970 number of wind turbines where each wind turbine capacity size is 1.5 MW with 443 MWh Li-ion battery. While electrolyzer and hydrogen storage tank capacity remained the same. The total net present cost for this configuration is $749 M while cost of energy is $0.172 /kWh. While Initial capital is $653 M and operating cost is $4.82 per year. Cost summary including cost of each component throughout the project lifetime is shown in figure 15. Cash flow over the project lifetime shows that high capital cost is required at the start of project. Other costs component replacement cost, operating cost and salvage cost are shown in the following figure 16.

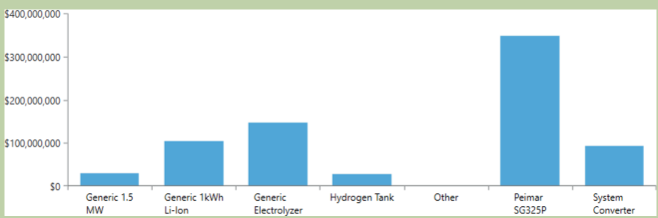


Figure 15. Cost Summary by Component

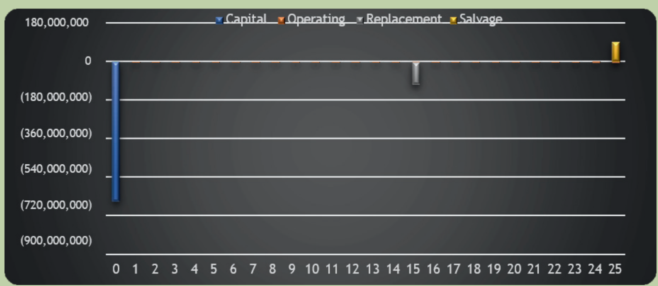


Figure 16. Cash Flow Summary

- **Electrical Output Summary**

To meet the total electrical load of the off-grid system, share of wind and solar electricity production is shown in table 2. Table 3 shows total ac primary load of the system that needs to be addressed by wind and solar. Electrolyzer is a primary load, so major share of electricity consumption is by electrolyzer.

Table 2. Electricity Production Summary

Component	Production (kWh/Year)	Percent (%)
Peimar SG325P	1,986,753,526	37.7
Generic 1.5 MW	3,289,100,736	62.3
Total	5,275,854,262	100

Table 3. Electricity Consumption Summary

Component	Production (kWh/Year)	Percent (%)
AC Primary Load	218,896,603	14.8
Electrolyzer Load	1,255,379,933	85.1
Total	1,474,276,536	100

- **Peimar SG325P Solar:**

To meet the electricity load demands, Homer pro calculated the size of Solar panels to be a total rated capacity of 830 MW that generate 1,986,753,526 kWh/year with a capacity factor of 27.3%. The share of electricity from solar is 37.7% with levelized cost of $0.00878/kWh. The total number of operating hours for solar plant is 4399 hours/year. Figure 17 shows the PV power output for 365 days.

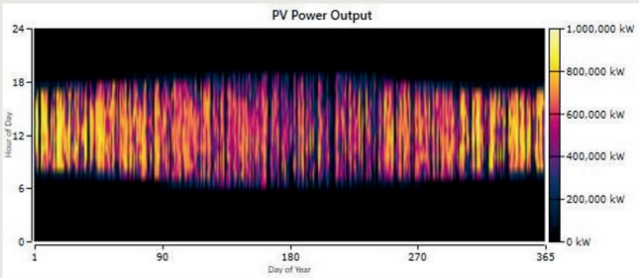


Figure 17. PV Power Output

- **Generic 1.5 MW Wind Turbine**

For the off-grid system configuration, HOMER Pro calculated the total number of wind turbines required are 970, while each turbine is of 1.5 MW capacity. The total rated capacity for wind turbines is calculated to be 1455 MW. The mean output of the wind farm is 375 MW and total annual energy production (AEP) is 3,289,100,736 kWh/year. The wind farm operating hours are 6220 hours per year. Its capacity factor is 25.8% and levelized energy cost is $0.000442 /kWh. Figure 18 shows yearly wind energy production.

