Techno-Economic Analysis of Hybrid Renewable Energy Systems for CPEC's Emerging Economic Zones and Hydrogen Production from Surplus Energy

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(2024)

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

in partial fulfillment of the requirements for the degree of

Master of Science in

Energy Systems Engineering

Supervisor: Dr. Syed Ali Abbas Kazmi

U.S. Pakistan Centre for Advanced Studies in Energy (USPCAS-E)

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

(2024)

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ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor, Dr. Syed Ali Abbas Kazmi, for his invaluable guidance, support, and encouragement throughout this research. His expertise and insights were instrumental in shaping the direction and quality of this work.

Special thanks go to my family, especially my mother and father, whose unwavering support and belief in my abilities have been a constant source of strength. I am also grateful to my friend Muhammad Haroon, who provided both emotional and intellectual support during the challenging moments of this journey.

I am also indebted to the administrative staff at the U.S.-Pakistan Center for Advanced Studies in Energy (USPCAS-E) for their assistance and cooperation throughout my time here.

To all who have contributed to this work, whether mentioned here by name or not, I extend my heartfelt thanks.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

AIC	Allama Iqbal Industrial City
RE	Renewable Energy
CPEC	China-Pakistan Economic Corridor
SEZs	Special Economic Zones
KPK	Khyber Pakhtunkhwa
IC	Initial Cost
IRENA	The International Renewable Energy Agency
TL	Transmission Line
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
NPV	Net Present Value
IRR	Internal Rate of Return
GHG	Greenhouse Gas

O&M Operation and Maintenance

USD United states Dollar

$ United states Dollar

Mtoe Million Tons of Oil Equivalent

ABSTRACT

This thesis is a techno-economic investigation of indigenous renewable energy systems for the CPEC SEZs as a strategic approach to enhancing energy reliability, sustainability, and economic viability. Also, surplus Energy from these intermittent resources will be used to generate green hydrogen production. The study focuses on under progress four key SEZs, specifically Dhabeji in Sindh, Allama Iqbal Industrial City in Punjab, Rashakai in KPK, and Bostan in Balochistan. Estimating the techno-economic feasibility of various indigenous RE energy configurations, including solar, wind, hydro, and biomass. By optimizing energy mixes using RETScreen software and leveraging surplus renewable energy for hydrogen production, the research offers a comprehensive framework for sustainable industrial growth in Pakistan.

The analysis reveals that hybrid energy systems, such as the 30%-70% solar-wind mix in Dhabeji, achieve a favorable Levelized Cost of Energy of 0.0421 USD/kWh, demonstrating the best balance between cost and reliability. Bostan's withs its high irradiance value with fully solar configuration emerges as the most cost-effective option overall, with an LCOE of 0.0415 USD/kWh. For green hydrogen production, Dhabeji's 70%-30% solar-wind mix yields a competitive Levelized Cost of Hydrogen (LCOH) at $3.77 per kg, while Rashakai with cost of LCOE of 0.0461 USD/kwh a solar-hydro setup achieves the LCOH at $3.362 per kg, which is due to the surplus energy available all months of the year. The study further highlights that increasing system capacity by 10% significantly reduces hydrogen production costs across all SEZs.

The findings reveal that the wind energy with least cost to generate and the solar with its lowest cost at higher irradiance area of Bostan. The research also revalues with increasing the such hybrid energy systems for the industrial centers results in economical green hydrogen production on site. The thesis concludes by providing strategic recommendations for optimizing energy policies, financial incentives, and technology integration, offering practical insights for policymakers, investors, and industrial stakeholders. These outcomes contribute to Pakistan's broader energy transition objectives, positioning its SEZs as models of low-carbon, resilient industrial zones.

Keywords: Renewable energy integration, Special Economic Zones (SEZs), green hydrogen, techno-economic analysis, energy mix optimization, LCOE, LCOH, hybrid energy systems, surplus energy.

CHAPTER 1: INTRODUCTION

1.1 Context and Background

Industrial energy is of global importance to keep the socio-economic development of any country. Globally industries Contribution of GHGs due to its extensive usage of the fossil fuels is main challenge to revert climate change and other fossil fuel related environmental crises. 50% of global energy mix contributes to the industries of which, mostly used in form of heating and cooling followed by used in the form of electricity causing a global 25% production of GHGs [1], [2].

The sustainable Development goals by UN focuses its SDG-7, 9,13 to use an alternate clean energy source for sustainable development and clean environment [3].Pakistan being a primary agriculture currently in transition towards global industrial giant need the use of the indigenous renewable resources for its industrial growth. A report ministry of planning and development and special initiatives on Pakistan energy demand indicates the use of the primary energy need to be reached at 87.9 Mtoe by 2025 and d 99.2 Mtoe by 2030.the current industrial energy demand on 20.0Mtoe which is expected to be around 25 Mtoe [4].

China BRI with the CPEC, which aims to provide cooperation between China and Pakistan in different socio-economic sectors. The long-term plans in energy sectors includes the buildup of different power projects by private sector under the defined rules, which promotes the security on investment and ease of business by tax exemptions. The progress of the China-Pakistan Economic Corridor (CPEC) appears to be gradual, with incremental advancements. However, the developments in the industrial and energy sectors seem promising with positive indicators. The SEZs under CPEC which are partially complete with the under-process zones of are Rashakai SEZ, Bostan SEZ under western and Allama Iqbal industrial city and Dhabeji under eastern SEZ route [5].

1.2 Problem statement

Despite increase in energy production from Pakistan's energy security initially improved from 2011 to 2014 but then deteriorated from 2015 to 2017.This is due to the thermal energy power plants which uses imported fossil fuels, leading to increased energy insecurity. The study emphasizes the need for a shift towards renewable energy sources, such as solar and wind, to enhance energy security [6]. These problems are not only restricted to policies but also the technical infrastructure which lack in modernization. The clusters of centralized loads in industrial and residential Centers causing the network to bear 88% of the total industrial and residential load. With 35.7% net energy Import mostly in the form of fossil fuels [7]. To solve these problems the decentralized indigenous RE resources can supply the necessary energy for newly develop SEZs, while surplus Energy will be use to convert to hydrogen which an excellent energy carrier.

The main problem with RE is its intermittent nature so the surplus energy is to be stored in the form of electrochemical energy or alternatively with hydrogen production. The power systems setup for industries will be more useful if the localized surplus energy be converted into Hydrogen. This will not only make the System more economically viable but also the value addition green hydrogen will also be ensured [8].

1.3 Objectives of the Study

The industries with the potential of 60 GW from hydropower, 40 GW from solar, 346, MW from wind we aimed to provide the indigenous energy resources of the localized SEZs to fulfill their industrial demands. Surplus energy of these intermittent RE resources will be use to generate Green Hydrogen. The hydrogen can either be directly supplied to industries or their derivates as these are needed to be used in industry as feed stock [9]. These special economic zones have proper setup of petroleum and chemical industries where hydrogen can used as multiple feedstocks like from production of ammonia, petrochemical refinement, food processing, electronics and for other chemical preparations. Out of totally Globally produced Hydrogen 55% is used for ammonia production and 25% for petroleum refinement. this multipurpose usage of hydrogen will have the effect of value addition to the whole energy system setup [10].

The integration of renewable energy and hydrogen production within Pakistan's Special Economic Zones (SEZs) presents a promising solution to the nation's energy challenges. By harnessing indigenous renewable resources and converting surplus energy into green hydrogen, these zones can not only meet their industrial energy demands but also contribute to a more sustainable and economically viable energy system. This approach aligns with global trends towards cleaner energy and offers significant potential for value addition within Pakistan's evolving industrial landscape. To optimize this integration, we will conduct a resource techno-economic assessment using the RETScreen software, ensuring that the most efficient and cost-effective strategies are implemented.

CHAPTER 2: LITERATURE REVIEW

2.1 Global & Pakistan emissions Outlook

Since the Industrial revolution the GHG emissions mostly from industries has extensively been analyzed. An early comprehensive analysis of the industrial sector's contribution to GHG emissions, indicated the GHG emissions within the industrial accounts for approximately one-third of global carbon dioxide emissions. Survey based methodology indicate that while GHG emissions in industrialized countries have decreased since the mid-1970s, newly industrializing countries have seen a rise in absolute emissions, albeit at a slowing rate. Significant opportunities for reducing emissions through the adoption of lower-emitting technologies, improved energy efficiency, and the introduction of innovative processes, particularly in developing economies. The research underscores the necessity of technology transfer and policy interventions to facilitate the transition towards lower GHG emissions in the industrial sector, emphasizing that effective strategies must be implemented to mitigate future emissions and promote sustainable industrial practices [11]. In case of Pakistan its contribution of Global emissions is just 0.9% of global [12].The industrial emissions are not as high as compared to other the industrial giants as the combined generation of GHGs by china, Russia India, Brazil and USA with combined population of 61.2% generates 61.6%, particularly the emissions by industrial process and industrial power sector rose by 43% and 34% respectively from 2005 to 2022. With the growth of population and industrial sector it will need to migrated, as the report indicates the rise of industrial process and power sector by 44% and 56% for same period [13]. Another significant contribution comes from Umer et al., who conducted a detailed assessment of the greenhouse gas (GHG) emissions associated with Pakistan's power sector, using a novel time-varying carbon intensity approach. The study found that Pakistan's electricity generation is predominantly fossil fuel-based, with 60.9% of electricity derived from thermal sources, leading to significant carbon emissions. The carbon intensity in Pakistan was found to peak during the colder months of January and

December, reaching values of 650 gCO2-eq/kWh and 550 gCO2-eq/kWh, respectively. This increase is primarily due to the reduced availability of hydropower during these months, which forces greater reliance on more carbon-intensive energy sources [14].

The application of the Box-Jenkins approach to overall energy demand, especially for Pakistan, is helpful; indeed, an ARMAX model to analyze time-series data provides identification, estimation, and forecasting. Findings show that factors like price level, wage mass, and productivity directly affect energy demand in industrial sectors. Due to its price dynamic, industrial coal is considered a Giffen good. The industrial sector accounted for 39.79% of total energy demand, mainly relying on gas and electricity. The development and application of power led to a serious gap between supply and demand--one that electricity and gas deficits have expanded even further. The paper concludes that eliminating these deficits, especially the latter, is necessary for the industrial sector as well as the population to meet their increasing energy demand next year[15].

There is an urgent need in Pakistan to seek means of harnessing these resources for energy so that it can meet its rapidly increasing requirements and substantially reduce the heavy dependence on imported oil, currently amounting to 63% of all electricity generated in Pakistan. This is a large slice off any country's power shares pie[16].

2.2 SEZs Development in Pakistan

The influence of SEZs on structural transformation has vital importance, especially in the context of developing countries such as Pakistan. Otchia and Wiryawan employed a dynamic panel data model, to meticulously appraise the long-term impact of SEZ policies on country economy structure particularly in Asia. They adopted a methodology that attempts to measure the pre and post-enactment of SEZ policies on the GDP contributions within different sectors — agriculture, industry (low-tech manufacturing or high-tech), services[17]. Another successful example of SEZs from global projects is AEQUZ SEZ in Belagavi, India, which has a positive impact on regional development, where it has generated over $1.5 billion in exports and created 10,000 jobs, though the need for improved governance and more diverse industry attraction remains critical [18]

The strategic importance of using local resources in developing replicable and resilience energy system is greatly demonstrated by development of Special Economic Zones (SEZs) under the China-Pakistan Economic Corridor (CPEC). This is especially important in the case for special economic zones, such as Dhabeji, Bostan or Rashakai, and Allama Iqbal industrial city that are envisioned to displace imported fossil fuels with domestic renewable energy. The proposing literature highlights that those zones are typically far from effective warmth and electric powers to era, develop the centering of such systems [19]. And the industrial areas Under CPEC are uses around half of demand for energy, it enhances a sort of growing need. CPEC related SEZs: The analysis concludes that while these Zones assist greatly in developing infrastructure, specifically for FDI and industrial expansion; but the issues of inconsistent policies and governance are still prevalent. For example, SEZs in Pakistan have managed to attract $2.1bn investments but policy implementation and infrastructure development remain a challenge [20]. In addition, the forward-looking analysis of potential SEZs in Pakistan shows that modulating China type success factors with such zones could produce economic benefits like enhancing GDP up 25% and more if necessary reforms are enforced [20].

Overall, these studies emphasize the importance of strategic planning, tailored policies, and effective governance in maximizing the socio-economic benefits of SEZs in developing economies.

