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Integration and economic viability of fueling the future with green hydrogen: An integration of its determinants from renewable economics

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HIGHLIGHTS

- Green hydrogen energy is a clean alternative fuel to increase energy security.
- Sustainable Solution for Severe Energy Crises in Emerging Economies.
- Comparisons of various renewable energy sources to produce hydrogen.
- The guarantee of hydrogen origin is essential to ensure its energy cleanness.

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ABSTRACT

The volatility of fossil fuel and their increased consumption have exacerbated the socio-economic dilemma along with electricity expenses in third world countries around the world, Pakistan in particular. In this research, we study the output of renewable hydrogen from natural sources like wind, solar, biomass, and geothermal power. It also provides rules and procedures in an attempt to determine the current situation of Pakistan regarding the workability of upcoming renewable energy plans. To achieve this, four main criteria were assessed and they are economic, commercial, environmental, and social adoption. The method used in this research is the Fuzzy Analytical Hierarchical Process (FAHP), where we used first-order engineering equations, and Levelized cost electricity to produce renewable hydrogen. The value of renewable hydrogen is also evaluated. The results of the study indicate that wind is the best option in Pakistan for manufacturing renewable based on four criteria. Biomass is found to be the most viable raw material for the establishment of the hydrogen supply network in Pakistan, which can generate 6.6 million tons of hydrogen per year, next is photovoltaic solar energy, which has the capability of generating 2.8 million tons. Another significant finding is that solar energy is the second-best candidate for hydrogen production taking into consideration its low-cost installation and production. The study shows that the cost of using hydrogen in Pakistan

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ranges from $5.30/kg to $5.80/kg, making it a competitive fuel for electric machines. Such projects for producing renewable power must be highlighted and carried out in Pakistan and this will lead to more energy security for Pakistan, less use of fossil fuels, and effective reduction of greenhouse gas emissions.

Introduction

Being used in almost every aspect of our daily life, it is truly hard to think of a world without power or fuel. Energy is a fundamental demand for any country, which constitutes the foundation of its economy [1]. The consumption of fossil fuels currently covers about 85% of the world's demand for energy. Oil, coal, and other Non-renewable fossil fuels are formed through stagnant changes in the organic materials over long periods in time [2,3]. Energy has mainly renewable and non-renewable sources. However, it is the non-renewable energy sources, particularly fossil fuels, which are the most widely consumed [4,5]. It is necessary now, After the anticipated energy dilemma, to look for all alternative energy resources that can be technologically developed. In addition to the need to find modern energy resources, we also need to establish climate-friendly energy requirements [6]. Pakistan is in such strong need of climate-friendly changes as being one of the most affected countries by climate change, including changing weather, floods, and droughts, which in turn affect agricultural production and economic growth [7–14]. Thus, hydrogen energy, which is considered to be the energy source of the future, plays a primary role in Pakistan's energy crisis and can also offset the damaging effects of greenhouse gases GHGs, which are so harmful not only to Pakistan but worldwide.

Pakistan has a 3000 MW gap between energy supply and energy demand, and there are 6–12 h of total power outages every day [15]. This means that this country is transitioning from a severe energy crisis. Not only that, but Pakistan also imports most of its oil supplies from Middle Eastern countries and OPEC [16]. Being an importing country, Pakistan spends most of its budget on imported fuels in order to meet its demands. Statistically speaking, Pakistan imported 6.6 million tons of oil from the international market, valued at US$3.4 billion from July to March in the fiscal year 2019 [17]. Another important factor that affects fuel economy is the Inflation rate. Rising fuel prices affect all sectors like automobile, power generation, and agriculture. Due to the many disadvantages of fossil fuel with its rising prices and reserves expenditure, the world is turning to renewable energy sources, such as alternative fuels that are economically and environmentally stable using and optimizing the residual energy for the pre-installed equipment to meet its needs [18]. Though Pakistan has not succeeded in using advanced technologies to install alternative fuels, however, in some areas of Pakistan, there are some renewable energy projects installed such as solar, wind, and biomass energy [19]. Although the installed capacity of thermal energy is about 25,000 MW, which requires fossil fuel to operate the power plants, which represents 67.74% of the country's energy structure, the country cannot meet the demand of 21,701 MW, leaving a gap of 6,000. MW [20]. between 2008 and 2009, the Pakistani government spent 9 billion U.S. dollars to deal with this huge energy supply and demand gap, which brought a heavy burden to the national economy [21–23]. Renewable energy is a lasting source of steady and stable energy which leads to achieving high levels of energy security.

The increase in population has led to mobility acceleration creating an increasing demand for transportation fuel and this, in turn, led to more gas emissions [24–27]. Being a developing country that does not correctly identify and implement automobile standards and requirements, Pakistan's gas emission rate is higher than the limits specified by the European Union (EU), which has a significant impact on the environment and human health [28]. A recent literature study shows that the world is shifting its attention from the economics of fuel to providing alternatives with less gas emission. A review study by Shahid and Jamal stated that biodiesel is an alternative fuel that is more suitable for engines which has a short operating time and less brake power and high fuel consumption compared to pure diesel.

In addition, Uddin et al. (2021) [29] reported that because of the energy dilemma, third-world countries such as Pakistan and India have adopted a high proportion of natural gas. Kalair et al. (2021) [30] recommended that Pakistan should mix ethanol with gasoline as an alternative fuel, and reduce gasoline consumption by 5–10% by 2030. Shabbir et al. (2020) [31] made a comparison between biodiesel and gasoline. The study shows how promising biodiesel is for Pakistan being affordable and more environmentally friendly.