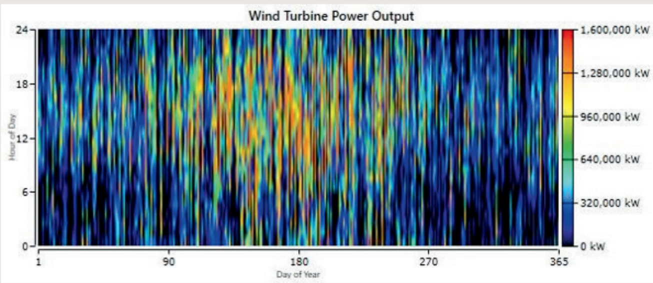


Figure 18. Wind Power Output

- **Battery Pack**

To provide auxiliary electricity supply to the system, lithium-ion batteries are also added in the system. HOMER pro calculated that 443 MWh nominal capacity is good for this optimal system. 1 kWh Li-ion battery has autonomy of 14.2 hours, and its expected life is 15 years. The battery pack replacement cost after 15 years adds additional cost in the system. Fig. 19 shows the state of charge of the battery that is 100% during sunlight hours. Battery is used during night-time or during cloudy weather when sunlight is not available, and system depends on wind and battery.

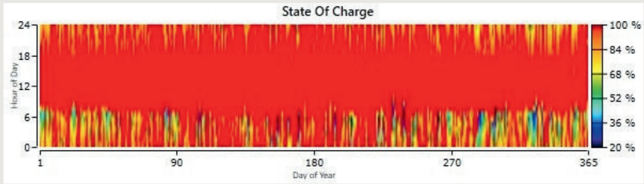


Figure 18. Wind Power Output

- **Hydrogen Production**

Electrolyzer is the major primary load of this hybrid energy system. Electrolyzer mean input is 143 MW while the rated capacity of electrolyzer is 300 MW. HOMER Pro finds out that this electrolyzer is sufficient to meet the large hydrogen load demand of a steel industry. Specific energy consumption of electrolyzer to produce one kg of hydrogen is 46.4 kWh. This electrolyzer system can produce 27 million kg per year with a capacity factor of 47.8% and 6863 operating hours per year. The produced is further fed into hydrogen load, in a steel industry for direct iron ore reduction process. The levelized cost of hydrogen production is $1.39 per kg. Figure 20 shows monthly hydrogen production from electrolyzer.

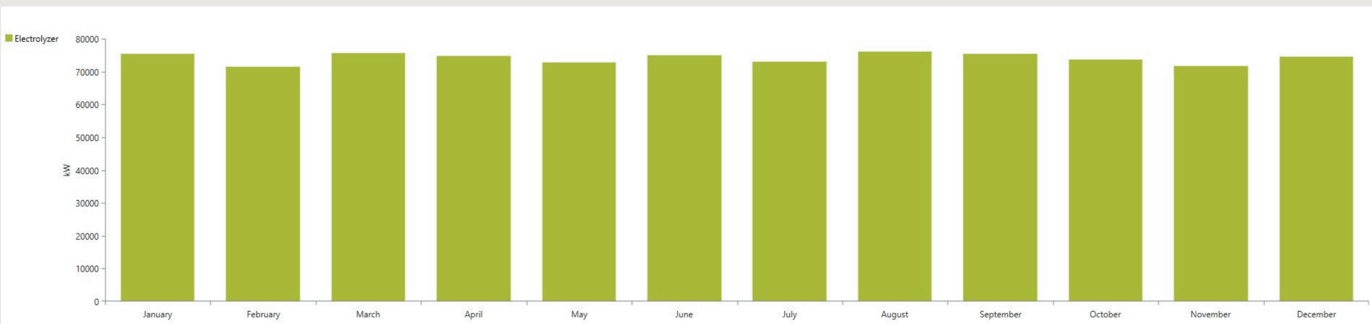


Figure 20. Monthly Hydrogen Production

3.2 On-Grid Hybrid System

The second scenario is hybrid system is connected to grid instead of battery. During the time when auxiliary supply is required, power grid will supply electricity at $0.13/kWh for peak hours and $0.11/kWh for off peak hours. Grid peak hours are 06:00 PM to 10:00 PM according to K-Electric tariff structure July 2023. [50] Grid rate schedule is shown in figure 21. HOMER calculated optimal system configuration for grid tied system that consists of 675 MW of solar PV and 1355 MW wind plant. This on grid system has total net present cost of $241 M with operating cost of -$13.8 M and initial capital of $516 M. The COE for this optimal system is $0.0188 per kWh. While LCOH is $0.446/kg. The cost summary of the on-grid system is shown in figure 22.