2.3 Renewable Energy Integration in SEZs

Industrial sectors are now looking at introducing renewable energy resources into their integration system, considering it as a fundamental approach to reduce dependence on fossil fuels and improve the reliability of power supply. Unified energy system of renewable resources (such as decentralized generation, local environmental impact and global reduction with definite benefits in terms of sustainable development for the region) that would increase energy security. Smart grid technologies needed to integrate efficient renewable energy resources in industrial applications, focusing on the potential of different sources including solar energy; wind and biomass [21], [22]. According to Chou et al the inclusion of renewable energy can help increase sustainability and it would facilitate cost competitive power provision into SEZs which will attract more investments for technology transfer opportunities leading to employment. It also underscores the strategic role of renewable energy in making SEZs an enduring zoning model and suggests green infrastructure policies that can lend support to imperative bytes. [23].Similarly, Shafkhatov et al. [24], shed light on the incorporation of renewable energy resources in distribution networks for industrial complexes, while emphasizing on drawbacks shown by instable behavior from RESs such as solar and wind. The findings of their study stress the role connecting technologies and protection devices play in ensuring power quality and system stability on a factory floor. These trends underscore the importance of devising effective energy management strategies such that renewable sources can be operated in ways to maximize their usage across different site contexts where storage solutions are not available. The report shows that Pakistan is facing serious energy problems in response to these needs, and according to the CPEC Study Center of Bahria University Head also argues that with regard specifically if we talk about Pakistani economy which can be link through renewable resources on Although it increases up 16,000 MW by 2030. The areas include both short-term actions as well as long term action for balancing cervical gait will not result materialization without improvements along the Route implements polices incentives at all levels inherent Timing flexibility Governance allows complete reliance. CPEC advantages include 15 to 20% enhanced energy generation capacity expected due the development of optimized use renewable sources along the route. [25].

These findings collectively underscore the importance of strategic energy planning and the optimization of renewable energy resources to meet the growing energy demands of SEZs while ensuring environmental sustainability and economic viability.

2.4 Background on Renewable Energy Systems of Pakistan

The techno-economic importance of renewable energy in Pakistan is significant, given the country's growing energy demand and reliance on imported fossil fuels. Renewable energy sources such as wind, solar, and biomass offer a sustainable solution to diversify the energy mix, reduce energy import bills, and enhance energy security. Economically, investing in renewables can create jobs, spur industrial growth, and attract foreign investment, particularly in the Special Economic Zones. Abbas and Aslam provide a comprehensive analysis of Pakistan's untapped renewable energy resources, revealing that the country currently fulfils only 5.4% of its energy demand from renewable sources, including biomass, wind, and solar, with an additional 25% from hydropower. However, the potential for renewable energy in Pakistan is vast, with estimates indicating nearly 60,000 MW from hydropower, 40,000 MW from solar, and 346,000 MW from wind [26].Another parallel study on RE potential study on Pakistan, emphasizing the country's significant but underutilized resources. Pakistan's current installed capacity is 34,233 MW, but it can only generate 22,000 MW against a peak load of 25,000 MW, leading to a shortfall of 3,000 MW. The paper also notes that using just 0.071% of Pakistan's land area for solar photovoltaic (PV) generation could meet the country's current electricity demand. Moreover, the cost of off-grid solar power is found to be Rs 14.8 per kWh cheaper than regular electricity supply [27].In Case of Photovoltaic potential, combination of ground measurements and satellite data was carried out. According to the data, DNI and GHI both surpass 2000 kWh/m². The analysis's conclusions show that the annual mean GHI is highest in the southwest and falls as one moves north, reaching its lowest point in the northern regions. Pakistan's GHI is predicted to be 2071 kWh/m² on average, with certain places having peak values over 2300 kWh/m² DNI attains its maximum values in arid plateaus or rocky deserts where minimal dust. Across Pakistan, DNI levels are generally highest with maximum in northwest Baluchistan surpass 2700 kWh/m². The results show both GNI and is consistent throughout the year and, in most cases, has little intrannual variability, maki ng it ideal for the installation of solar energy systems [28]. The transition to renewable energy in Pakistan, particularly within the context of large-scale projects like the Quaid-e-Azam Solar Park (QASP), demonstrates significant potential for addressing the country's energy crisis. The QASP, a 100 MW solar PV project, has been shown to be financially viable with a simple payback period of 5.6 years and a benefit-cost ratio (BCR) of 1.33. The project's Net Present Value (NPV) is calculated at $31.66 million, reflecting a strong return on investment, particularly given the low operational and maintenance costs associated with solar PV technology [29] . Similarly, a techno-economic analysis of a wind farm in Balochistan highlights the region's untapped potential, where a 50 MW wind farm demonstrates an internal rate of return (IRR) of 14.8% and a levelized cost of electricity (LCOE) of $0.045 per kWh, making it a competitive option compared to conventional energy sources [30] . Also, the analysis of biomass energy resources within Pakistan reveals that, despite its current underutilization, biomass could significantly contribute to the energy mix if the right policy frameworks and technological investments are put in place [31] .

Focusing on wind energy, one study reports a significant internal rate of return of 14.8% and a levelized cost of electricity of $0.045 per kWh, highlighting wind energy's financial viability in Pakistan's transition to a decarbonized energy sector [32]. The current scenario of wind energy in Pakistan reveals a potential capacity of 50 GW, with 1.2 GW already installed, though challenges such as regulatory issues and technological gaps remain significant [33]. The wind power potential at Jhimpir is highlighted as a major contributor to Pakistan's renewable energy targets, with wind speeds of 7 m/s at 60m height and a power generation capacity estimated at 43,000 MW [34]. Hydropower, another critical component of Pakistan's renewable energy mix, requires a shift from individual project assessments to integrated energy system planning to reduce ecological impacts by 20% while maintaining energy output [35]. Hybrid energy policies in CPEC's SEZs show promise, with potential to reduce energy costs by 12% and increase reliability by 18%, making these zones more sustainable and economically stable [36].

Analysis on such hybrid system need a technical and managerial innovation. The paper on energy-mix dynamics for optimization in a developing economy highlights the use of decomposition techniques to optimize power generation strategies, demonstrating significant cost savings of up to 17.58% in operational fuel costs through optimal capacity combinations, with a projected load demand of 2250 MW for Afam and 2350 MW for Sapele power stations in Nigeria [37]. A study focusing on scenario-based techno-reliability optimization of off-grid hybrid renewable energy systems reveals the viability of hybrid systems across multiple cities, where reliability is improved by 23% and cost efficiency by 18% through the integration of solar and wind energy [38]. Additionally, a comprehensive analysis and multi-objective optimization of sustainable production systems based on renewable energies suggests that integrating multiple renewable sources can increase system efficiency by 22% and reduce emissions by 45%, showcasing the potential of such systems in achieving sustainability goals [39]. The integrative decision-making framework for techno-economic planning of renewable-dominated standalone hybrid microgrids at a provincial scale in Pakistan highlights the role of optimization in achieving a 30% reduction in energy costs while enhancing system reliability by 35% [40].

The overall analysis of CPEC-related energy projects, including renewable sources, underscores the strategic importance of these initiatives in reducing Pakistan's energy deficit and enhancing energy security, however, deploying these renewable energy projects presents certain risks, with a moderate risk index calculated at 0.65 for solar projects and 0.72 for wind projects, underscoring the need for careful strategic management [41]. Another paper employs the Multi-Criteria Decision Making (MCDM) approach to identify and mitigate risks associated with renewable energy projects, noting that political and financial risks are the most significant, while solar energy emerges as the most favored renewable resource among stakeholders [42].

Integrating renewable energy into SEZs, has both the potential benefits and the associated risks however with robust policies frameworks and incentives to encourage private sector investment.

2.5 Green Hydrogen Production from RE

Hydrogen is regarded as future fuel, with its uses in multiple industrial and energy sectors. Focusing on potential usage of hydrogen in multiple fronts starting from its use as a fuel in aerospace, a vital reactant in chemical reactions, and a promising ingredient in cleaner energy solutions, particularly in fuel cells for power generation and as a sustainable substitute for vehicle propulsion. It explores how the processing of heavier crude oils and stricter environmental regulations demanding the elimination of sulfur and nitrogen compounds have led to the increased significance of hydrogen in the petroleum refining sector. The adaptability and growing value of hydrogen and predicts a sharp increase in demand, especially in the petroleum refining industry. However, it also notes the obstacles posed by cost, storage, and technology that prevent widespread implementation[43]. Hydrogen production technologies continue to evolve, with electrolysis and Steam Methane Reforming (SMR) being prominent methods. Recent studies, such as those by Horri and Ozcan , highlight innovative approaches in water electrolysis, including the development of decoupled and membrane less electrolysis cells. These technologies are particularly promising for seawater splitting, which offers a sustainable alternative to freshwater electrolysis but faces challenges like chlorine evolution and electrode degradation. The potential reduction in hydrogen production costs to as low as $2/kg when integrated with renewable energy sources [44]. Liu et al. provided a comparative analysis of green, blue, and grey hydrogen, revealing that while grey hydrogen is currently the cheapest at $1.29/kg, green hydrogen is becoming increasingly competitive with advancements in renewable technologies[45].

In a study focusing on hybrid renewable energy systems in Kayseri, Turkey, a combination of solar panels, wind turbines, diesel generators, and hydrogen storage was found to be the most effective for producing hydrogen and generating power. This system achieved a renewable fraction rate of 68.2%, a net present cost of $4.01 billion, and the lowest energy cost per kWh at $0.376. The study underscores the importance of integrating hydrogen production into hybrid systems to minimize costs and environmental impact [46]. A techno-economic analysis revealed that green hydrogen could be produced at a 28% efficiency rate using solar energy, with a levelized cost of hydrogen (LCOH) potentially reduced to less than $2 per kg under optimized conditions. This is competitive with steam methane reformers, which produce hydrogen at $1.2 to $2.8 per kg with CO2 sequestration [47].Research in Oman on a grid-connected system combining photovoltaic and hydroelectric power found that the system could produce 170,939 kg of green hydrogen annually at a levelized cost of $2.25/kg, demonstrating economic feasibility while reducing CO2 emissions [48].A study on off-grid photovoltaic energy systems in Baghdad, Iraq, found that hydrogen production costs ranged from $5.39/kg to $3.23/kg, with the optimal electrolyzer size being 8 kW, which aligned best with a 12 kW PV array for cost-effective hydrogen production [49]. A study on optimizing the day-ahead operation plan for an electricity-hydrogen integrated energy system (E-H IES) showed that considering wind turbine and photovoltaic forecasts for extra days could improve overall system economy and reduce the abandonment of wind and PV power. The lifetime of battery energy storage systems was also significantly improved [50].

The Asian Development Bank's 2023 prefeasibility report on hydrogen production highlights the immediate need for self-sustainable energy production in Pakistan to meet the 2030 target of 30% renewable energy. The report suggests utilizing hydro energy from dams, runoff rivers, and solar energy, although economic viability remains a challenge. For instance, using curtailed hydro and solar energy, which is expected to be up to 50% by 2030, could be promising if low-cost Chinese AEC electrolyzers are employed, particularly when CO2 emissions become taxed. However, the scenarios are less economically viable without these considerations. In Pakistan, a study assessed wind energy resources for hydrogen production, identifying Sanghar as the most suitable site. The Nordex N90/2500 wind turbine at 80m hub height was recommended, offering the lowest cost of hydrogen production at $2.29k/ton. This highlights the economic viability of wind-to-hydrogen production in Pakistan [51]. Meanwhile, Mohsin et al. (2020) noted that renewable hydrogen production in Pakistan using wind energy could range from \$4.012/kg to \$4.320/kg, emphasizing its potential to reduce carbon emissions[52].

2.6 Hydrogen as carrier and more

Hydrogen is gaining recognition as a critical energy carrier due to its potential for large-scale, long-duration energy storage, which is crucial for managing the intermittency of renewable energy. Shiraishi et al. concluded that hydrogen could provide a strong answer to the challenge of reconciling renewable generation with grid demand, by providing long term energy storage and thus increasing overall stability in our shift towards all-electric power system [53] . Hayakawa et al. emphasize how hydrogen exhibits distinct versatility as a carbon-free energy molecule capable of supporting decarbonization across transportation, industry and even in the contributions to both "energy storage medium" (e.g. synthetic gas production) and conventional direct fuel [54]. When coupled with industrial by-products and renewable energy merging, the use of excess hydrogen adds significant economic advantages as well environmental benefits. Gerfauo and Dias estimate that 756 tons of hydrogen are emitted to the atmosphere a year for surplus hydrogen generated as by-product in sodium chlorate production. The researchers believe that the hydrogen produced in this way can be used not only for heating, but also as an input material for Power-to-X technologies such as so-called Power-to-Liquid and thereby further reduce CO2 emissions of the facility while simultaneously increasing its energy autonomy. [54]. Another study, that unveiled the aforesaid methodologies for shaping energy supply systems in SEZs built on renewable electric and cogeneration technologies. Their conclusions are similar to the rest of the literature discussing how using excess power for producing hydrogen might be beneficial both economic and environmentally, for SEZs. This way may not only solve the problem of intermittent renewable energy sources, but also offer a solution for producing green hydrogen which is essential to future energy systems [55].

For Pakistan, these insights are highly relevant as the country seeks to harness indigenous resources for energy supply in its SEZs, ultimately aiming to produce green hydrogen. The structural changes induced by SEZs could provide a strong foundation for integrating advanced energy technologies and promoting sustainable industrial practices.

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CHAPTER 3: METHODOLOGY

The selected Four location of currently in progress economic zones of Dhabeji Sindh, Rashakai KPK, Allama Iqbal Industrial City Faisalabad Punjab and Bostan Baluchistan are taken into consideration. Dhabeji and Allama Iqbal Industrial City lies on eastern route of CPEC while Bosatn SEZ and Rashakai SEZ lies on western route. Firstly, load assessment of these industrial zones is carried out, then the technical and economical assessment of these locations will be finalized. Finally, surplus energy will be used to generate Green Hydrogen. The recourse assessment for renewables will be done using RETScreen Software.