Looking back to the previously mentioned literature review, we can see that the world is more concerned with renewable energy, gas emission reduction, alternative fuel sources such as bioethanol, fuel cells, biodiesel, renewable hydrogen, hybrid, and electric vehicles (EVs). On the contrary, it is noticeable that the economic, environmental, and social aspects of such fuels are not explored or studied. The economy in third world countries is seriously affected by the economics of fuel as the inflation rate is going higher and the energy crisis is magnified [32–35]. So, in order to implement economically and environmentally stable fuels which help the development of any country, such issues must be resolved and discussed [36]. Pakistan should follow the steps of developed countries and move from gasoline vehicles to fuel cell electric vehicles. In order to achieve such transition, Pakistan needs to assess, plan and develop an energy system coherent with its energy resources, and that system is also commensurate with economical, user-friendly, and climate-friendly applications. Unfortunately, there is very little literature that specifically discusses this aspect of Pakistan's energy system. There is almost no research on the development of the hydrogen economy in Pakistan and related technical issues.

With this goal in mind, this research draws on renewable sources of green H2 produced through wind, solar, biomass, and geothermal energy, and identifies applicable solutions to the energy shortage problem in Pakistan. For this, four main criteria were evaluated: economic, commercial, environmental, and social acceptance. The study uses a two-step model, a Fuzzy-analytical hierarchal process, and first-order engineering techniques to explore H2 production by the selected renewable energy sources. The cost of producing renewable hydrogen is also examined. Based on the empirical results of the fuzzy analysis, the optimization of wind energy resources is best suited for the four criteria (economic efficiency, environmental impact, commercial potential, and social acceptance) to produce hydrogen energy in Pakistan. In addition, the research uses a first-order engineering model and standardized energy costs to measure the production of renewable hydrogen and its cost.

The remaining of this document goes as follows: Section Renewable resources of Pakistan the background, Section Methods description Methodology, Section Results and discussions Results and analysis, Section the results, Section discussion, and finally Section Conclusion and policy implications conclusion and policy implications.

Renewable resources of Pakistan

Solar resource

Solar power can be used to produce hydrogen [37]. Under the World Bank's Energy Sector Management Assistance Program (ESMAP), Pakistan's solar energy resources have been examined and studied. The research assumes that Pakistan's climate and geographic location confirm excellent potentials for solar energy [38].

These considerable parameters imply that the useable surface of solar hydrogen production exceeds 150,000 square kilometers. It is roughly estimated that more than 100 solar thermal power plants can be installed in less than 2% of the area, each with a power of 200 MW [39]. Thus, solar power generation may reach 20 GW, and there is also the possibility for expansion. Moreover, Power engineers have multiple options for setting up CSP (concentrated solar power) or photovoltaic applications, since reports show that the cumulative value of direct normal irradiance and global horizontal irradiance reaches 2000 kWh/m^2 in most of Pakistan [40]. Other factors that make solar energy a referable choice for Pakistan include the following: first, more than half of its area, estimated at 796,095 square kilometers, is highly exposed to solar power and almost empty of residents. Second, main rivers exist to help supply water, which is essential for electrolysis. Third, the solar radiation is high with relatively minimum cloud coverage (see Fig. 1).

There are many renewable energy sources in Pakistan such as wind, solar, biomass, and geothermal energy. This variety in renewable sources is continent for the use of new conversion processes to produce green hydrogen [42,43]. Therefore, this article evaluates and estimates the possibilities of existing renewable energy sources to produce hydrogen. The primary goal is to choose the best renewable energy (RES) that increases green hydrogen production nationwide. Table 1 represents the minimum and maximum solar radiation values, and also Table 2, the area-wise Solar radiation %, these data collected from NASA atmospheric and meteorology center.

The statistics in Table 2 show that 150,000 square kilometers of the area have access to solar radiation and this is the most suitable exposure to maximize the production of green hydrogen. Therefore, we need to promote techniques that are more modern in order to produce green energy in the system [45]. According to a previous estimate, less than 2% of the site can be installed for 100 solar power plants, and these small areas generate 20 GigaWatt of power in the system. Furthermore, green hydrogen production statics is more dependent on the existence of solar energy [46,47]. These studies show that we need approximately 20.5–20.7 acres to generate 1 MW of solar energy.

Wind resource

Speaking about wind power generation, Pakistan reportedly has enormous potential in this regard [48]. Although 23 wind energy projects have been put into commercial production and operation so far in Pakistan, most of which are placed in Gharo and Keti Bandur (60 km \ 170 km). Other parts of the country have yet to be evaluated to see the capability for wind power generation plans. Such assessment of wind resources in Pakistan with the help of USAID and Pakistan Meteorological Department is conducted by National Renewable Energy Laboratory (NREL). Fig. 2 shows the Wind map in Pakistan where each color indicates the class of wind, thus clarifying wind power potentials in each area. Additionally, there have been significant efforts to determine the best locations to establish and develop wind farms whether in urban and rural regions.

Pakistan's wind energy potential is assessed in terms of global units and it was found to have seven classes of wind source. Classes 4, 5, 6, and 7 have the best and highest capability for green hydrogen generation and provide a future possibility for wind farm installation. Table 3 shows these classes from one to seven of wind potential, clearly defined in terms of lengths from 10 to 50 m and parameters above the ground. Results show that in about 9% of Pakistan, the potential for wind power installation is huge. Four to seven wind class levels may provide economical and practical wind energy production.

Table 4 clarifies the hydrogen energy potential of Pakistan's wind resources. According to estimates, we produce (45,000 tons) of hydrogen energy, which is equivalent to 53 kW-hours per kilogram [51–55]. Pakistan was making 900 MW of wind power, which can produce 360 tons of hydrogen energy.