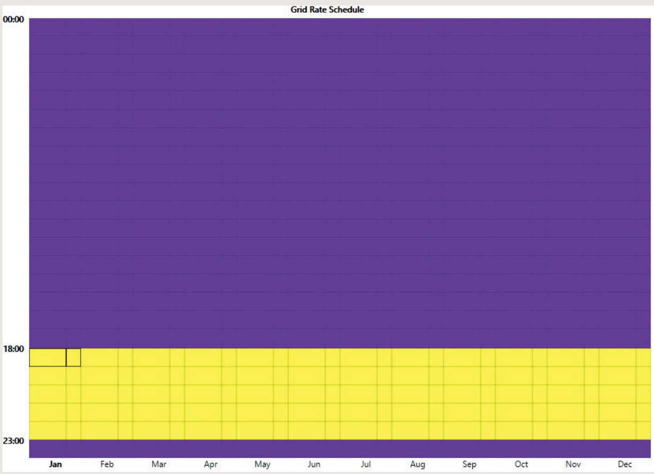


Figure 21. Grid Rate Schedule

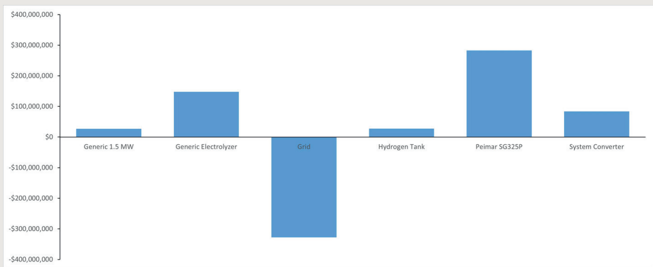


Figure 22. Cost Summary

By the addition of grid into the system reduces the overall net present cost, as the system does not require battery storage. Excess electricity from wind and solar plant is sold to the national power grid. The cashflow over the project lifetime is shown in figure 23.

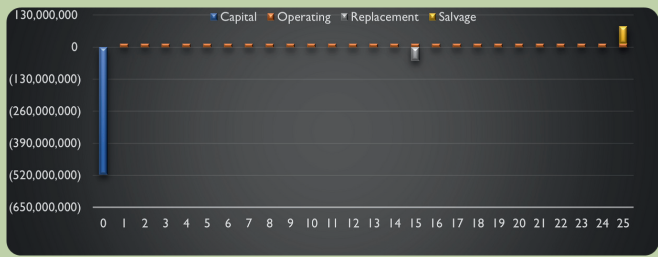


Figure 23. Project Cashflow

- **Electrical Summary**

In this case, there is no unmet electrical load and capacity shortages in the system. Table 4 & 5 show the electricity generation & consumption percentage contribution in fulfilling total electrical load demand. Solar PV has a share of 34.3% while wind power has a share of 64.8%. However, only 0.868% electricity is being purchased from the grid while 22% excess electricity is sold to the grid.

Table 4. Production Summary

Component	Production (kWh/Year)	Percent (%)
Peimar SG325P	1,613,851,081	34.3
Generic 1.5 MW	3,051,742,951	64.8
Grid Purchases	40,869,775	0.868
Total	4,706,463,807	100

Table 5. Consumption Summary

Component	Production (kWh/Year)	Percent (%)
AC Primary Load	219,000,000	11.6
Electrolyzer Load	1,254,207,892	66.1
Grid Sales	422,866,127	22.3
Total	1,896,074,019	100

- **Solar Electrical Output**

For grid tied hybrid system, HOMER calculated rated capacity of solar panels to be 675 MW that has mean electrical output of 4,421,510 kWh/day. This solar plant can produce 1,613,851,081 kWh/year with a capacity factor of 27.3% and total operating hours of 4399 hours per year. Figure 24 shows daily PV Power output throughout the year.