3.1 Demand Assessment of SEZs

The outlook of the respective SEZs and their associated industries is derived from relevant studies and the natural resources available in these regions. Dhabeji, Faisalabad, Rashakai, and Bostan SEZs, along with their optimal industrial setups, are detailed in Table

Cotton is predominantly produced in Punjab (70%) and Sindh (28%), making textile industries a suitable choice for the Dhabeji and Faisalabad SEZs [56].Similarly, sugar cultivation is prevalent in all three Provinces except Balochistan. Central and southern regions such as Faisalabad and Sahiwal of Punjab, Thatta and Badin of Sindh, and in Khyber Pakhtunkhwa, notably in Dera Ismail Khan and Mardan[57]. In the case of tobacco, cultivation is concentrated in Khyber Pakhtunkhwa (75%), primarily around Nowshera, and Swabi, which encourages the establishment of tobacco-related industries in the Rashakai SEZ [58].Additionally, the neighboring districts of Mardan, Swabi, and Swat in the Rashakai region are known for marble deposits, making the inclusion of marble processing industries viable in this industrial zone[59].overall the industries and their details are taken from the CPEC authority, which has designated these fixed industries[60].

Table 3.1: Possible SEZs Industries setup and their demands

Industry	Demand (MW)	Dhabeji (Units)	AIC (Units)	Rashakai (Units)	Bostan (Units)
Textile	5	2	3	-	-
Tanning	1	2	2	2	2
Cement	10	2	2	2	1
Petrochemical	10	2	-	1	1
Inorganic Chemical	6	2	3	1	1
Food Processing	1	3	5	2	2
Fruit Processing	0.5	4	5	4	5
Sugar	4	1	3	2	-
Sports	1	2	-	1	-
Marble	5	-	-	2	-
Tobacco	0.5	-	-	4	-
Manufacturing West Route	4	-	-	5	4
Manufacturing East Route	6	4	4	-	-
Total (**MW)**		**99**	**98.5**	**83**	**48.5**

3.2 Load Assessment

Cotton is Kharif crop which is sown in early April, may and is harvested around September so that the industries are in full load during the end of year. Overall all industries are assumed to be run at 95% of time yearly which makes 8322 working days. Cement plant is assumed to work for 82% of the days considering they cannot run at full capacity every day of the year due to several factors that requires periodic shutdowns. These low load periods may be due to maintenance, inspections and for safety measures. All other industries are operated for 95% of year while the seasonal dependent plant like fruit and sugar industry are assumed to vary their load according to their availability in season. For sugar industry during off season mostly load is in the form of packaging and storage energy requirement. The peak for sugar industry which is harvested in October/November so the industry will in full swing from November till April. Rest of the season industry will be assumed to run at 15% load[61].home appliance, agriculture equipment manufacturing and spare and electronic parts manufacturing are generalized under the name of manufacturing industry. The assed load is graphed in the Figure 3.1 to Figure 3.4.

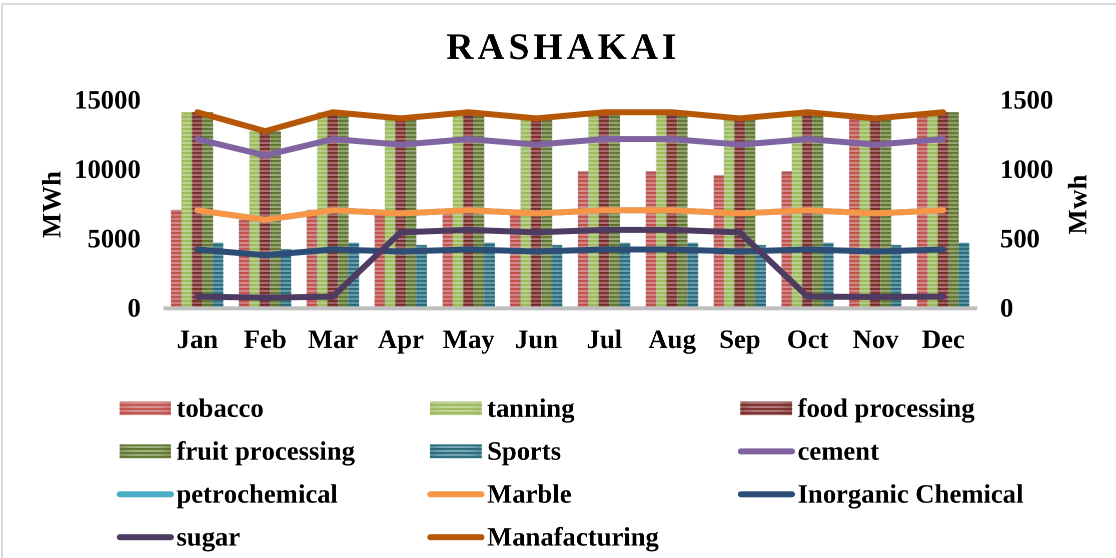

Figure 3.1: Yearly Load for Various Industries in Rashakai SEZ

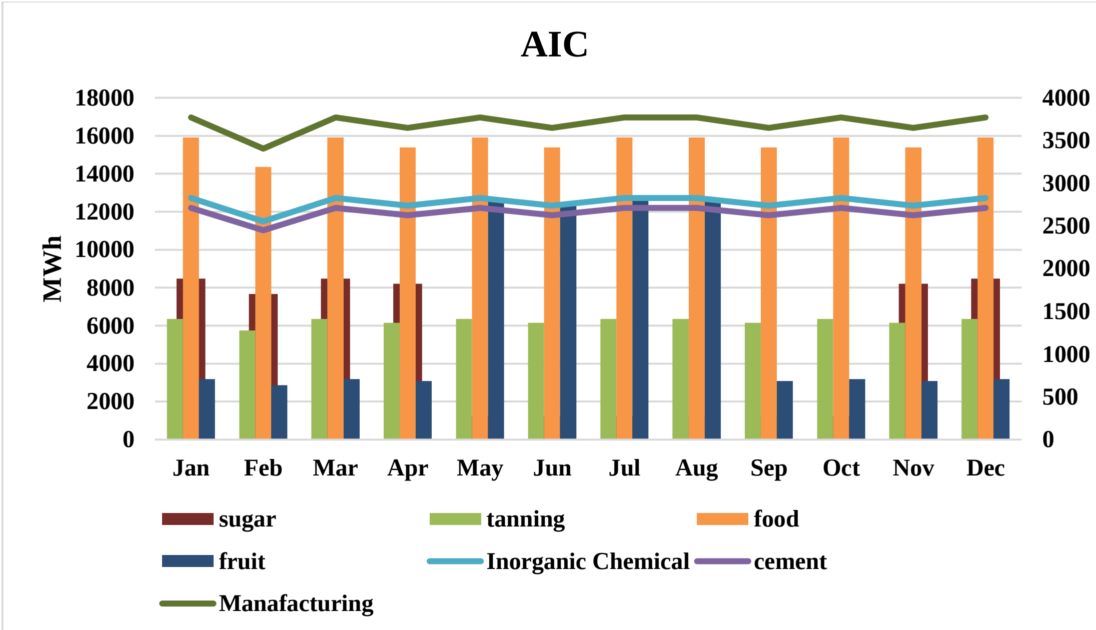

Figure 3.2: Yearly Load for Industries in Allama Iqbal Industrial City

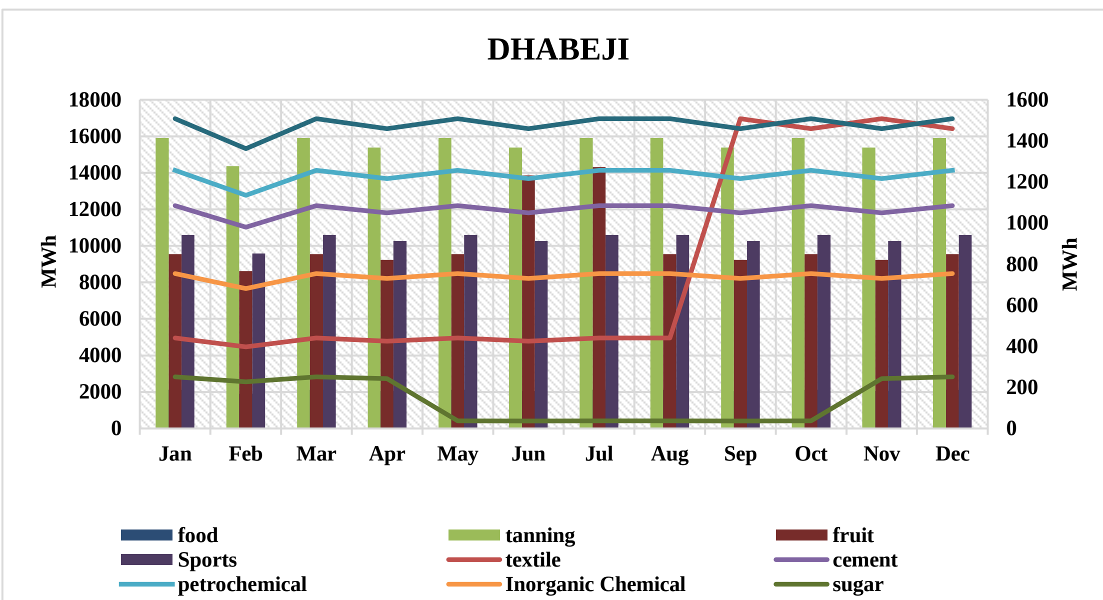

Figure 3.3: Yearly Load for Industries in Dhabeji SEZ

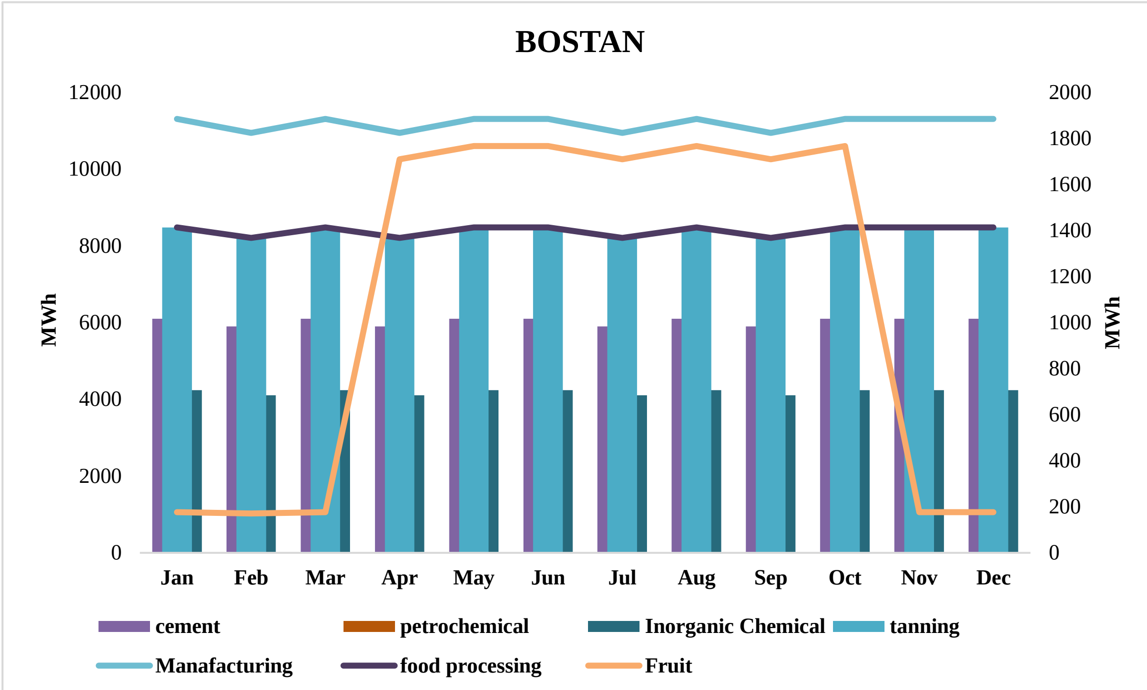

Figure 3.4: Yearly Load for Industries in Bostan SEZ

3.3 Resource Assessment

For the resource assessment and economic analysis of Special Economic Zones (SEZs), RETScreen was utilized as the primary tool. This comprehensive clean energy management software, developed by Natural Resources Canada, is renowned for its capability to evaluate energy production, savings, costs, emission reductions, financial viability, and risk across various energy projects. Specifically, for Allama Iqbal Industrial City, the indigenous resources assessed include agricultural biomass and solar energy. For the Dhabeji SEZ, a wind-solar hybrid system was evaluated, while for Bostan in Baluchistan, only solar resources are available. In the case of Rashakai SEZ, located near the Kabul and Indus Rivers, a hybrid approach using hydro-solar resources was analyzed.

RETScreen facilitated a detailed evaluation of these diverse energy sources across different SEZs, providing critical insights into the energy needs and economic viability, thereby supporting sustainable development through optimized energy resource utilization.

All SEZs have used the solar energy combined with other local Indigenous resources. Solar tracking is of fixed mode to minimize cost and complexity with panels facing due South. The values for slope for respective are taken with most suitable position [62]. Form RETScreen database we have used Jinko Solar, specifically the JKM600N-78HL4 600W model. The system is designed with a nominal operating cell temperature of 45°C and a temperature coefficient of 0.4%. The setup also accounts for a bifacial cell adjustment factor of 6%, which compensates for the additional energy generation from the rear side of bifacial panels. Additionally, the system includes miscellaneous losses of 3%, which cover potential inefficiencies such as those caused by wiring or shading. The inverter selected for this setup has a high efficiency of 97% and a capacity of 50 kW. This configuration ensures a robust and efficient solar energy system tailored for the SEZ, designed to maximize energy production while minimizing losses. Other Parameters vary with the location of SEZ.