Geothermal resource

Reports in the year 2012 state that 19% of total final energy consumption globally is mainly renewable energy. Nine percent corresponds to biomass energy, 3.8% corresponds to hydropower, while solar/wind energy and geothermal energy

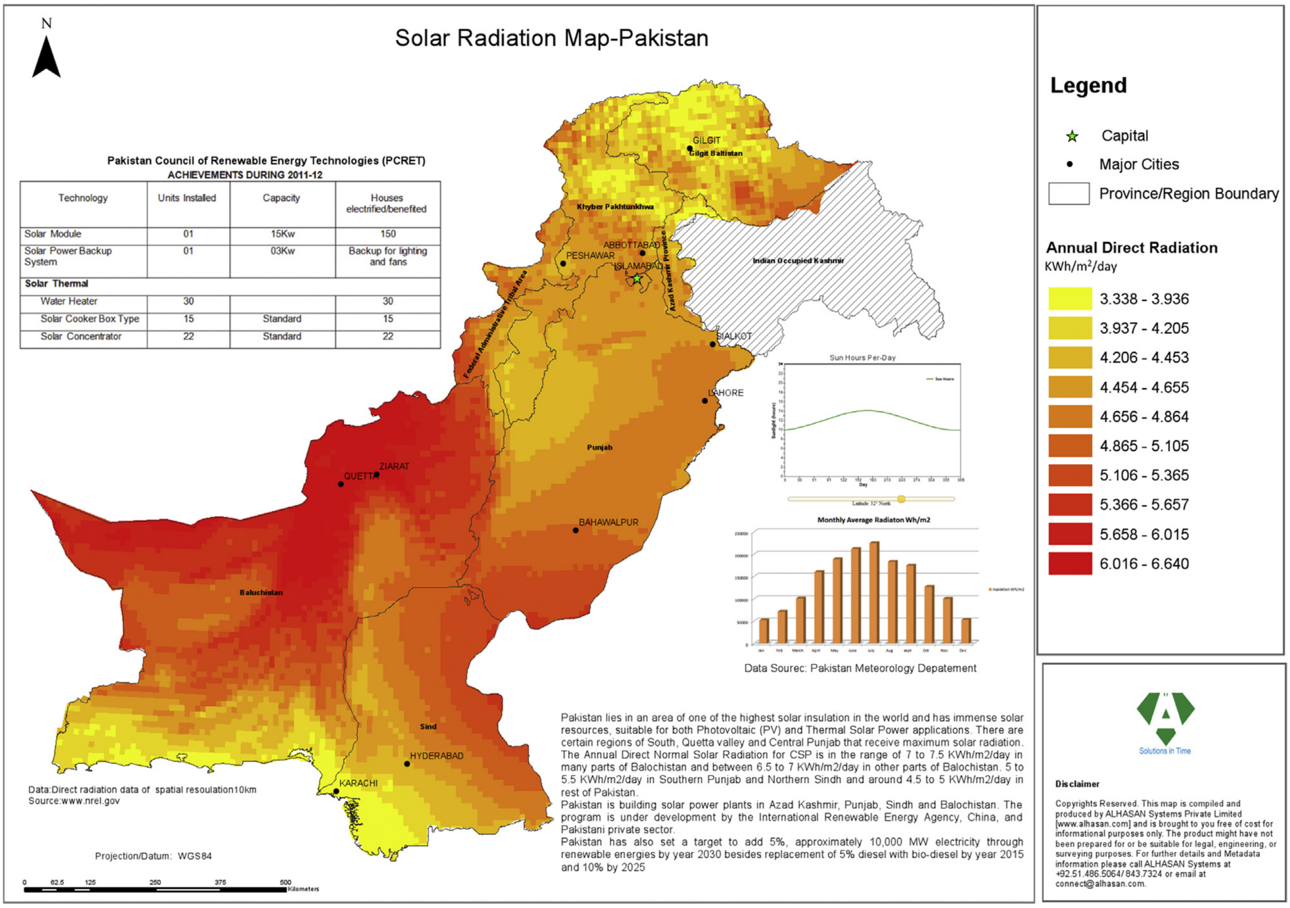

Fig. 1 – Global horizontal irradiance mapping of Pakistan Northern Region [41].

account for approximately 5.4% of the total percentage [57]. Even though geothermal resource's share seems to be marginal, but an in-depth examination of their potentials, prospects, and growth is very significant [58–60]. Recent research shows that Pakistan has variable geothermal resources. Table 5 lists the temperature of the areas that have the capacity to produce geothermal hydrogen.

The difference between HDR geothermal resources and traditional hydro-geothermal resources is that the latter can only generate power in geologically active areas. HDR power is formed by pumping water from the injection well into the hot dry rocks in the basement. The Enhanced geothermal systems (EGS) dismantle the rocks in the basement creating higher temperatures and thus improving the absorbance and penetrability. The absorbance and penetrability form a closed-loop circulation system that connects both the injection and the disposal well thus transiting the heat up to the surface. The resulting hot water and steam have a 120–370 °C temperature range and can be used to generate electricity through either steam engines or turbines.

Biomass energy

Biomass energy is regarded as a true alternative option with high prospects amongst all other renewable energy resources [61]. Pakistanis' main occupation is agriculture, which provides employment to 38.5% of its population and has an 18.5% contribution to the country's gross domestic product (GDP) [62]. The biomass usage in Pakistan is currently old-fashioned and unsystematic. The utilization of biomass feedstock requires a systematic process that can develop and maintain the hydrogen supply chain. Thus, the traditionally disorganized use of biomass must now be organized into a biomass supply chain that can sustainably yield, carry, reserve, and supply biomass raw materials. Like many other developing economies, biomass in the shape of crop residue is not traded like other commodities in Pakistan. Biomass has enormous power generation potential in an agricultural country like Pakistan, which can reduce the widening gap in energy supply and demand. Biomass resources are the main raw material for

Table 1 – Show the values of minimum and maximum solar radiation [44].

Mini or Max Solar radiation	Values (kWh/m²/day)
Minimum	5.2275
Maximum	7.0016

Table 2 – Solar irradiation in Pakistan areas [44].