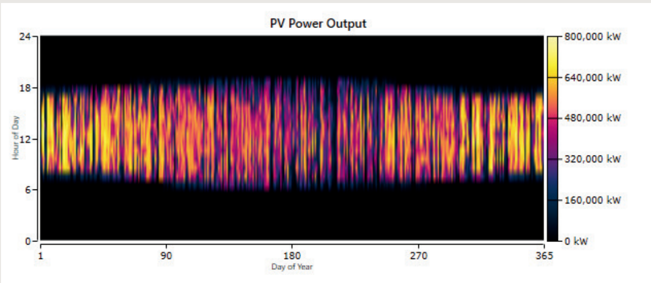


Figure 24. PV Power Output

- **Wind Power Output**

Total rated capacity for the optimal system is found to be 1355 MW that can generate 3,051,742,951 kWh/year with a capacity factor of 25.8%. The total operating hours of wind plant are 6220 hours per year while levelized cost is \$0.000442/kWh. Figure 25 shows wind turbine power curve. Figure 26 shows DMap graph of daily PV Power output throughout the year.

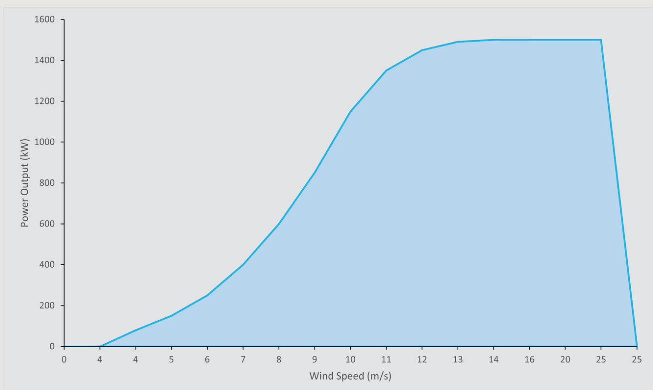


Figure 25. Wind Turbine Power Curve

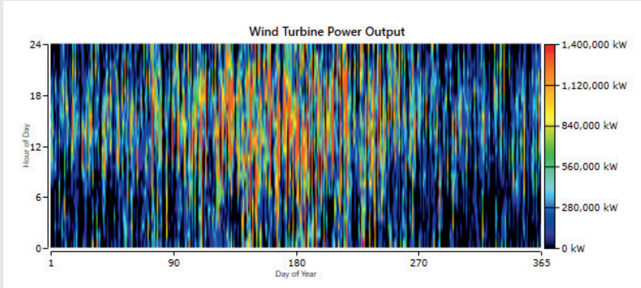


Figure 26. Wind Power Output

- **Electricity from Grid**

The grid connected system lowered the total net present cost of the system. Figure 27 shows that energy is purchased from grid during nighttime when solar and wind out power is low.

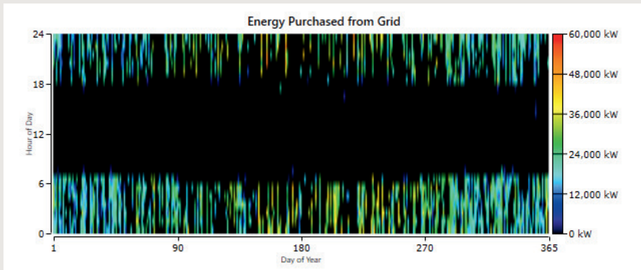


Figure 27. Daily Energy Purchased from Grid

- **Comparison of both Scenarios**

Off and on grid system comparison is made to check economic feasibility. It can be interpreted from table 6 that on-grid system costs are lower than off grid system. IEA estimates show that Levelized cost of hydrogen production per kg from renewable will range between 1.3-3.5 USD per kg.[51] Changing grid on peak and off-peak electricity purchasing and selling prices greatly affect the LCOE. Increasing grid power prices increases the cost of energy and net present cost of the system. Selling electricity to the grid during on peak hours is found to be more economical.

Table 6. Comparison of On and off Grid System

Parameters	Off -Grid	On-Grid
LCOE	$0.172/kWh	$0.0188/kWh
LCOH	$1.39/kg	$0.446/kg
NPC	$749 M	$241 M
Initial Capital	$653M	$516M
Operating cost	$4.82M	-$13.8M

3.3 Sensitivity Analysis

A sensitivity analysis is performed to see how LCOE and LCOH changes when economic constraints or cost components changes. Sensitivity variables are Discount Rate, solar irradiance, and wind speed. The values are variations of ±30% in the original value.