3.3.1 Dhabeji solar -wind Hybrid

The values of the wind and solar irradiance for Dhabeji is calculated by RETScrreen as shown in the Fig 3.4. The optimal slope for fixed panels for this location is found 29.1^0. The default values for wind speed is calculated in m/s above 10m of ground. As we are going to use the Goldwind GW140-120m model with rated capacity of 3MW. The Power data and Energy data curve in RETScreen is obtained by putting values of m/s obtained. We have used the NASA earth data to find the wind speed for five years which is averaged and, finally Interpolated for 120 m hub height, as shown by general wind profile power law formula in equation 3.1. Where V_2 is the wind speed at the target height $H2$ OF 100 m,V_1 is wind speed in m/s at height $H1$ of 50m. α is wind shear exponent of 0.12.

$$V_2 = V_2 \times \left(\frac{H2}{H1}\right)^{\alpha} \tag{3.1}$$

Fig 3.5 shows the wind speed against each month, including speed calculated at different years for 50m and interpolated value of speed at 120m.

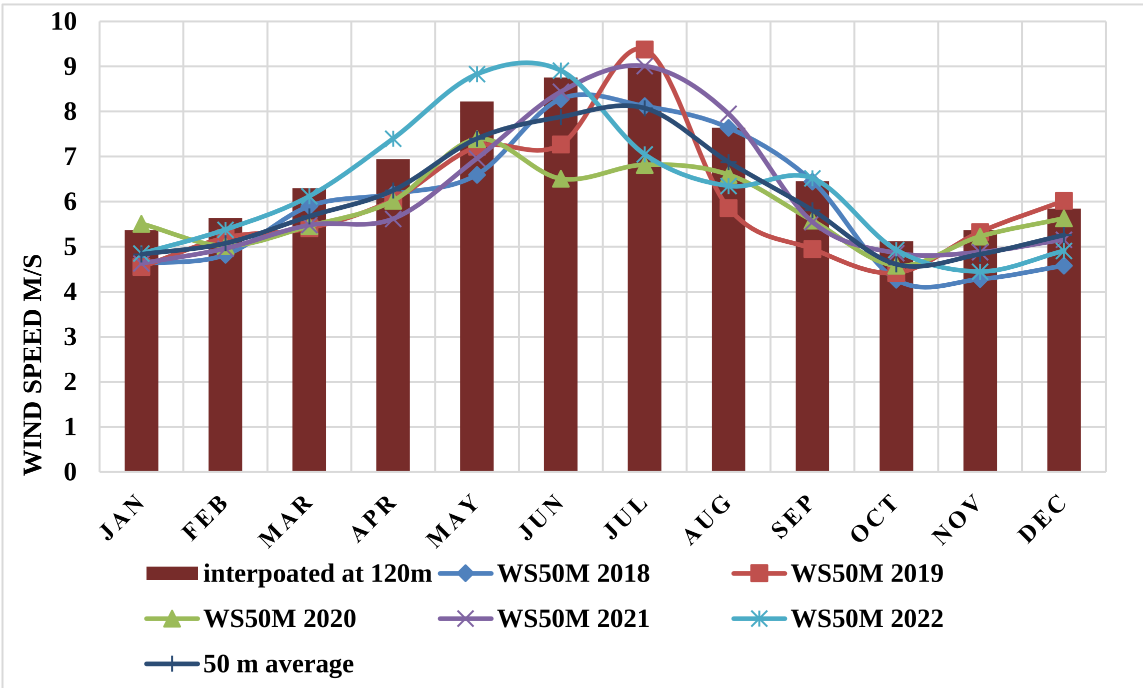

Figure 3.5: Wind Speed over the year

3.3.2 Allama Iqbal Industrial city, Solar-Biomass Hybrid

Faisalabad is among the top industrial cities of Pakistan with its notable Renewable resources of Agriculture Biomass and Solar energy. For solar the slope for orientation of solar panels is 27^0. The available crop residues include Rice Straw, Rice Husk, Sugarcane Trash, Sugarcane Bagasse, Cotton Stalks, Wheat Straw, Maize Straw, and Maize Cob. He avalablity of these in Faisalabad disctict is shown in Table 3.2 in 10^3×MT[63]. These sources are characterized by different prices, reflecting their potential value in biomass energy generation[64]. The Findings in paper are tabulated in Table 3.2. Fuel selection for steam turbine is mix of these biomass residues found, according to their percentage availability. The detailed fuel percentage is shown in Figure 3.6.

Table 3.2: Available Agriculture biomass in vicinity of Faisalabad

S. No.	**Crop Residues (10^3 MT)**	**Biomass (10^3 MT)**	**USD/ton**
1	Rice Straw	48.24	64
2	Rice Husk	5.62	87
3	Sugarcane Trash	1288.18	40
4	Sugarcane Bagasse	373.57	32
5	Cotton Stalks	46.94	64
6	Wheat Straw	120.91	66
7	Maize Straw	194.5	66
8	Maize Cob	35.4	60

Fuel type	Fuel mix
Rice - straw - t	2.282%
Rice - hull - t	0.2659%
Bagasse - t	78.63%
Cotton waste - t	2.221%
Wheat - straw - t	5.721%
Corn - straw - t	9.2%
Corn cob - t	1.675%
	100%

Figure 3.6: Fuel type Contribution for combustion

3.3.3 Rashakai Solar-Hydro, Hybrid

The Rashakai SEZ is located near the Kabul River and outflow of Tarblea dam on Indus river. This SEZ can exploit both hydro power and solar energy. Slope of 29^0 is optimal fixed orientation for solar system. The hydro power project is anticipated to be a run-of-river installation, utilizing technology provided by RETScreen, with an expected capacity factor of 49%[65].For simulations Kaplan turbines of General Electric are used.

3.3.4 Bostan Solar Setup

Bostan near Quetta is an apt location for tapping solar energy because it is a region of barren desert which is ideal for generation of sun power. While in other regions there could be more than one renewable energy resources that can be harnessed, in the case of Bostan, there is only the solar energy resource as other renewable energy resources are not available or are scarce. Using RETScreen modelling, the most suitable fixed tilt angle for solar plants in Bostan has been concluded to be at 26^o and the average solar energy generation stands at 6. 01 kWh/m^2/day. Due to high solar radiation, Bostan is suitable for solar power generation especially for the SEZs such as CPEC, which will provide sustainable and effective energy supply for industrial usage.

3.4 Initial Costs of system

These projects are averaged with the lifetime of 25 years, with the salvage value of 10% of their initial cost[66] [67]. In power system setup, each system is designed with 2.5 Km of road and 2.5 Km of transmission line, along with one substation. The costs, calculated in USD and derived from the RETScreen database. Specifically, the costs include $73,153.50 for each kilometer of road and transmission line, and $1,463,070 for each substation.

The financial considerations for the project include several key factors. The inflation rate is set at 10%, while the discount rate is 7%. The financing structure is composed of a 70% debt ratio and 30% equity. The debt carries an interest rate of 3%, with a term of 15 years, though no specific annual debt payment is recorded. For the revenue side, the electricity export escalation rate is set at 3%. Additionally, a fuel escalation rate of 3% is applicable exclusively to the biomass component, as no fuel is used in other systems. Notably, the project benefits from the tax exemptions available in Pakistan for renewable energy technologies, including exemptions from customs or sales taxes and income taxes, which further enhance its financial viability and sustainability [68]. The initial cost for solar, wind Biomass and the hydropower system are $876, $1292, $1950 and $1753 respectively taken from IRENA renewable generation cost report 2022[65] .

3.4.1 Photovoltaic System Cost

The IC for the Photovoltaic system is $876 per kW as taken from IRENA generation cost 2022.The breakdown cost as per this report and Quaid Azam solar power plant shown in Table 3.3 [69][65].

Table 3.3: Breakdown of Solar Cost

IC	Main Costs	Breakdown of system	Percentage of IC	USD
Initial Cost	Feasibility	pre-feasibility	0.70%	$6.13
	Development	initial stage development	1.70%	$14.89
	Power System	solar PV+I invertors	37%	$324.12
		Road access	RETScreen	$73,153.50
		TL	RETScreen	$73,153.50
		Substation	RETScreen	$1,463,070
	Engineering & management	safety/soft charges	16.60%	$145.42
	Balance and Misc.	Electrical	23%	$201.48
		(Transformer, inverter gears, cables)		
		Site excess and staging	5.00%	$43.80
		Foundation/mounting	6.00%	$52.56
		Assembly & Installation	6.00%	$52.56
		Contingencies	4%	$35.04
Total				$876.00

3.5 Biomass based System Cost

The Agriculture The agricultural biomass, available consistently throughout the year as demonstrated in Table 3.2, provides a sustainable source of energy. The price of biomass feedstock residue has been carefully calculated, along with the initial costs for the steam turbine, boiler, and associated equipment[64]. Given the high level of agricultural activity in Punjab, fuel availability is estimated at 80%. The associated cost is calculated to be $1950 per kW, as illustrated in Table 3.4 [65].

Table 3.4: Breakdown of Biomass Cost

IC	Main Costs	Breakdown of system	Percentage of IC	USD
Initial Cost	Power System	Conversion System	47%	$916.50
		road	RETScreen	$1,463,070
		TL	RETScreen	$1,463,070
		Substation	RETScreen	$73,153.50
	Engineering & management	safety/soft charges	18%	$351.00
	balance and Misc.	Electrical	6%	$117.00
		Civil works	16%	$312.00
		Ash handling	1%	$19.50
		Fuel handling	10%	$195.00
		Prime move	2%	$39.00
Total				$1,950.00

3.5.1 Wind system Cost

The cost of wind energy in Pakistan is around $1250 per. The cost of wind for utility scale wind farm wind power for the 3MW plant is breakdown according to NERAL report on wind turbine cost and IRENA report in Table 3.5. [65], [70].

Table 3.5: Breakdown of Wind system Cost

IC	**Main Costs**	**Breakdown of system**	**Percentage of IC**	**USD**
Initial Cost	Feasibility	pre-feasibility	0.31%	$4.00
	Development	initial stage development	1.24%	$16.00
	Power System	Wind turbine	65.17%	$842.00
		road	RETScreen	$1,463,070
		TL	RETScreen	$1,463,070
		Substation	RETScreen	$73,153.50
	Engineering & management	safety/soft charges	4.02%	$52.00
	Balance and Misc.	Electrical	11.22%	$145.00
		Site excess and staging	3.41%	$44.00
		Foundation/mounting	4.57%	$59.00
		Assembly & Installation	3.41%	$44.00
		Contingencies	6.66%	$86.00
Total				$1,292.00

3.5.2 Hydro Power Cost

Hydropower Cost is shown in table 3.6. It is to be noted that the cost of river are taken for big runoff river projects as per IRENA report.

Table 3.6: Breakdown of hydropower Cost

IC	**Main Costs**	**Breakdown of system**	**Percentage of IC**	**USD**
Initial Cost	Engineering & mang	safety/soft charges	16%	$280.48
	balance and Misc.	Electrical	6%	$105.18
		Mechanical	33%	$578.49
		Civil	45%	$788.85
Total				**$1,753.00**

3.6 Operation & Maintenance Cost

This information O&M cost shown in table 3.7 are taken from report by the International Renewable Energy Agency focusing on renewable production costs, emphasizing the efficiency and output potential of various renewable energy sources[65].

Table 3.7: Operation and Maintenance Cost

Energy Source	**Capacity Factor**	**USD/kW**
Hydro	49%	35.6
Biomass	-	19.5
Wind	38%	21
Solar	-	13.2

CHAPTER 4: RESULTS

All four resources equally (50% each) contribute to the respective Economic zone except the Bostan where the Electricity Generated by solar power plant shown in figure .4. The Figure1 to figure 3 shows the electricity Generated by RE resource of Dhabeji, Rashakai and Faisalabad respectively. Since all locations have solar resource, so the chart depicts values starting from 50% contribution of each resource, followed by 70% solar and 30 % contribution of other indigenous resource and finally 30% solar and 70% indigenous resource. The surplus Electricity to generate Hydrogen is also shown in the figures.