Solar Insolation (kWh/m²/day)	%
5 to 6	69.31
>6.0	30.69

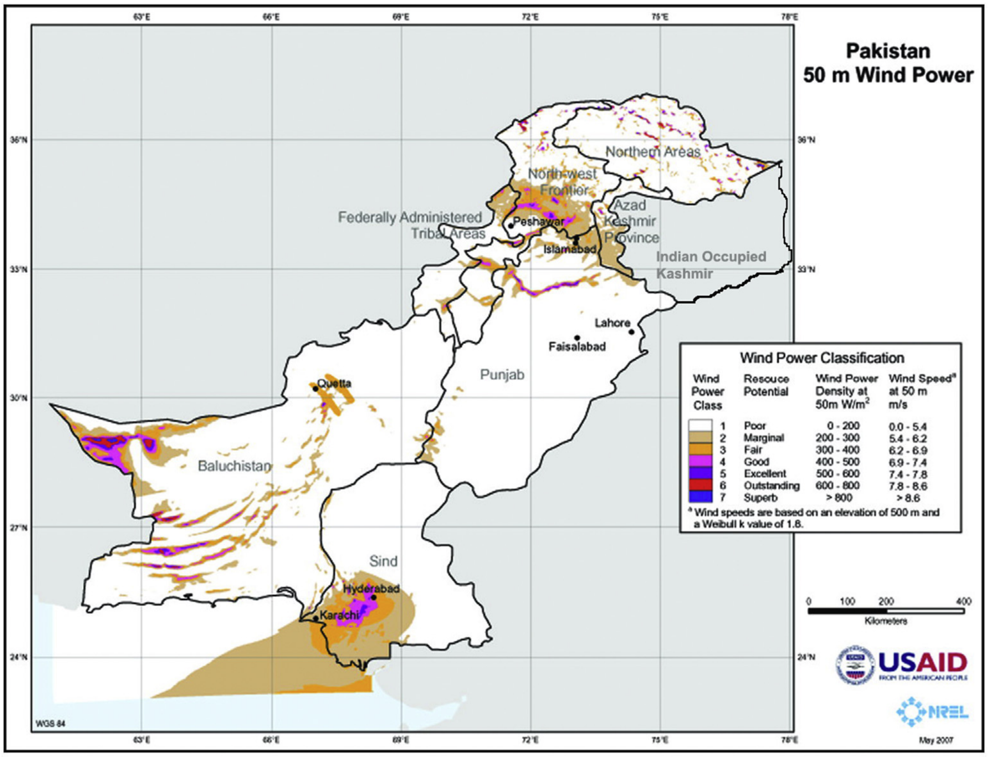

Fig. 2 – Pakistan wind resource assessment map [49].

Table 3 – Resources of wind energy potential in Pakistan [50].

Wind energy class	Wind potential	10 m		50 m	
		Wind speed	Wind Energy density	Wind speed	Wind Energy density
Class 1	Very Poor	0–4.6 (m/s)	0–100(Wm-^{2})	0–5.5 (m/s)	0–250 (Wm^{-2})
Class 2	Marginal	4.6–5.2 (m/s)	100–150(Wm^{-2})	5.4–6.2 (m/s)	250–350 (Wm^{-2})
Class 3	Moderate	5.2–5.8 (m/s)	150–200(Wm^{-2})	6.2–7.0 (m/s)	350–450 (Wm^{-2})
Class 4	Good	5.8–6.2 (m/s)	200–250(Wm^{-2})	7.0–7.5 (m/s)	450–550 (Wm^{-2})
Class 5	Excellent	6.2–6.6 (m/s)	250–300(Wm^{-2})	7.5–7.9 (m/s)	550–650 (Wm^{-2})
Class 6	Outstanding	6.6–7.5 (m/s)	300–400(Wm^{-2})	7.9–8.7 (m/s)	650–850 (Wm^{-2})
Class 7	Superb	>7.5 (m/s)	>400(Wm^{-2})	>8.7 (m/s)	>800(Wm^{-2})

hydrogen production. In the case of Pakistan, the expenditure of producing hydrogen from biomass is also competitive. In order to convert biomass to hydrogen, there must be a thorough evaluation of the used technology to make it a viable method [63]. However, as people realizing that biomass feedstock is a precious material of the new energy supply chain, its collection and follow-up processes will be systematically shaped. Table 6 shows the estimated hydrogen production of various crop residues in Pakistan.

Table 4 – Estimated hydrogen generation using wind energy [56].

Potential	Unit	Ten h - Aval	Conversion	Unit (rate of 53)
86,875	MW	868,750	16,610,898	(KWh/kg)
87752.5	MW	877,525	16,778,680	(KWh/kg)
60,812	MW	608,120	11,627,533	(KWh/kg)
235,439.5	MW		45,017,112	(KWh/kg)

Municipal solid wastage energy

Generally speaking, solid waste is divided into eight categories according to its sources, such as (i) industrial solid wastes, (ii) municipal solid wastes, (iii) fertilizers, (iv) mining solid wastes, (v) solid excretory products from human and livestock, (vi) biocides and pesticides (vii) biomedical or hospital wastes and (vii) e-waste or electronic wastes. Municipal solid waste comes from household commercial, educational, and construction activities, including waste generated from households, office buildings, markets, shops, cafeterias or restaurants, educational institutions, industrial sites, water supply, and sewage treatment facilities, construction, and demolition sites [64–66]. The solid waste generated by mining includes dust, slag, toxic chemicals, mineral waste, etc., in this case, it will lead to vegetation depletion. Fertilizers and pesticides make the land sterile and the soil becomes solid waste. Poor sanitation results in the accumulation of solid waste from livestock and human excrement. Electronic waste

Table 5 – Temperature, areas and application of geothermal energy in Pakistan.

Areas	Maximum Temperature	Application
1. Karachi city	70–145 °C	Vegetable, Green housing Concrete Block curing fruits drying process Soft drink carbonation Pulp and paper processing Food processing site
2. Muzaffarabad	185° 230 °C	Ethanol and Biofuels Production Binary Power plant
3. Chagai	200–300 °C	Hydrogen generation flesh and dry steam power plan
4. Chakwal	60–90 °C	Aquaculture Heat Pump Mushroom culture Biogas production
5. Kolte, Tatta Pani, and Tato	100–200 °C	Fabric Dyeing Binary power plant Pulp drying Refrigeration & Ice making Cement & Aggregate Drying Lumber drying HVAC

or electronic waste is the latest and has increased in the last 20 years, which is called electronic waste. Municipal solid waste is increasing at a high rate that may increase. The country 2019s urban population is increasing rapidly [7]. However, the developing country Pakistan still does not adequately manage municipal solid waste recycling methods to convert it into valuable materials. When using traditional forms of single-use waste, can affect the environment, socio-economic and public health. You are advocating wasting energy on time. It is helpful for the government to meet the challenge. Biomedical waste is the most dangerous waste, including disinfectants, pathogens, and other harmful drugs and personal care products. Renewable hydrogen production in Pakistan makes municipal solid waste viable and affordable. Major cities in various countries produce 30 million tons of municipal solid waste every year [67].