Table 7. Sensitivity Variables

Nominal Discount (%)	Solar Scaled Average (kWh/m2/Day)	Wind Scaled Average (m/s)
12.00	5.45	6.22
8.4	3.815	8.086
15.6	7.0185	4.354

- **Sensitivity Analysis Results**

The surface plot in figure 28 shows nominal discount rate at x-axis and Wind speed at y-axis when solar radiations are constant at 5.45 kWh/m2. Cost of energy is superimposed on the plot and net present cost is plotted in the surface of plot. The graph shows that at higher discount rate, COE and NPC are higher at average and low wind speed. However, at higher wind speeds, NPC and COE are lower.

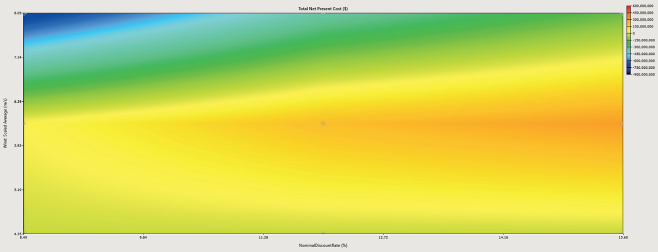


Figure 28. Surface Plot at Average Solar Radiations 5.45 kWh/day

The surface plot in figure 29 shows nominal discount rate at x-axis and solar radiations at y-axis when wind speed is constant at 6.22 m/s. It can interpreted from the plot that at higher solar radiations, NPC is lower as shown in blue color and cost of electricity production is also less. While areas with low solar radiations, faces high NPC and high COE. As, nominal discount rate increases, cost of electricity production also increases.

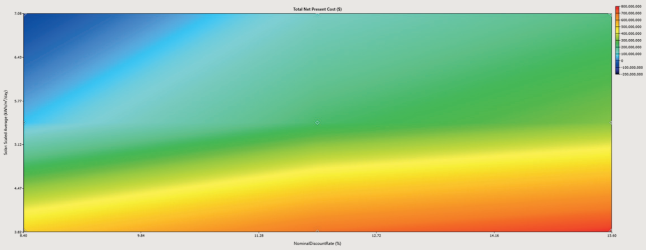


Figure 29. Surface Plot at Average Wind Speed 6.22 m/s

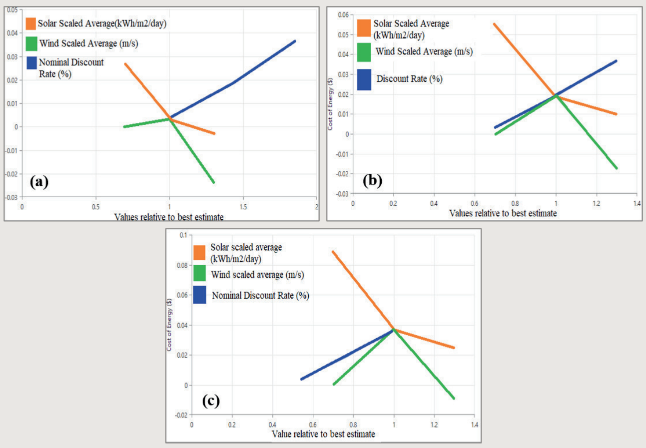


Figure 30. Discount rate a) 8.40% b) 12% c) 15.60%

Figure 30 shows spider plot cost of energy at average scaled wind and solar value for different discount rates of 8.40%, 12%, 15.60%.

3.4 Survey Results

To determine green hydrogen social viability in Pakistan, a comprehensive survey was conducted, targeting researchers, scientists, industrial professionals, and government officials as the primary participants. The survey encompassed a range of inquiries, with a focus on several significant aspects. A total of 40 samples were collected for the study, responses for personal factors are shown in graphs below in figure 31.

Majority respondents are men whose age range is between 18-25 and 26-45, 65% of the audience is from research community, 27% are industry professionals and government officials. Young people with the age range 18-25 are unemployed. 39% people shows their location of residency in Punjab province while 34% respondents live in Islamabad.