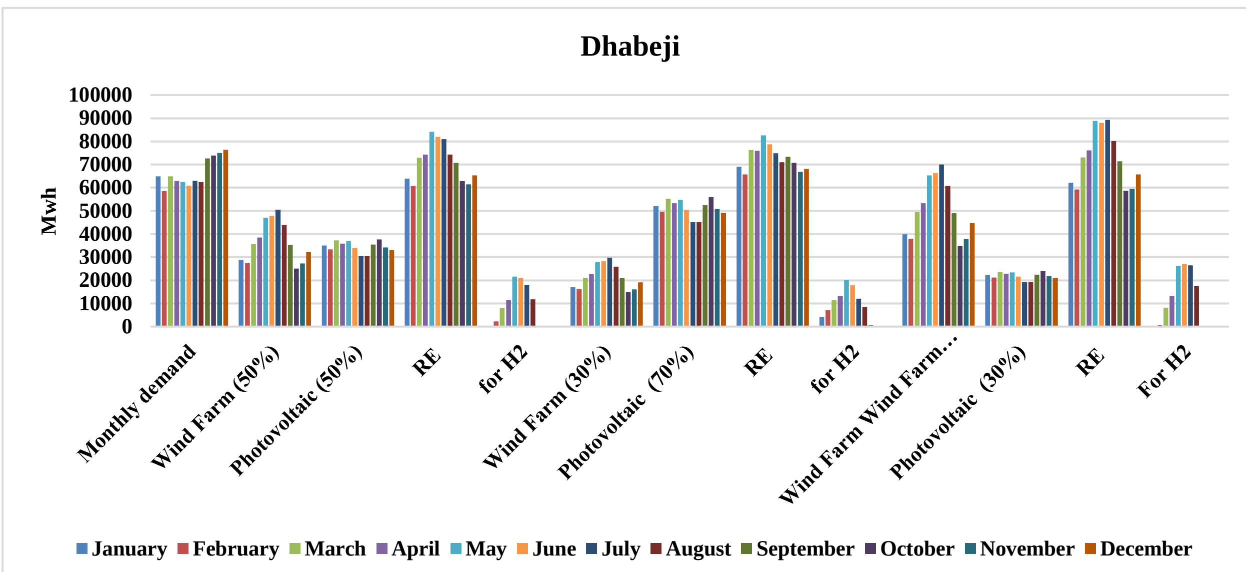

Figure 4.1: Wind-Solar contribution of 50%-50%, 30%-70% and 70% -30% respectively

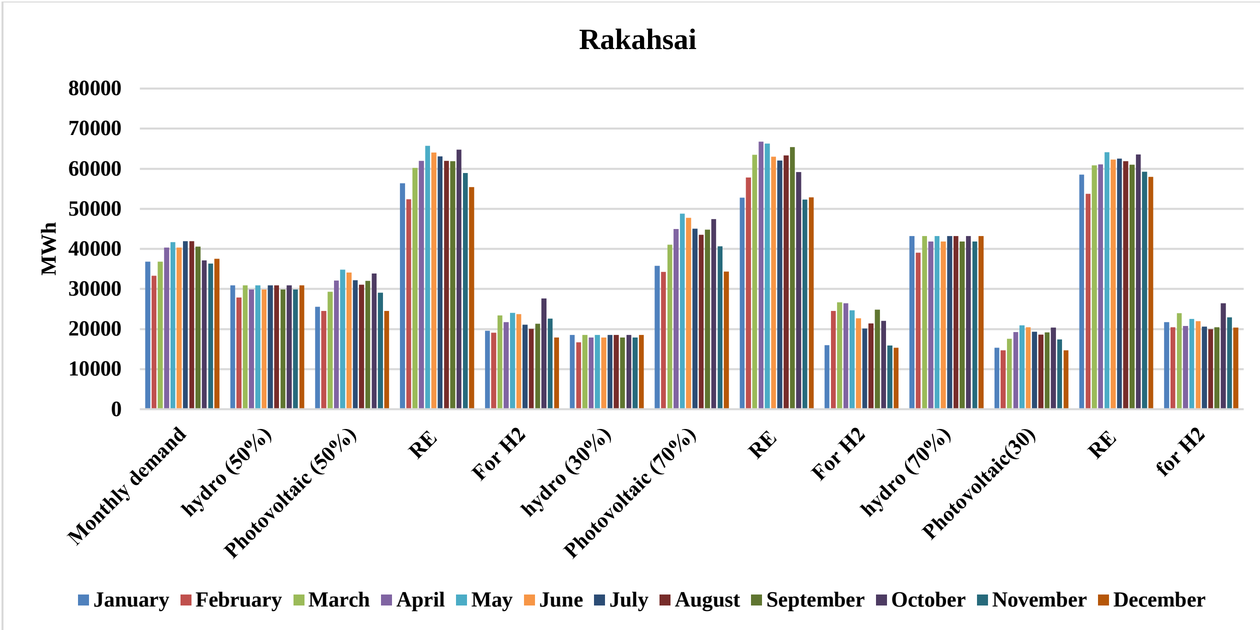

Figure 4.2: Hydro- Solar Hybrid of 50%-50%, 30%-70% and 70%- 30% respectively

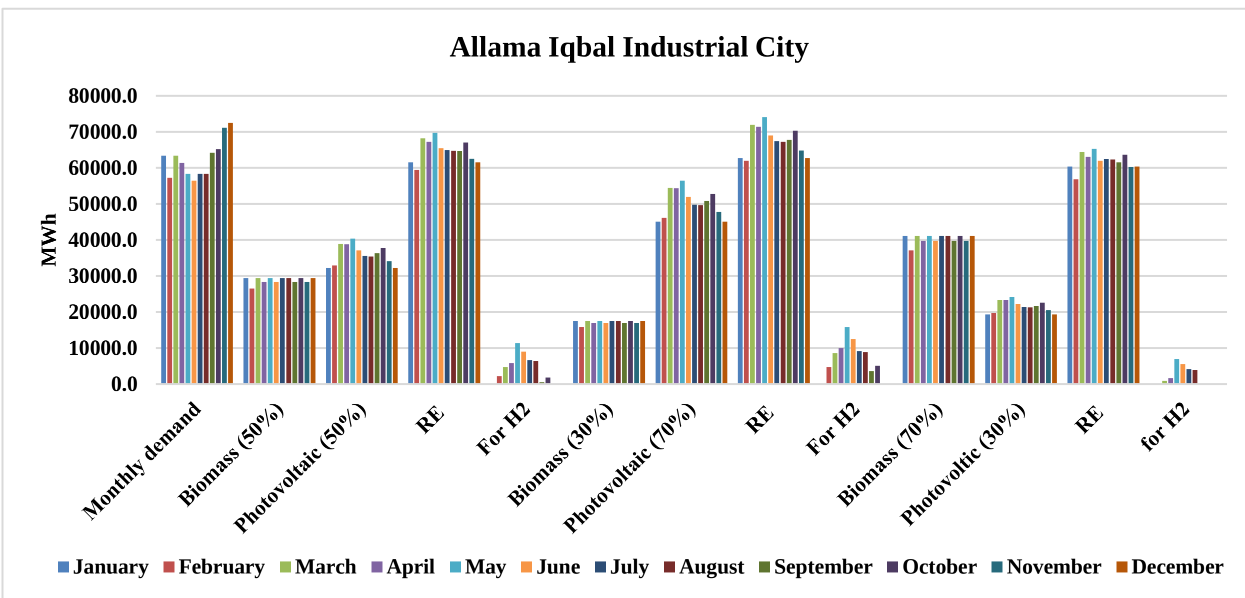

Figure 4.3: Biomass-Solar Hybrid of 50%-50%, 30%-70% and 70% -30% respectively

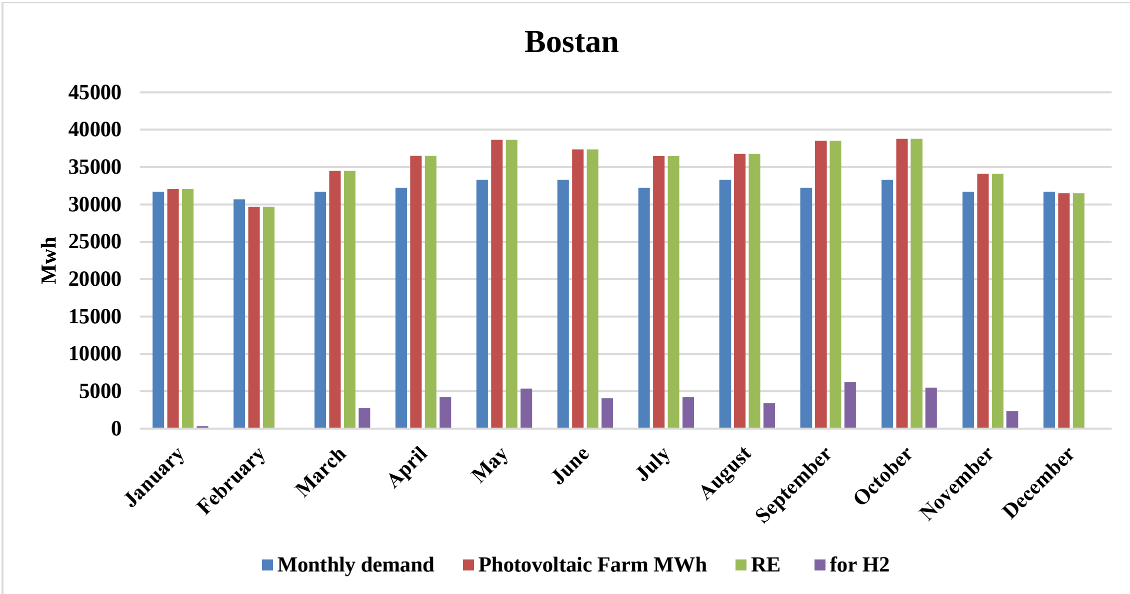

Figure 4.4: Generation of photovoltaic power plant Bostan

4.1 LCOE

The levelized cost of Energy is calculate by RETScreen. These costs including The Capital Cost of power plant and the O&M Cost. As the costs are discussed and detailed information is given is section 3.4. The Results for LCOE from RETScreen are for all SEZs are graphed in figure 4.5. The analysis of the LCOE for the four SEZs using indigenous renewable energy sources reveals some important insights. Dhabeji, which utilizes solar and wind energy, has a slightly lower LCOE when the resource mix is 30%-70%, favouring wind, at 0.0421, compared to 0.0428 with a 50%-50% mix. Rashakai, combining solar and hydro energy, finds its most cost-efficient scenario in the 70%-30% mix, where the LCOE drops to 0.0461. In contrast, the LCOE rises slightly to 0.0472 when hydro becomes the dominant resource. Faisalabad, using solar and biomass, shows the lowest LCOE at 0.0509 with a 70%-30% mix favoring solar. However, the LCOE increases significantly to 0.0574 when the biomass contribution is higher, making it the most expensive option among the SEZs analyzed. Bostan, relying entirely on solar energy, has an LCOE of 0.0415, making it the most cost-effective SEZ overall.

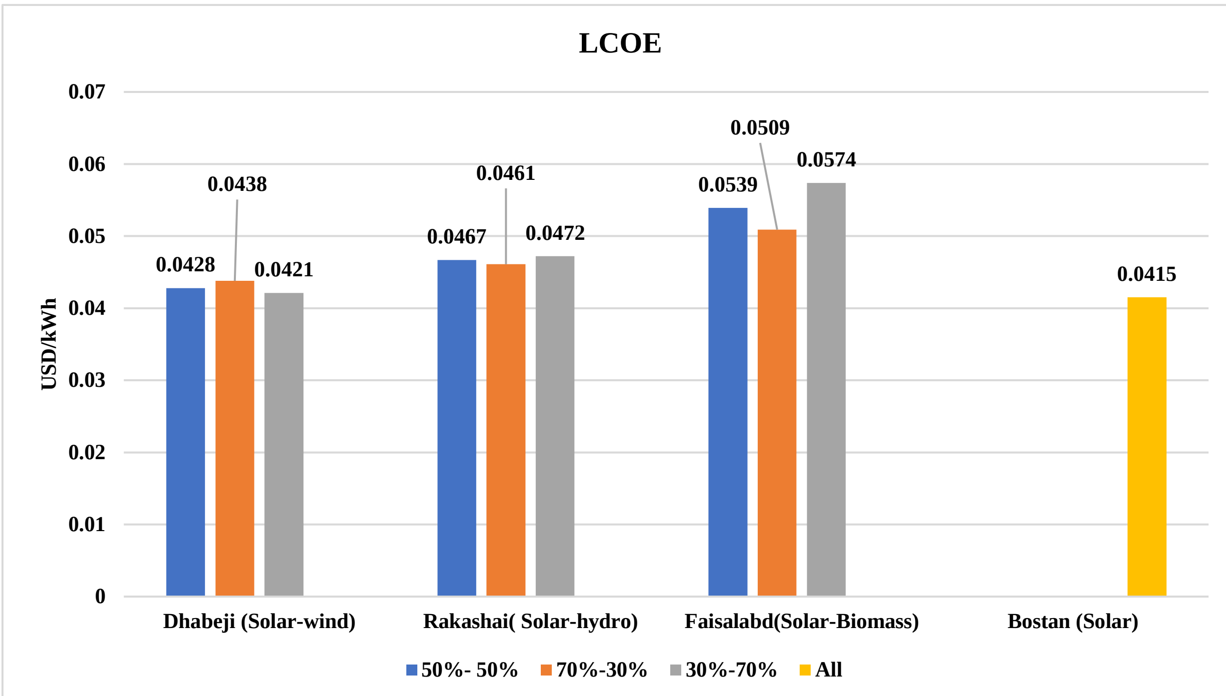

Figure 4.5: LCOE for SEZs with Different RE contribution

4.2 Economic Feasibility Analysis of Exporting Renewable Energy

The Parameters to export This Generated Energy Under the regulations set by NEPRA are discussed in section 3.4 of Chapter 3. Decision to use the specified export electricity rates for different renewable energy sources is based on the authoritative guidance provided by the NEPRA's report titled[71]. The rates used are solar at 0.054 USD, hydro at 0.025 USD, biomass at 0.053 USD, and wind at 0.12 USD reflect the officially sanctioned prices for purchasing electricity from these sources, as outlined by NEPRA. These rates are pivotal for accurately assessing the economic feasibility of exporting generated energy from various renewable sources to the grid. The use of these benchmark rates ensures that the analysis aligns with the current regulatory framework, providing a realistic and standardized reference point for evaluating the financial viability of renewable energy projects. By adhering to these rates, the thesis ensures that the projections and assessments reflect the prevailing economic conditions and regulatory expectations, thereby enhancing the validity and relevance of the economic analysis within the context of the fiscal year 2023-24. The findings of these economic analysis are discussed in next sections.