Small hydropower

Another promising option for electrical energy that will help reduce the energy crisis is small hydro. The potential of small hydroelectric plants in many countries of the world is enormous. In China, 43,000 small hydroelectric plants generate 19,000 MW of electricity. Similarly, Pakistan's geographic location and water resources allow for the production of 60,000 MW of electricity. However, only 7,172 MW out of the huge potential available came from hydropower in the years 2016–2017. Table 7 shows Pakistan's hydropower resources.

Multiple organizations and institutions in Pakistan are working hard to study and develop small hydropower plants [69]. To achieve that, Pakistan should portion out more funds to establish a study center that effectively produces power from renewable sources. Similarly, the Punjab provincial government has started four hydroelectric projects with a capacity of 20 MW (see Table 8). Upon completion, these projects will get more hydrogen production into the system.

Renewable energy challenges

The term "renewable energy" refers to energy derived from natural resources. Renewable energy has recently sparked increased interest, and it has emerged as one of the most important sources of energy generation [70]. There will be numerous challenges in deploying energy from this technique. One of the most serious interests is power generation in the field of renewable energy, based on natural resources that are uncontrollable by humans [71]. Solar energy, for example, is only generated when sunlight is available and shuts down at night; wind energy, on the other hand, is dependent on wind availability; if the wind speed is very low, the turbine will not turn, resulting in no power flow to the grid [72]. Too much wind, on the other hand, can damage the generator, requiring the maintenance of a delicate balance in order to ensure consistent energy generation. Because of the uncertainty in energy production in renewable energy technologies, integration is becoming more difficult. High-power quality must be maintained at all times to ensure network efficiency and stability [73]. The system can run at low costs and with high reliability

Table 6 – Estimation of each crop residues for hydrogen energy production.

Crop type	Residues from crop	Existing Residue (1000 MT)	Hydrogen production (1000 tones)
1. Cotton	Stalks	3300	254
	Husk	3300	254
	Cobs	11,900	915
2. Barley	Stalks	110	8
3. Bajra	Husks	152	12
	Cobs	950	73
	Stalks	142	11
4. Dry Chilly	Stalks	285	22
5. Wheat	Stalks	7200	554
	Husks	36,000	2,769
6. Maize	Stalks	600	46
	Husk	90	7
7. Rice	Boll Shell	10,400	800
	Stalks	1400	108
	Straw	10,400	800
	Total	86,229	6633

Table 7 – Represent the micro-hydropower in Pakistan [68].

Source Type	Province	Locations	Range	Unit	Total Potential	Unit
Canal	Sindh	160	5–50	(Megawatt)	130	(Megawatt)
Natural/Falls	KPK	130	0.25–30	(Megawatt)	800	(Megawatt)
Canal	Punjab	350	0.25–50	(Megawatt)	600	(Megawatt)
Natural/Falls	Azad Kashmir	45	0.25–60	(Megawatt)	300	(Megawatt)
Natural/Falls	Gilgit-Baltistan	250	0.2–30	(Megawatt)	1250	(Megawatt)

Table 8 – Represent entire small-hydro projects in Pakistan and these maximum generating power 98.41 MW.

S. No	Site	Province/District	Volume
1	Daragai, Malakand	Khyber–Pakhtunkhwa province	20
2	Pehur, HES, Swabi	Khyber–Pakhtunkhwa province	18
3	Rescue, HES, Chitral	Khyber–Pakhtunkhwa province	4.2
4	Rsishi, HES, Chitral	Khyber–Pakhtunkhwa province	1.2
5	Nandipur, Upper Chenab Canal	Punjab province	13.8
6	Rasul, Upper Jhelum Canal	Punjab province	13.8
7	Shadiwal, Upper Jhelum Canal	Punjab province	13.5
8	Cichocki, Upper Chenab Canal	Punjab province	13.2
9	Renala, Lowr Bari Doab Canal	Punjab province	1.1

thanks to the quality of the power supply. On the other hand, poor power quality can have serious consequences for the power grid and industrial processes. It could lead to high costs and equipment failure. Power quality issues include things like frequency disorder, voltage/current harmonics, low power factor, voltage variation, and transmission line transits [74].

Most renewable energy power plants require a lot of space to be connected to the grid. Since renewable energy is usually determined by location, users may be delayed. First, some renewable energy sources are simply not available in some places. Second, the distance between the grid and renewable energy is extremely important in terms of efficiency and cost [75]. In addition, weather, climate, and geographic location all affect renewable energy, so a type of energy production may not be suitable for the region. While there has been progress in this area, there is still a lack of understanding and awareness of the necessity and benefits of renewable energy [76]. Capital and Investment allowances have enabled the implementation of renewable energy technologies. Potential recipients and Applicants of renewable energy incentives should be clearly advised and assisted by government agencies on how to apply. The high initial installation cost is one of the main obstacles hindering the development of renewable energy [77]. Solar and Wind power plants are known for their high cost. In addition, energy storage systems are expensive and pose a major challenge in megawatt power generation. However, as markets, industries and renewable energy policies evolve, they face increasingly complex and multifaceted challenges [78]. The fact that significant reserves of fossil fuels are still available stymies the desire to give renewables sufficient weight. Renewables face significant commercialization challenges in the face of mature nuclear technologies and fossil fuel, including underdeveloped infrastructure and a lack of economies of scale [79]. Furthermore, from a technical standpoints, policy and market, the combination and integration of various energy sources is becoming more difficult, necessitating capacity building. The ability to build, monitor, and maintain energy infrastructure, as well as train scientists, decision-makers, and manufacturers at both the national and global levels, is critical to the success of new technology deployment [80]. Lack of sound policies and Costs are two of the most important barriers for developing economies. Startup costs, a lack of approaches to balancing price disparities between renewables and fossil fuels, and overarching structural barriers, such as the energy industry's centralized nature, stymie support and implementation of new initiatives, discourage investment in renewables, and frustrate more localized approaches to energy access [81].