Place based factors show that people living nearby an industry or a chemical plant face high environmental pollution than people living far from industrial area. They disagree to have the hydrogen pipeline near their home. While younger people who are in energy sector are more enthusiastic about green hydrogen development and they agreed for building hydrogen pipeline infrastructure near their home. Younger people who have master's degree show more familiarity with the concept of green hydrogen than older people.

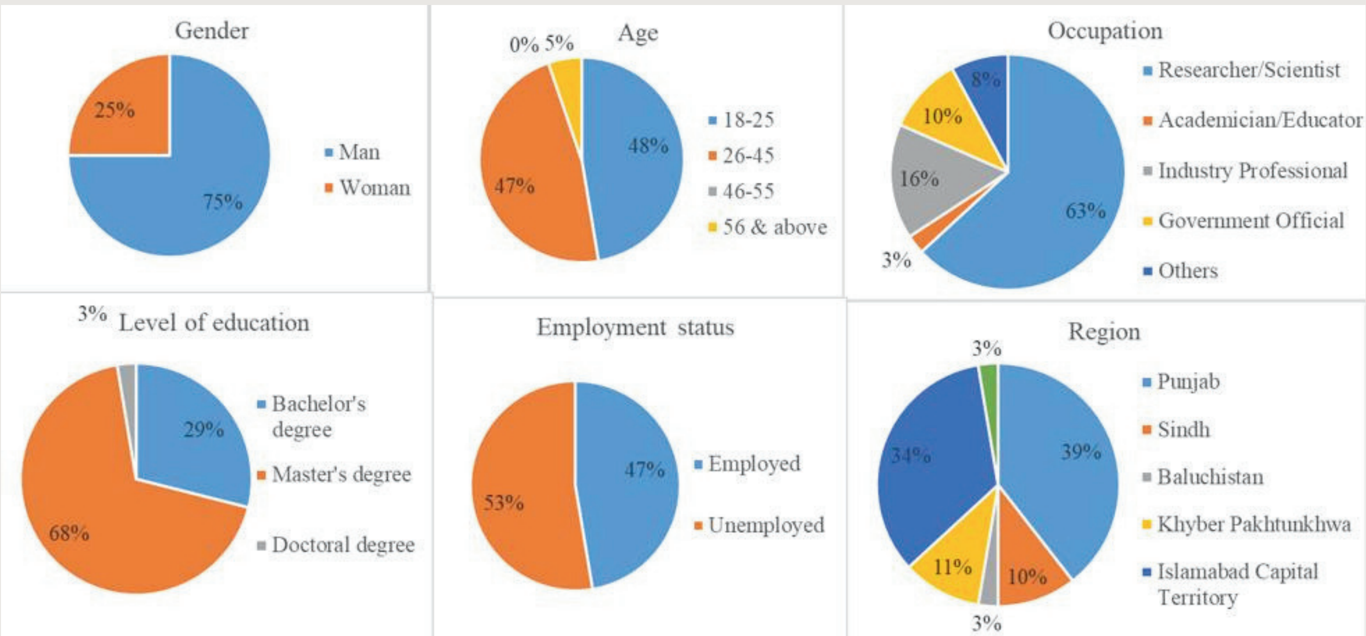


Figure 31: Personal factors based Results

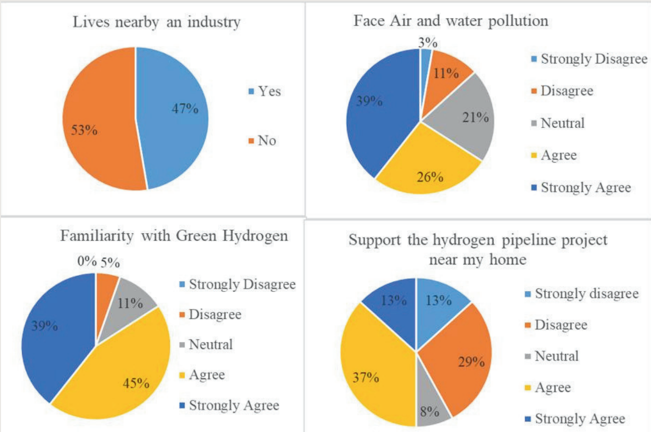


Figure 32. Place based Factors Results

Project based survey questions responses show that people who are already working in energy and power sector are aware of the energy crisis and believe that renewable energy sources can overcome the energy crisis in Pakistan. According to their opinion, most suitable hydrogen production technology is water electrolysis as it is a zero emissions process. The most feasible renewable energy sources are wind and solar. As Pakistan is a developing country and is facing energy crisis, so hybrid system of wind and solar would be the most feasible solution as indicated by survey results. Regarding the proposition of active collaboration between the Pakistani government and China under the China-Pakistan Economic Corridor (CPEC) for the development of green hydrogen, the responses are as follows: 21% strongly agree, while a majority of 50% express agreement. Regarding the establishment of a policy to ensure the advancement of green hydrogen, 34% strongly agree and 45% express agreement. Moreover, within