4.2.1 NPV

The Net Present Value (NPV) as indicated in Figure 4.6 highlights that Dhabeji's financial viability is strongest with a wind-dominant mix, resulting in an NPV of $953.078 million. The NPV decreases to $763.155 million and $571.488 million under equal and solar-dominant mixes, respectively, but remains positive across all scenarios. Rashakai's highest NPV of $129.758 million occurs with a solar-dominant mix, but the NPV becomes negative (-$13.054 million) when hydro is the dominant resource, indicating potential financial losses. Faisalabad's NPV is highest at $209.249 million with a solar-dominant mix, and Bostan, with its fully solar setup, achieves a solid NPV of $157.153 million, reflecting strong financial potential.

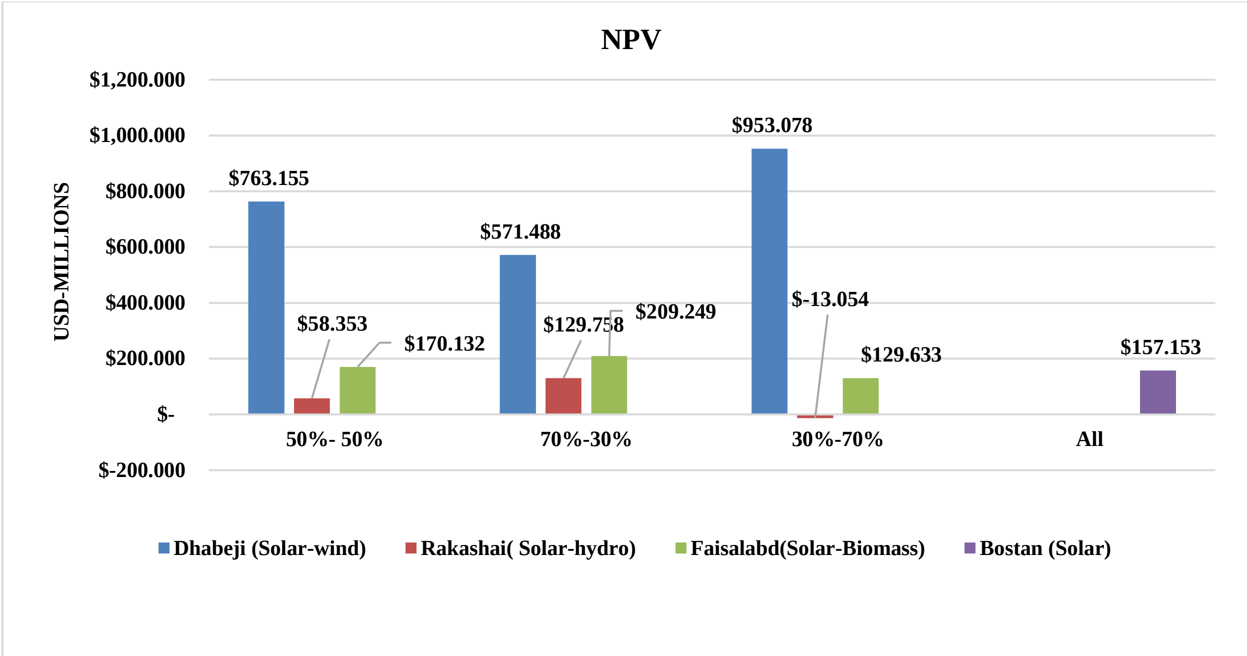

Figure 4.6: NPV for SEZs with Different RE contribution

4.2.2 IRR

The Internal Rate of Return analysis in figure 4.7 indicates that Dhabeji has the highest profitability with an IRR of 62.90% when the energy mix heavily favors wind. The IRR decreases to 50.76% and 37.35% under equal and solar-dominant mixes, respectively, but remains strong across all scenarios. Rashakai's IRR peaks at 14.31% with a solar-dominant mix, but drops to 10.28% and 6.27% with more balanced or hydro-dominant mixes, respectively, indicating less attractive returns. Faisalabad maintains relatively stable IRRs, with the highest at 17.92% under a solar-dominant mix, while Bostan achieves a moderate IRR of 23.79%, suggesting good profitability from its fully solar setup.

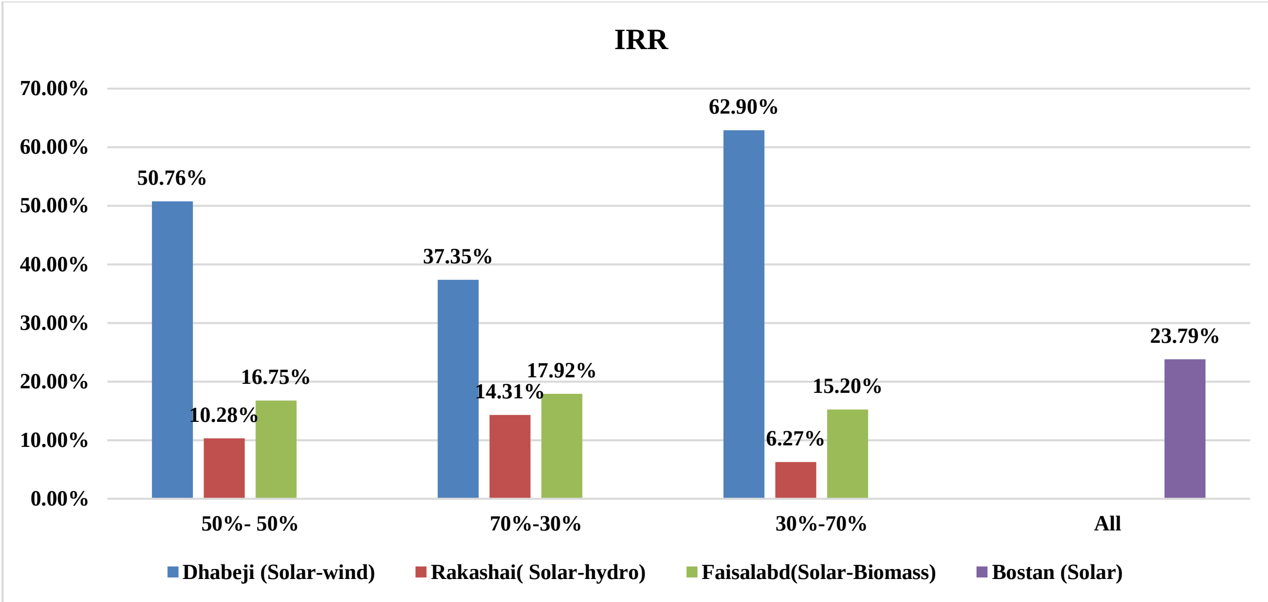

Figure 4.7: IRR for SEZs with Different RE contribution

4.4.3 Payback Period

The Equity Payback Period analysis shows that Dhabeji recovers its investment fastest with a wind-dominant mix, achieving a payback period of 1.66 years. The payback period extends to 2.09 and 2.88 years under equal and solar-dominant mixes, respectively. Rashakai, however, faces much longer payback periods, with the shortest being 8.68 years under a solar-dominant mix, and the longest at 24.13 years with a hydro-dominant mix. Faisalabad's payback period ranges from 6.65 years under a solar-dominant mix to 8.73 years with more biomass, while Bostan's fully solar setup results in a moderate payback period of 4.65 years. The graphical representation is in the Figure 4.8.

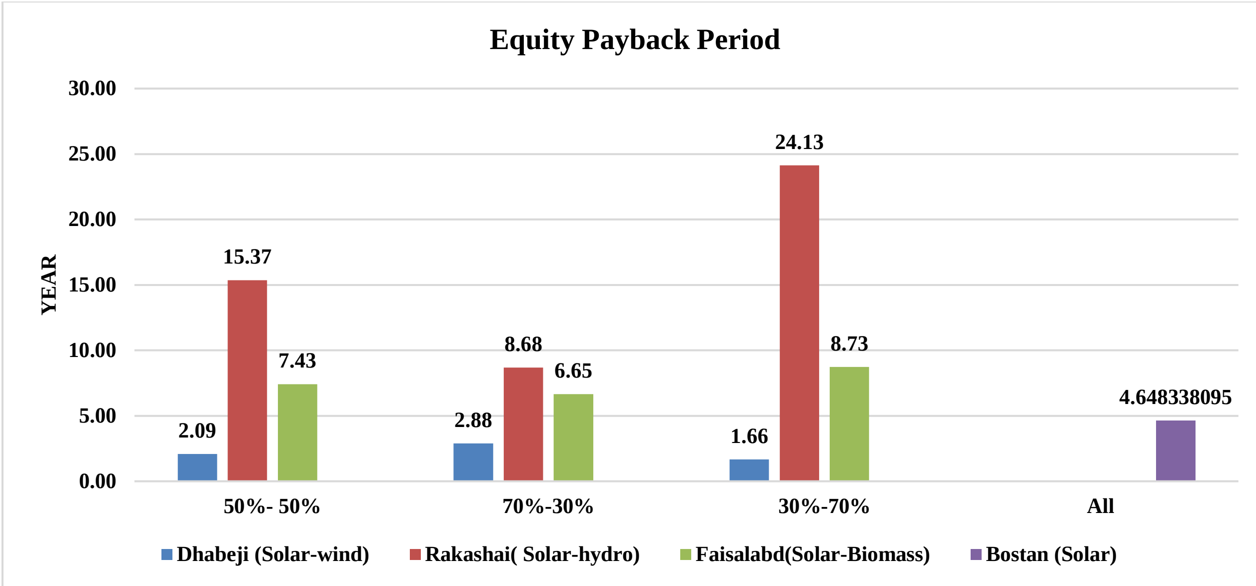

Figure 4.8: Payback Period for SEZs with Different RE contribution

4.5 LCOH

The surplus energy available after supplying the SEZ is assumed to be available for 8 hours per day. The size of the electrolyzer is calculated using the formula: as in equation 4.1.

$$Size\ of\ Electrolyzer = \frac{Surplus\ Energy\ average}{operating\ hours} \tag{4.1}$$

For the initial cost estimate of an alkaline electrolyser system, IRENA report provides a capital cost range of 500 to 1,000 USD/kW for systems larger than 10 MW. For this analysis, a midpoint value of 700 USD/k was selected, reflecting a practical and industry-aligned estimate. The electrolyser system's lifetime was reported to be 60,000 hours. However, considering that it would not operate continuously throughout the year, a

10-year operational lifetime was assumed. Operational and maintenance costs were estimated to be 1% of the initial capital cost[72].

Modern alkaline electrolysers, with recent advancements, require approximately 50 kWh to produce 1 kg of hydrogen[73]. Therefore, the hydrogen production can be calculated using the following formula in equation 4.2, where SE is the size of the electrolyser in MW and OT is the operating time in hours.

$$Hydrogen\ Produced = \frac{OT \times SE \times 1000}{50kWh} \tag{4.2}$$

Finally, levelized cost of hydrogen will be calculated from equation 4.3 whereas the figure 4.9 gives the LCOH per kg at different locations.

$$LCOH = \frac{LCOE + Electrolyzer\ Cost}{Hydrogen\ Cost} \tag{4.3}$$

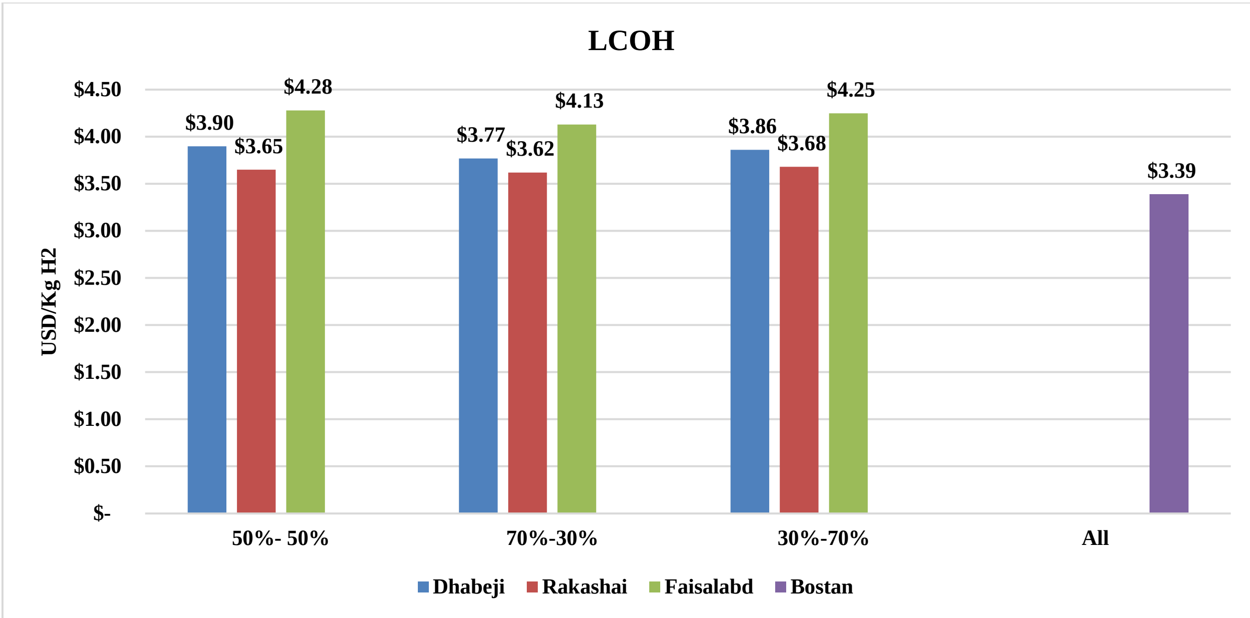

Figure 4.9: LCOH for SEZs with Different RE contribution

The analysis of the Levelized Cost of Hydrogen (LCOH) across the different scenarios reveals critical insights into the cost-effectiveness of hydrogen production in the four SEZs. When the system size is increased by 10%, the surplus energy generated in each scenario increases, thereby reducing the LCOH. Conversely, a decrease in system size by 10% results in less surplus energy, which drives up the LCOH.