Methods description

Fuzzy set theory

If you do not use the right measuring values, it is difficult to solve the real problem. Therefore, policymakers use explicit values, not literary values because them being vague. In order to give clear and certain data, we use the Fuzzy set theory, and decision-makers can evaluate decisions in the absence of readable values. It is very useful for verbal feedback to get clear data for decisions. The fuzzy set theory was developed by Zadeh developed in 1965, which uses fuzzy triangular numbers (TFN) to derogate the ambiguity of language. We use triangular fuzzy numbers (TFN) to classify renewable energy (RES), which is the most appropriate method for classifying. Construct a triangular fuzzy number $F_{ij} = a_{ij}, b_{ij}, c_{ij}$; where the middle number b_{ij} and a_{ij}, c_{ij} is the left and right number in TFN. Let us assume that a fuzzy number is divided into two numbers. Where Fuzzy (1) = (A1, B1, C1) and Fuzzy2 = (A2, B2, C2). We apply different mathematical operations to fuzzy numbers as follows:

$$\text{Add } (+): (A1,\ B1,\ C1) + (A2,\ B2,\ C2) = (A1+A2,\ B1+B2,\ C1+C2) \tag{1}$$

$$\text{Multiply } (\ ): (A1,\ B1,\ C1) \times (A2,\ B2,\ C2) = (A1 \times A2,\ B1 \times B2,\ C1 \times C2) \tag{2}$$

$$\text{Divide } (/): (A1,\ B1,\ Z1)\ ?1 = (1/C1, 1/B1, 1/A1) \tag{3}$$

Fuzzy-AHP

The Analytical Hierarchy Process (AHP) is a multiple-choice decision analysis (MCDA) method that compares specific options or alternatives and assigns weights to criteria. The AHP level can be used to convert complex problems into sub-problems. Each level of sub-questions contains conditions and attributes. However, these standards are provided based on the cumulative weighting process and their relative importance. Similarly, in various fields, the analytical hierarchy process has been used for classification purposes. Use pairwise comparisons to estimate the importance of the criteria in the stratification method. However, the AHP method has the following disadvantages:

- Unstable decision
- Ambiguous decisions
- The classification in the judgment is subjectively incorrect
- Decision makers based on the results of the Analytical Hierarchy Process model.

According to the limitations of the Analytical Hierarchy Process, its qualitative analysis produces the absolute magnitude of decisive evaluation, and these linguistic results cannot be transformed into mathematical forms. Due to these limitations, it is recommended to convert the linguistic results of the analytic hierarchy process into fuzzy numbers. With this in mind, we apply each language value as a fuzzy number as the reciprocal of each universal language value. Therefore, using the fuzzy method has the following advantages:

- Fuzzy set theory is a powerful tool for cutting out vagueness.
- It allows decision-makers to use this method to evaluate decision choices when there is no clear data.
- The fuzzy set theory uses fuzzy triangular numbers (TFNs) [82] to remove the ambiguity of linguistic values.
- It is used to classify renewable energy sources.

The fuzzy pairwise comparisons are represented by this matrix, as shown below:

$B = (b_{ij})n \times m$. Let's use the example of a triangular fuzzy number (TFN): $F_{ij} = (x_{ij}, y_{ij}, z_{ij})$.

The following process is also part of the Fuzzy AHP:

1. Using a hierarchical structure and a triangular fuzzy number (TFN) to build pairwise compression.
2. The following is the value of the Fuzzy synthetic set:

$$SE_i = \sum_{i=1}^{m}(R_{ij}) \times \left[\sum_{i=1}^{n}\sum_{i=1}^{m}(R_{ij})\right]^{-1} \tag{4}$$

$$\text{s.t} \sum_{i=1}^{m} R_{ij} = \left(\sum_{i=1}^{m} x_{ij}, \sum_{i=1}^{m} y_{ij}, \sum_{i=1}^{m} z_{ij}\right) \tag{5}$$

$$\sum_{i=1}^{n}\sum_{i=1}^{m} R_{ij} = \sum_{i=1}^{n}\sum_{i=1}^{m} x_{ij},\ \sum_{i=1}^{n}\sum_{i=1}^{m} y_{ij},\ \sum_{i=1}^{n}\sum_{i=1}^{m} z_{ij} \tag{6}$$

$$\left[\sum_{i=1}^{n}\sum_{i=1}^{m} R_{ij}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n}\sum_{i=1}^{m} x_{ij}}, \frac{1}{\sum_{i=1}^{n}\sum_{i=1}^{m} y_{ij}}, \frac{1}{\sum_{i=1}^{n}\sum_{i=1}^{m} z_{ij}}\right) \tag{7}$$

The equation numbers 4,5,6 and 7 measure the $F_{ij} = (x_i, y_i, z_i)$..

3. Comparison of *SEi* values and calculate what's possible degree of $SE_i = (x_j, y_j, z_j) \geq SE_i = (x_i, y_i, z_i)$.

   The formulation equivalent is as follows:

$$V \quad (SE_j \geq SE_i) = height,\ (SE_i \cap SE_j) = z_{sj}$$

$$(d) = \begin{cases} 1,\ if\ y_j \geq y_i \\ 0,\ if\ x_i \geq x_j \\ \dfrac{x_i - z_j}{\left(y_j - z_j\right) - \left(y_i \geq x_i\right)} otherwise \end{cases} \tag{8}$$

where d shows the intersection between z_{sj} and z_{si}; A comparison between the values is required of $V\ (SE_i \geq SE_j)$ and $V\ (SE_j \geq SE_i)$ with the values of SE_i and SE_j.