the process of formulating this policy, a significant portion, 46%, strongly supports involving the local community, while 40% agree with this inclusion of stakeholders. In response to the inquiry about the kind of policies the government should establish to promote hydrogen development, 3% strongly advocate for and 21% agree with implementing tax policy reforms and introducing new schemes that facilitate the advancement of Green Hydrogen in Pakistan.

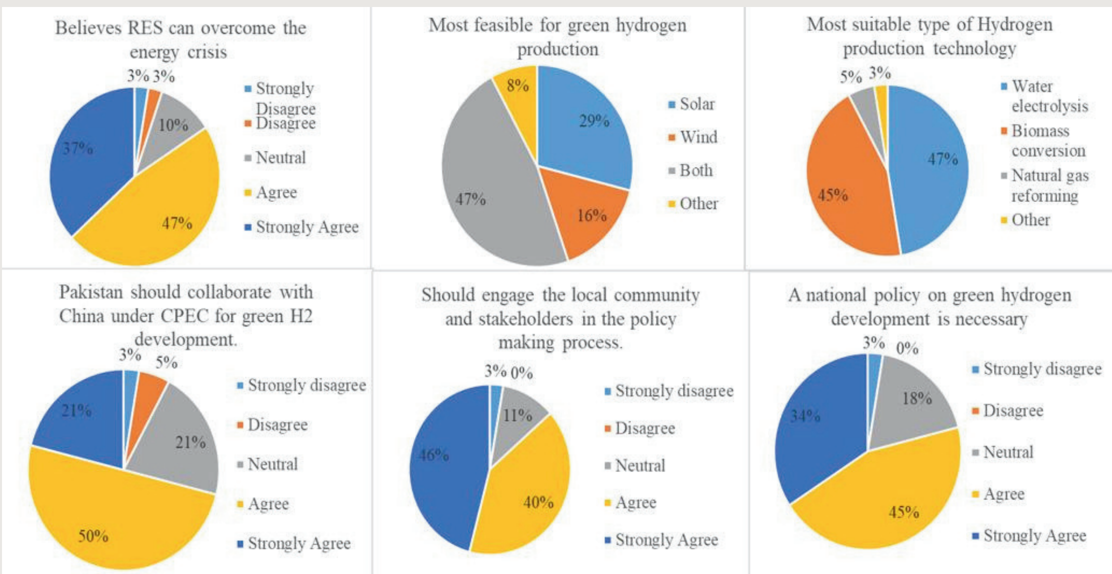


Figure 33: Project based Results

4. Socio-Economic Significance

Green hydrogen can play a significant role in industrial decarbonization specifically iron and steel industry decarbonization. Many countries have started implementing green hydrogen production plants exploiting RES. Pakistan can also exploit its wind and solar potential resources especially alongside the coastal areas of Sindh and Baluchistan. However, building a large infrastructure is a very promising for a developing country, but if Pakistan can deploy this technology, it will be very beneficial for its economic growth. Green hydrogen technology also reduces the cost of electricity, that is a biggest challenge for the current electricity providers. Green hydrogen technology implementation in Pakistan holds significant socio-economic importance for the region. Firstly, it enhances energy security by reducing dependence on imported fossil fuels and diversifying the energy mix. This, in turn, supports economic growth by job creation, developing infrastructure, and attracting foreign direct investments (FDI), resulting in new sectors and supply networks associated with hydrogen generation.