Dhabeji exhibits a reduction in LCOH under all sets of conditions when the surplus energy fraction increases, and with $3.77 per kg of hydrogen as well; this value is achieved for the case where 70%-30% solar-hydro mix constitutes. Rashakai has the lowest LCOH for a 70%-30% scenario both is just $3.62 per kg which basically says that here also solar dominator approach must be more cost-effective way of producing hydrogen in this SEZ too. The 50%-50% and 30%–70% blends show slightly higher LCOHs due to the cost of hydrogen produced without excess energy.

The 70%-30% solar-biomass mix in Faisalabad also yields the lowest LCOH at $4.13 per kg compared to $4.28 and $4.25 both in $/kg for the rest of ranges i.e; 50%-50%, and 30%-70%. This indicates that it is beneficial to have as large of a contribution from the sun as possible, despite an energetic source will be more stable if obtained by biomass. While LCOH of Faisalabad is followed by the highest figure among SEZs nonetheless suggesting that its energy mix offer less cost-competitive edge for hydrogen production.

Bostan is only solar-powered and has the lowest LCOH, an average of $3.39 per kg across all sites. The main reason for this is the abundant, and rather predictable, surplus energy available throughout most of the year as seen in earlier datapoints. This contributes towards the high efficiency of hydrogen production where Solar is the primary energy source in this SEZ, making it have low hydrogen cost as compared to other region having combination energy sources.

Taken together, the analysis indicates that increasing system capacity to produce more excess electricity substantially reduces LCOH at all SEZ locations. It is significant that cost-effective hydrogen production requires solar energy, which can be the dominant or only source of such an energy in some scenarios. Dhabeji and Bostan emerge as the two most economically favourable locations for hydrogen production, while Faisalabad's higher LCOH requires optimization of its energy mix to bring costs down.

CHAPTER 5: CONCLUSIONS AND FUTURE RECOMMENDATION

The main focus was to determine the load demand of these SEZs, and examine local renewable energy resources supported by an outlook on green hydrogen generation from excess surplus power. Resource assessment: The resource potential for renewable power generations has been done through RETScreen software and shows high values of each SEZ. Dhabeji, using a solar-wind hybrid system and Faisalabad having used an additional combination of both energy from the sun with biomass present potential in regularity of electricity generation. The hydro-solar hybrid solution from Rashakai took advantage of its close proximity to major rivers while the pure play on solar energy in Bostan was perfectly suited for strong irradiation.

Quantified through economic analysis, the system capacity by 10% results in a meaningful improvement to Levelized Cost of Hydrogen (LCOH) though surplus energy production thereby reducing hydrogen costs across all SEZs. According to the study, Dhabeji and Bostan were found as economic locations for hydrogen production with LCOHs of $3.77/kg and $3.39/kg respectively in case of optimum energy mix scenarios. At $4.13/kg, Faisalabad is charged a higher LCOH compared to other cities which could indicate that it can improve its energy mix with optimization options. The load assessment underscored the need to customise energy mix for each SEZ as per it's given industrial profile. Fluctuations in energy use by season, especially with agriculture and industry examples illustrate the value of systems that can accommodate changing demands. The financial viability of hydrogen production depends on the ability to produce excess energy, particularly in peak production months.

The thesis provides evidence to that a hybridized power system comprising several RES could enhance the energy security and sustainability of SEZs in Pakistan on a combined basis. The thesis filters down a regional, pragmatic solution to its energy need by focusing on the local resources available and types of optimization that this particular energy mix can achieve in these industrial clusters. The financial analysis, with a focus on LCOH in particular, demonstrates a route to economic green hydrogen production that fits within the global trend of decarbonization and accelerating renewable energy adoption.

Although the present analysis provides a robust baseline but it should be worked upon more specifically for still detailed optimization of energy mix especially in SEZs such as Faisalabad to make LCOH lower leading eventual higher overall efficiency. Further studies could analyse the benefits of including more downstream advanced energy storage systems and smart-grid technologies, as well as use more efficient hydrogen production methods (e.g., proton exchange membrane electrolyzers) to increase opportunities for economic competitiveness while complementing feasible sustainable Hybrid Energy Projects. Support on the part of policy and regulatory frameworks by continued government will be important in enabling renewable energy systems and hydrogen production facilities to become mainstream. We could also speed up progress by investigating public-private partnerships and international collaborations. As more SEZs are developed, there is a significant opportunity to create a meshed network of interconnected energy systems. This network could not only enhance the production and distribution of hydrogen but also manage the energy needs of residential and industrial sectors more effectively. Such integration would improve overall energy efficiency, reduce costs, and provide a more reliable energy supply across the SEZs and neighbouring areas. In conclusion, this thesis not only highlights the renewable energy potential within Pakistan’s SEZs but also lays the groundwork for future developments in green hydrogen production, positioning these zones as pivotal players in the country’s energy transition and economic growth. The integration of additional SEZs into a connected energy network could further enhance the effectiveness and sustainability of these initiatives, making a significant contribution to Pakistan's energy security and industrial development.

REFERENCES

[1] "COP27: UN report shows pathways to carbon-neutrality in 'energy intensive' steel, chemicals and cement industries."

[2] K. Kaygusuz, "Energy efficiency and renewable energy sources for industrial sector," *Energy Services Fundamentals and Financing*, pp. 213–238, Jan. 2021, doi: 10.1016/B978-0-12-820592-1.00009-9.

[3] U. Sdg, "Sustainable development goals," *The energy progress report. Tracking SDG*, vol. 7, pp. 805–814, 2019.

[4] F. A. Memon, M. A. Yousaf, and M. Shahid, "Pakistan Energy Demand Forecas."

[5] "https://cpec.gov.pk/."

[6] S. Malik, M. Qasim, H. Saeed, Y. Chang, and F. Taghizadeh-Hesary, "Energy security in Pakistan: Perspectives and policy implications from a quantitative analysis," *Energy Policy*, vol. 144, p. 111552, Sep. 2020, doi: 10.1016/j.enpol.2020.111552.

[7] F. Saeed, Z. A. Abbas, M. Rehan Akhtar, M. H. Yousuf, A. Idrees, and H. A. Tauqeer, "Intelligent Hybrid Energy Resource Connected Demand Side Load Management System-Case of Pakistan," in *2021 4th International Conference on Energy Conservation and Efficiency (ICECE)*, IEEE, Mar. 2021, pp. 1–5. doi: 10.1109/ICECE51984.2021.9406295.

[8] J. Ramsebner, P. Linares, A. Hiesl, and R. Haas, "Techno-economic evaluation of renewable hydrogen generation strategies for the industrial sector," *Int J Hydrogen Energy*, vol. 60, pp. 1020–1040, Mar. 2024, doi: 10.1016/j.ijhydene.2024.02.167.

[9] Y. Abbas and R. A. Aslam, “Potential of Untapped Renewable Energy Resources in Pakistan: Current Status and Future Prospects,” in *ASEC 2023*, Basel Switzerland: MDPI, Oct. 2023, p. 108. doi: 10.3390/ASEC2023-15274.

[10] R. RAMACHANDRAN, “An overview of industrial uses of hydrogen,” *Int J Hydrogen Energy*, vol. 23, no. 7, pp. 593–598, Jul. 1998, doi: 10.1016/S0360-3199(97)00112-2.

[11] W. R. Moomaw, “Industrial emissions of greenhouse gases,” *Energy Policy*, vol. 24, no. 10–11, pp. 951–968, Oct. 1996, doi: 10.1016/S0301-4215(96)80360-0.

[12] “UPDATED NATIONALLY DETERMINED CONTRIBUTIONS 2021,” 2021.

[13] G. D. P. F. B. M. M. M. S. E. B. W. M.-F. F. Q. R. R. M. A. T.-M. P. K. J. G. G. R. S. B. D. M. J. O. D. B. A. S.-M. J. V. E. Crippa M, “GHG emissions of all world countries,” Luxembourg, 2023.

[14] M. Umer, N. Abas, S. Rauf, M. S. Saleem, and S. Dilshad, “GHG emissions estimation and assessment of Pakistan’s power sector: A roadmap towards low carbon future,” *Results in Engineering*, vol. 22, p. 102354, Jun. 2024, doi: 10.1016/j.rineng.2024.102354.

[15] Dr. R. A. K. Raza, M. F. A. Faizan, and J. Naz, “Analysis of Sectoral Energy Demand in Pakistan,” *Reviews of Management Sciences*, vol. 5, no. 1, pp. 63–77, Apr. 2023, doi: 10.53909/rms.05.01.0215.

[16] Y. Abbas and R. A. Aslam, “Potential of Untapped Renewable Energy Resources in Pakistan: Current Status and Future Prospects,” in *ASEC 2023*, Basel Switzerland: MDPI, Oct. 2023, p. 108. doi: 10.3390/ASEC2023-15274.

[17] C. S. Otchia and B. A. Wiryawan, “The impact of special economic zones on structural change,” *J Int Trade Econ Dev*, pp. 1–21, Feb. 2024, doi: 10.1080/09638199.2024.2309927.

[18] Murugesh H. M and Prof. S. B Akash, "SEZs and Socio-Economic Development-A Case Study of AEQUZ Belagavi," *International Journal of Advanced Research in Science, Communication and Technology*, pp. 10–16, Mar. 2023, doi: 10.48175/IJARSCT-8653.

[19] S. M. S. A. Aslam H, "CPEC and Special Economic Zones (SEZs)," Oct. 2019.

[20] E. Hussain and M. F. Rao, "China–Pakistan Economic Cooperation: The Case of Special Economic Zones (SEZs)," *Fudan Journal of the Humanities and Social Sciences*, vol. 13, no. 4, pp. 453–472, Dec. 2020, doi: 10.1007/s40647-020-00292-5.

[21] S. Nirmal and T. Rizvi, "A Review of Renewable Energy Systems for Industrial Applications," *Int J Res Appl Sci Eng Technol*, vol. 10, no. 9, pp. 1740–1745, Sep. 2022, doi: 10.22214/ijraset.2022.46903.

[22] M. Bilal, M. K. Ali, U. Qazi, S. Hussain, M. Jahanzaib, and A. Wasim, "A multifaceted evaluation of hybrid energy policies: The case of sustainable alternatives in special Economic Zones of the China Pakistan Economic Corridor (CPEC)," *Sustainable Energy Technologies and Assessments*, vol. 52, p. 101958, Aug. 2022, doi: 10.1016/j.seta.2022.101958.

[23] C.-H. Chou, S. L. Ngo, and P. P. Tran, "Renewable Energy Integration for Sustainable Economic Growth: Insights and Challenges via Bibliometric Analysis," *Sustainability*, vol. 15, no. 20, p. 15030, Oct. 2023, doi: 10.3390/su152015030.

[24] E. R. Shafkhatov, E. N. Zamyatina, and B. I. Garipov, "Integration of Renewable Energy Resources in the Distribution Network of Industrial Enterprises," in *2020 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)*, IEEE, Jan. 2020, pp. 856–858. doi: 10.1109/EIConRus49466.2020.9039015.

[25] K. S. Khan *et al.*, “Statistical Energy Information and Analysis of Pakistan Economic Corridor Based on Strengths, Availabilities, and Future Roadmap,” *IEEE Access*, vol. 8, pp. 169701–169739, 2020, doi: 10.1109/ACCESS.2020.3023647.

[26] M. Umer, N. Abas, S. Rauf, M. S. Saleem, and S. Dilshad, “GHG emissions estimation and assessment of Pakistan’s power sector: A roadmap towards low carbon future,” *Results in Engineering*, vol. 22, p. 102354, Jun. 2024, doi: 10.1016/j.rineng.2024.102354.

[27] S. M. Shahzad, “RENEWABLE ENERGY RESOURCES IN PAKISTAN: PAVING A WAY FORWARD,” *Pak J Sci*, vol. 74, no. 4, Jan. 2023, doi: 10.57041/pjs.v74i4.760.