4. This step calculates minimum chances degree (*i*) of $(SE_j \geq SE_i)$: where $ij = 1,2, \ldots, k$.

$$V\ (SE \geq SE_1, SE_2, SE_3, \ldots, SE_k),\ \text{for } i = 1,2,3,\ldots,\ k = V[\times (SE \geq SE_1) \text{and } (SE \geq SE_2)\ and \ldots (SE \geq SE_k)] = \min V(SE \geq SEi)\ \text{for } i = 1,2,3,\ldots,k \tag{9}$$

Assume

$$d'(Bi) = \min V(SEj \geq SEi),\ \text{for } i = 1,2,3,\ldots,k$$

We then define this latter vector as

$$W' = (d'(B1), d'(B2), \ldots, d'(Bn))^T \tag{10}$$

where B1 (i = 1,2, 3, …, n) represents n elements:

Next the final step normalizes the weights of each vector as follows:

$$W = (d(B1), d(B2), \ldots, d(Bn))^T \tag{11}$$

Here is a non-fuzzy number indicating W. Hydrogen production from water electrolysis is also a suitable way to maintain efficiency performance of 80–90%, demonstrates considerable potential in a variety of hydrogen-production technologies. The amount of renewable hydrogen produced from wind energy is provided in the following equation.

$$h = \frac{\eta_{el} E_{out}}{ecel} \tag{12}$$

where h is the amount of hydrogen generated, Eout is the wind electricity input to the electrolyzer for hydrogen production, ecel is the electrolysis process performance, which ranges between 80 and 90%, and ηel is the electrolyzer energy consumption, which is normally 5–6 (KWh/Nm3). $\Delta H = 286$ kJ mol^{-1} is needed for the decomposition of water (H2O) to produce H2. The ultimate chemical reaction of water electrolysis can be written as:

$$H_2O \rightarrow H2 + \frac{1}{2}O_2 \tag{13}$$

The charge transfer and enthalpy shift of the reaction determine the thermoneutral voltage VTH

$$V_{TH} = \Delta H/2F \tag{14}$$

F shows the molar charge constant, which is measured inefficiency. In relation to VTH of n number of cells, electrolyzer process performance (η_{el}) can be measured almost precisely by electrolyzer voltage (Vel),

$$\eta_{el} \approx 1.48n/V_{el} \tag{15}$$

Overvoltage is caused by a variety of failure factors, including physical, electrochemical, and transmission-related losses, which increase in proportion to current density. When attached to a wind turbine, the electrolyzer can run at a variety of current and power speeds.

The total cell reaction response can be said to be the number of the two half-reactions while voltages of the reduction (E^0_{red}) and oxidation [83] (E^0_{ox}) half-reactions.

$$E^0_{cell} = E^0_{ox} + E^0_{red} \tag{16}$$

The capacity of an isolated half-cell cannot be calculated explicitly. As a comparison, the normal hydrogen half-reaction was chosen and given a standard reduction potential of exactly 0.000 V,

$$2(1\ M) + + 2e- = H2_{(1atm)}\ (E^0_{red} = 0.00V)$$

And

$$(\text{Cathode})\ Cu2 + + 2e - . \rightarrow C(s).(\text{reduction})\ ECu2 + /Cu = 0.34V \tag{17}$$

Therefore,

$$E^0_{cell} = E^0_{ox} + E^0_{red} \quad E^0_{cell} = 0.76 + 0.34v \quad E^0_{cell} = 1.10v \tag{18}$$

The Levelized Cost of energy is a useful metric for comparing the unit costs of various technologies over their economic Levelized cost of electricity (LCOE). The LOCE approach is often used as a benchmarking technique to compare the costs of various electricity production technologies. Wind power economics are determined by a variety of factors, including net construction costs, energy generation, repair and operating costs, location selection, and wind turbine characteristics. The ratio of increasing NPV of total costs (PVC) to the total energy (E tot) generated through the device is used to estimate the wind per unit cost (C W).

$$C_w = PV_c/E_{tot} \tag{19}$$

Electrolysis cost

Many studies have suggested an economical model of an electrolyzer cell, in which the expense of an electrolysis cell includes three main costs: cash, operation, maintenance, and replacement [84]. The quantity of producible hydrogen determines the total cost of the electrolyzer. The total cost of the electrolyzer is specified by the required hydrogen supply rate [85]. The effective electrolyzer workability and the average real capital cost per kWh at the nominal output are calculated as follows:

$$C_{ele,\ u} = \frac{M_{H_2} K_{el,th}}{8760.f\eta_u} \tag{20}$$

$$C_{ele,\ u} = \frac{M_{H_2} K_{el,th}}{8760.f\eta_u} \tag{21}$$

where ($C_{ele,u}$) is the electrolyzer unit rate, f is the strength factor, and is the electrolyzer power requirement. The assessment case suggests that the electrolyzer unit value is \$368/kWh, which is the purpose quantity. The per-unit expenditure (\$/kWh) of manufacturing wind power needs to be anticipated for selected sites. Table 9 provides the element includes the wind turbine's explicitly detailed energy value (C1), in addition to miscellaneous expenses (C2), construction expenses (C3), operating and maintenance expenses (C4), (C5) suggests inverter charges, and (C6) suggests battery financial institution costs.

It can be determined using the following formula,

$$PVC = I + C_2\left(\frac{1+i}{r-1}\right)\left[1 - \left(\frac{1+i}{1+r}\right)^L\right] - S\left(\frac{1+i}{1+r}\right)^L \tag{22}$$

The total cost can be measured as,

$$C_T = PVC + C_5 + C_6 \tag{23}$$

The fee of working and preserving a wind turbine is envisioned to be 25% of the yearly funding cost. Scrap is the idea to be well worth ten % of the yearly funding fee [86]. The funding fee (IC) is calculated as follows:

$$I_c = C_{ASPEC} + P_r \tag{24}$$

where CASPEC shows an average cost per unit kW and Pr determine the rated power cost of a wind turbine [87–89]. Table 10 presents the specification of selected wind turbine.

$$C_{cu} = = \frac{\text{Total cost}}{\text{Annual average yield}} \tag{25}$$

Table 9 – Rated power costs of wind turbine.