Green hydrogen contributes to the reduction of air pollution in Pakistan by replacing clean hydrogen for fossil fuels in a variety of sectors, hence improving air quality and public health. The current case study results showed zero greenhouse gases emission. It will help Pakistan reach its greenhouse gas reduction targets, which aids in climate change mitigation. However, water scarcity is a concern, and efficient water resource management is crucial for sustainable hydrogen production. Green hydrogen adoption as a fuel in Pakistan's energy mix aligns with Sustainable Development Goal (SDG)-7 (Affordable and Clean Energy) and SDG-13 (Climate Action), as it can support the country's transition towards a zero-carbon and climate-resilient future. It is also possible to achieve SDG-9 (Industry, Innovation, and Infrastructure) and SDG-17 (Partnerships for the Goals). Collaboration on hydrogen initiatives with neighbouring countries such as China can promote regional ties and economic integration. Furthermore, using this technology promotes technological developments, innovation, and scientific growth in Pakistan, while also enhancing energy access, particularly in distant areas.

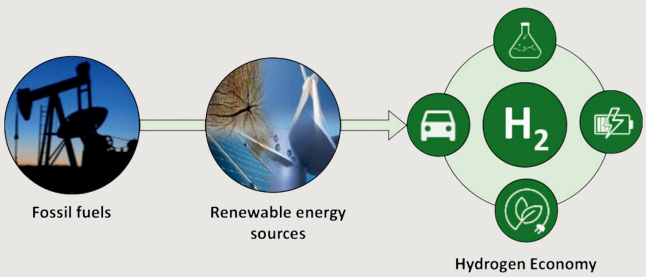


Figure 34. Place based Factors Results

Lastly, exploring export opportunities for green hydrogen and related technologies can create new revenue streams for Pakistan, benefiting both the domestic economy and regional diplomacy. To fully exploit these benefits, Pakistan should adopt a comprehensive plan that includes regulatory support, financial incentives, R&D projects, and international collaboration, as well as boosting public awareness about the possibilities of green hydrogen.

5. Conclusions

5.1 Outcomes

The techno-economic analysis of hydrogen production is carried out using HOMER Pro simulation software. The results showed that for a developing country like Pakistan green hydrogen production is only feasible when the hybrid system relates to the power grid. Sindh province coastal area shows high speed of wind energy and solar radiation are also above average. At this location, off grid hybrid system showed high NPC while the grid-tied system showed lower NPC. The on-grid hybrid system is economically feasible with levelized cost of hydrogen production $0.446/kg. The levelized cost of electricity for grid connected system is $0.0188/kWh. Economical and technical efficiency of the system will increase when there are higher wind speeds and high solar irradiations. This was determined by the help of sensitivity analysis which also showed that discount rate is also an important factor in determining techno-economic feasibility. Furthermore, survey results showed that public awareness about new technology is the first step that authorities should focus on. People living nearby industry experience more environmental pollution than people living far away from large infrastructure plants. Young researcher community showed more support for the implementation of green hydrogen infrastructure. Industry professionals and government officials suggested

suggested that a comprehensive policy is very necessary for the implementation of green hydrogen infrastructure in Pakistan. Current tax and incentives schemes and policy regulations do not encourage green hydrogen adoption. Many professionals think that leveraging China–Pakistan Economic Corridor (CPEC) would be a significant plus point for Pakistan in terms of foreign direct investment and economic growth of the country. Moreover, survey responses suggest that it is important to engage the local community and stakeholders in the policy making process.

5.2 Future Recommendations

Green hydrogen is the best proposed solution for the decarbonization of industrial sector. Based on this study some future recommendations are given below:

- A comprehensive hydrogen economy roadmap is required for Pakistan like other countries have already published their roadmap strategy.
- A national policy for green hydrogen development on a large scale should be the next step for the government.
- Strategies and objectives are required to establish to communicate to stakeholders the industrial sector's in decarbonization.
- To introduce the industry to the technology and kickstart the manufacturing scale-up process while demonstrating a strong commitment to extensive decarbonization, it is advisable to establish medium to large-scale demonstration plants.
- Currently, green steel, ammonia, and methanol are not fully recognized for their reduced greenhouse gas (GHG) emissions. Thus, a system is required to monitor and account for the upstream emissions associated with these products, ultimately establishing a specialized market that appreciates these environmentally friendly attributes.

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https://uspcase.nust.edu.pk

ilo@uspcase.nust.edu.pk

USPCAS-E Building, NUST Sector H-12,
Islamabad, 44000 Pakistan