[28] S. Stökler, C. Schillings, and B. Kraas, “Solar resource assessment study for Pakistan,” *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 1184–1188, May 2016, doi: 10.1016/j.rser.2015.12.298.

[29] Y. Choi, M. Mae, and H. Bae Kim, “Thermal performance improvement method for air-based solar heating systems,” *Solar Energy*, vol. 186, pp. 277–290, Jul. 2019, doi: 10.1016/j.solener.2019.04.061.

[30] M. F. H. Masum, P. Dwivedi, and W. F. Anderson, “Estimating unit production cost, carbon intensity, and carbon abatement cost of electricity generation from bioenergy feedstocks in Georgia, United States,” *Renewable and Sustainable Energy Reviews*, vol. 117, p. 109514, Jan. 2020, doi: 10.1016/j.rser.2019.109514.

[31] S. Fatima and M. Zeeshan, “Energy potential assessment and geospatial site suitability analysis for crop residue-based power plants in Pakistan,” *Sustain Prod Consum*, vol. 45, pp. 488–508, Mar. 2024, doi: 10.1016/j.spc.2024.01.023.

[32] M. U. Shah, S. Khanum, A. Waqas, A. K. Janjua, and S. Shakir, “A techno-economic and socio-environmental planning of wind farms for sustainable

development and transition to a decarbonized scenario: Pakistan as a case study," *Sustainable Energy Technologies and Assessments*, vol. 55, p. 102969, Feb. 2023, doi: 10.1016/j.seta.2022.102969.

[33] M. H. Baloch, G. S. Kaloi, and Z. A. Memon, "Current scenario of the wind energy in Pakistan challenges and future perspectives: A case study," *Energy Reports*, vol. 2, pp. 201–210, Nov. 2016, doi: 10.1016/j.egyr.2016.08.002.

[34] A. H. Soomro, M. Abbasi, Saira Umer, and E. Shaikh, "Assessment of Global Wind Power Generation at Jhimpir Pakistan-A Case Study," *Sir Syed University Research Journal of Engineering & Technology*, vol. 13, no. 1, pp. 42–47, Jun. 2023, doi: 10.33317/ssurj.540.

[35] M. H. Baloch, G. S. Kaloi, and Z. A. Memon, "Current scenario of the wind energy in Pakistan challenges and future perspectives: A case study," *Energy Reports*, vol. 2, pp. 201–210, Nov. 2016, doi: 10.1016/j.egyr.2016.08.002.

[36] M. Bilal, M. K. Ali, U. Qazi, S. Hussain, M. Jahanzaib, and A. Wasim, "A multifaceted evaluation of hybrid energy policies: The case of sustainable alternatives in special Economic Zones of the China Pakistan Economic Corridor (CPEC)," *Sustainable Energy Technologies and Assessments*, vol. 52, p. 101958, Aug. 2022, doi: 10.1016/j.seta.2022.101958.

[37] S. L. Braide and D. C. Idoniboyeobu, "Energy-Mix Dynamic for Optimization of Power Generation Strategy and Expansion in a Developing Economy Growth," in *2022 IEEE Nigeria 4th International Conference on Disruptive Technologies for Sustainable Development (NIGERCON)*, IEEE, Apr. 2022, pp. 1–5. doi: 10.1109/NIGERCON54645.2022.9803006.

[38] M. H. Rasool, U. Perwez, Z. Qadir, and S. M. H. Ali, "Scenario-based techno-reliability optimization of an off-grid hybrid renewable energy system: A multi-city

study framework," *Sustainable Energy Technologies and Assessments*, vol. 53, p. 102411, Oct. 2022, doi: 10.1016/j.seta.2022.102411.

[39] M. Korpeh, P. Asadbagi, R. Afshari, A. Rashidi, and A. Lotfollahi, "A comprehensive analysis and multi-objective optimization of a sustainable production system based on renewable energies," *Appl Therm Eng*, vol. 242, p. 122483, Apr. 2024, doi: 10.1016/j.applthermaleng.2024.122483.

[40] S. Nawaz Khan and S. Ali Abbas Kazmi, "Integrative decision-making framework for techno-economic planning and sustainability assessment of renewable dominated standalone hybrid microgrids infrastructure at provincial scale of Pakistan," *Energy Convers Manag*, vol. 270, p. 116168, Oct. 2022, doi: 10.1016/j.enconman.2022.116168.

[41] M. Z. Baig and M. Jahanzaib, "Risk Assessment of Sustainable Renewable Energy Resources on CPEC Route," *International Journal of Academe and Industry Research*, vol. 3, no. 1, pp. 1–25, Mar. 2022, doi: 10.53378/352855.

[42] M. Z. Baig and M. Jahanzaib, "Risk Assessment of Sustainable Renewable Energy Resources on CPEC Route," *International Journal of Academe and Industry Research*, vol. 3, no. 1, pp. 1–25, Mar. 2022, doi: 10.53378/352855.

[43] R. RAMACHANDRAN, "An overview of industrial uses of hydrogen," *Int J Hydrogen Energy*, vol. 23, no. 7, pp. 593–598, Jul. 1998, doi: 10.1016/S0360-3199(97)00112-2.

[44] B. Amini Horri and H. Ozcan, "Green hydrogen production by water electrolysis: Current status and challenges," *Curr Opin Green Sustain Chem*, vol. 47, p. 100932, Jun. 2024, doi: 10.1016/j.cogsc.2024.100932.

[45] L. Pingkuo and G. Junqing, "Comparative analysis on the development potential of green hydrogen industry in China, the United States and the European Union," *Int J*

Hydrogen Energy, vol. 84, pp. 700–717, Sep. 2024, doi: 10.1016/j.ijhydene.2024.08.298.

[46] B. Akarsu and M. Serdar Genç, "Optimization of electricity and hydrogen production with hybrid renewable energy systems," *Fuel*, vol. 324, p. 124465, Sep. 2022, doi: 10.1016/j.fuel.2022.124465.

[47] M. A. Khan, I. Al-Shankiti, A. Ziani, and H. Idriss, "Demonstration of green hydrogen production using solar energy at 28% efficiency and evaluation of its economic viability," *Sustain Energy Fuels*, vol. 5, no. 4, pp. 1085–1094, 2021, doi: 10.1039/D0SE01761B.

[48] M. Zghaibeh *et al.*, "Optimization of green hydrogen production in hydroelectric-photovoltaic grid connected power station," *Int J Hydrogen Energy*, vol. 52, pp. 440–453, Jan. 2024, doi: 10.1016/j.ijhydene.2023.06.020.

[49] Q. Hassan, I. S. Abdulrahman, H. M. Salman, O. T. Olapade, and M. Jaszczur, "Techno-Economic Assessment of Green Hydrogen Production by an Off-Grid Photovoltaic Energy System," *Energies (Basel)*, vol. 16, no. 2, p. 744, Jan. 2023, doi: 10.3390/en16020744.

[50] W. Dai, J. Chen, Y. Zhang, D. Lin, and Y. Shi, "Optimal day-ahead operation strategy of an electricity-hydrogen integrated energy system considering extra-day forecast information," in *2021 IEEE Sustainable Power and Energy Conference (iSPEC)*, IEEE, Dec. 2021, pp. 863–870. doi: 10.1109/iSPEC53008.2021.9735690.

[51] J. Ahmad *et al.*, "Wind-to-Hydrogen Production Potential for Selected Sites in Pakistan," *IEEE Access*, vol. 9, pp. 134874–134898, 2021, doi: 10.1109/ACCESS.2021.3116259.

[52] J. Liu, Q. Abbas, M. Alharthi, M. Mohsin, F. Rasul, and N. Iqbal, "Managerial policy and economic analysis of wind-generated renewable hydrogen for light-duty

vehicles: Green solution of energy crises," *Environmental Science and Pollution Research*, vol. 28, no. 9, pp. 10642–10653, Mar. 2021, doi: 10.1007/s11356-020-11018-1.

[53] K. Shiraishi, W. Y. Park, and D. M. Kammen, "The role of hydrogen as long-duration energy storage and as an international energy carrier for electricity sector decarbonization," *Environmental Research Letters*, vol. 19, no. 8, p. 084011, Aug. 2024, doi: 10.1088/1748-9326/ad5856.

[54] R. Merino-Martínez, R. Pieren, and B. Schäffer, "Holistic approach to wind turbine noise: From blade trailing-edge modifications to annoyance estimation," *Renewable and Sustainable Energy Reviews*, vol. 148, p. 111285, Sep. 2021, doi: 10.1016/j.rser.2021.111285.

[55] F. L. Byk, E. M. Ivanova, and L. S. Myshkina, "Formation of Energy Supply Systems for Special Economic Zones," *Problems of the Regional Energetics*, no. 3(63), pp. 56–70, Jul. 2024, doi: 10.52254/1857-0070.2024.3-63.05.

[56] "Cotton," ayaub agricultural research institute faisalabad. Accessed: Aug. 21, 2024. [Online]. Available: ahttps://aari.punjab.gov.pk/crop_varieties_cotton

[57] S. Afghan, M. Ehsan Khan, W. Raza Arshad, K. Bukhsh Malik, and A. Nikpay, "Economic Importance and Yield Potential of Sugarcane in Pakistan," in *Sugarcane - Its Products and Sustainability*, IntechOpen, 2023. doi: 10.5772/intechopen.105517.

[58] N. Ali, J. Abbas, M. Anwer, S. Murtazain, R. Zaidi, and N. Ali, "The Economic Analysis of Tobacco Industry: A Case Study of Tobacco Production in Pakistan," *International Journal of Research (IJR)*, vol. 2, Aug. 2015.

[59] Y. Mansoor and N. A. Syed, “Pakistan Marble Industry Challenges: Opportunities for China in Pakistan,” *JISR management and social sciences & economics*, vol. 10, no. 1, pp. 43–59, Jun. 2012, doi: 10.31384/jisrmsse/2012.10.1.4.

[60] https://cpec.gov.pk/special-economic-zones-projects, “Industrial Cooperation/Special Economic Zones(SEZs).”

[61] J. N. Greenfield, “Fiji/FAO Asia Pacific Sugar Conference,” Fiji, 1997, pp. 20–24.

[62] “Solar Panel Angles for Pakistan.” Accessed: Aug. 21, 2024. [Online]. Available: https://solarific.co/pk

[63] M. Irfan, A. Razzaq, S. Chupradit, M. Javid, A. Rauf, and T. J. Aini Farooqi, “Hydrogen production potential from agricultural biomass in Punjab province of Pakistan,” *Int J Hydrogen Energy*, vol. 47, no. 5, pp. 2846–2861, Jan. 2022, doi: 10.1016/j.ijhydene.2021.10.257.

[64] U. ur Rehman Zia *et al.*, “Financial Model of Levelized Cost of Electricity (LCOE) for Bioenergy Resources in Pakistan,” *Journal of Engineering Research*, Nov. 2022, doi: 10.36909/jer.ICEPE.19533.

[65] M. , A.-Z. S. , & R. P. Taylor, “IRENA (2023), Renewable power generation costs in 2022,” Abu Dhabi, 2023. Accessed: Aug. 21, 2024. [Online]. Available: http://www.irena.org/publications

[66] D. Mikindani, “WindValue, End-of-Life Decisions for Wind Farms,” *The Boolean: Snapshots of Doctoral Research at University College Cork*, pp. 13–18, Mar. 2024, doi: 10.33178/boolean.2024.1.3.

[67] R. Wiser, M. Bolinger, and J. Seel, “Benchmarking Utility-Scale PV Operational Expenses and Project Lifetimes: Results from a Survey of U.S. Solar Industry Professionals,” E-Scholarship Repository, Berkeley, CA (United States), Jun. 2020. doi: 10.2172/1631678.

[68] U. Zafar, T. Ur Rashid, A. A. Khosa, M. S. Khalil, and M. Rashid, “An overview of implemented renewable energy policy of Pakistan,” *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 654–665, Feb. 2018, doi: 10.1016/j.rser.2017.09.034.

[69] M. Asad, F. I. Mahmood, I. Baffo, A. Mauro, and A. Petrillo, “The Cost Benefit Analysis of Commercial 100 MW Solar PV: The Plant Quaid-e-Azam Solar Power Pvt Ltd.,” *Sustainability*, vol. 14, no. 5, p. 2895, Mar. 2022, doi: 10.3390/su14052895.

[70] T. Stehly, P. Beiter, and P. Duffy, “2019 Cost of Wind Energy Review,” Golden, CO (United States), Dec. 2020. doi: 10.2172/1756710.

[71] “National Electric Power Regulatory Authority (NEPRA). 2023. TRF-100 PPP Reference FY 2023-24.” Accessed: Aug. 21, 2024. [Online]. Available: https://nepra.org.pk/tariff/Tariff/Ex-WAPDA%20DISCOS/2023/TRF-100%20PPP%20REFERENCE%20%20FY%202023%2024%2014-07-2023%2018249-53.PDF

[72] E. , B. H. , M. R. , C. M. aibi, “Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal,” Abu Dhabi., 2020.

[73] A. Aghakhani, N. Haque, C. Saccani, M. Pellegrini, and A. Guzzini, “Direct carbon footprint of hydrogen generation via PEM and alkaline electrolysers using various electrical energy sources and considering cell characteristics,” *Int J Hydrogen Energy*, vol. 48, no. 77, pp. 30170–30190, Sep. 2023, doi: 10.1016/j.ijhydene.2023.04.083.