Average (CASPEC) (\$/kW)	Caspec (\$/kW)	Pt (kW)
700–1600	1150	>200
1775	1250–2300	20–200
2200–3000	2600	<20

In which CW and MH_2 represent the energy cost ($) and per year green hydrogen manufacturing respectively. Globally, the limitation on green hydrogen manufacturing, especially via wind energy from electrolysis, has received numerous attentions [90]. Pakistan simply uses a part of this potential, leaving aside the resource's usability. In this regard, this assessment adds to a reduction in non-renewable energy supply reliability. This research investigates the environment in nearly every part of Pakistan at the same time as serving as a condensed examination of domestic call for green wind-produced hydrogen.

$$Z = max_{e,h} \sum_{t \in 0}^{T} \left(P_t^e e_t^{grid} + P_t^h h_t \right) \tau \tag{26}$$

$$W_t = e_t^{grid} + e_t^h, \forall_t \in T \tag{27}$$

$$h_t = a.e_t^h, \forall_t \in T \tag{28}$$

$$h_t, e_t^{grid}, e_t^h \geq 0 \forall_t \in T \tag{29}$$

Pth (\$/kgH2) is the negligible hydrogen, while the ***Pth*** (\$/kWhe) is the consumer power costs production per hour and the wind energy. The **ht** (\$/kgH2/h) hydrogen production per hour and energy provided from wind power supplied to the national lattice, ht grid, replicate those costs (kWe). With the set T, t presents a defined period and consists of the time interval (60 min). (2) At time t, ***eth*** grid (kWe), the power produced from wind energy supplied to the country-wide grid, ***eth*** (kWe), and the energy consumed in producing renewable hydrogen at eth grid (kWe) are divided (kWe). At time t, limitation (3) depicts the manufacturing of green hydrogen with wind energy. The choice considerations, in keeping with limitation (4), are non-negative authentic numbers and the day-in advance marketplace power price. *Pth* grid energy is being supplied to the K.E., ht hourly hydrogen production, *Pth*, and the low hydrogen cost, and *eth* electricity scavenge deal is planned. The previous research discovered that via way of means of growing the populace density function, fuel intake by transportation decreases sub-linearly. Consequences of geographical classification (e.g., urban vs. rural) have been criticized in automobile petrol consumption research. Water electrolysis having the high-quality performance of 65–85%, use of electricity from renewable energy generated from wind, and it has an extra considerable capability among numerous technologies that generate hydrogen,

$$A_{H2} = \frac{\eta_{el} E}{LHV_{H2}} \tag{30}$$

A_{H2} represents the produced quantity of hydrogen. E represents the wind energy input to the electrolyzer to produce hydrogen, η_{el} is the efficiency of electrolysis process, and LHV_{H2} is the minimum calorific hydrogen value. Over an electrolysis system, the renewable hydrogen quantity H_{it} in the stated time is measured as follows:

$$H_{it} = M_t N_{Jt}^{el} H_{Jt}^{el} \forall_J \in J^{el} \quad t = 1, \ldots, n \tag{31}$$

where the element electrolyzed withinside the system is denoted through N_{Jt}^{el} even though Mt is the hours that examine withinside the electrolyzed system. Both the electrodes are of metal (e.g., platinum) and are linked to electricity in the water. We have considered [91] as a base case study for cost evaluation. As we argued, annual wind-generated renewable hydrogen manufacturing is a feature of marginal hydrogen charges and the electrolyzer system's power efficiency. As the marginal fee of the renewable hydrogen generated through wind increases, there will be a growth in hydrogen production till it levels off [92,93].

Results and discussions

Priority criteria and weights

The first step is to assemble a pairwise evaluation matrix. The creation of the pairwise evaluation matrix enables to locate of the relative relationship. Therefore, the usual precedence weights have been constituted, and the pairwise evaluation matrix is clarified in Table 11.

The obtained results of priority weights of criteria can be used to estimate the TFN against the values of each criterion as follow:

These results are to calculate the TFN values of each criterion as follows:

$$SE_1(\textbf{Commercial potential}) = (3.13,\ 4.03,\ 5.28) \times (1/22.07,\ 1/16.86,\ 1/12.99)$$

$$= (3.13 * 1/22.07,\ 4.03 \times 1/16.86,\ 5.28 \times 1/12.99)$$

$$= (0.142,\ 0.239,\ 0.406)$$

$$SE_2(\textbf{Environmental impacts}) = (3.18,\ 4.14,\ 5.4) \times (1/22.07,\ 1/16.86,\ 1/12.99)$$

$$= (3.18 \times 1/22.07,\ 4.14 \times 1/16.86,\ 5.4 \times 1/12.99)$$

$$= (0.144,\ 0.246,\ 0.416)$$

$$SE_3(\textbf{Economic benefits}) = (3.84,\ 5.09,\ 6.65) \times (1/22.07,\ 1/16.86,\ 1/12.99)$$

$$= (3.84 \times 1/22.07,\ 5.09 \times 1/16.86,\ 6.65 \times 1/12.99)$$

$$= (0.174,\ 0.302,\ 0.512)$$

$$SE_4(\textbf{Social acceptance}) = (2.84,\ 3.6,\ 4.74) \otimes (1/22.07,\ 1/16.86,\ 1/12.99)$$

Table 10 – Selected wind turbine specifications.

Swept Area (m^2)	Rotor Diameter (m)	Cut Out Speed (m/s)	Cut in Speed (m/s)	Hub Height (m)	Rated Power (KW)	Wind Turbine Model
9516	109	25	3	50	2500	GW-109/2500

Table 11 – The fuzzy evaluation criteria and results.

	CP	EI	EB	SA
Commercial potential (CP)	1, 1, 1	1.11, 1.62, 1.98	0.43, 0.55, 0.87	0.62, 0.79, 0.98
Environmental impacts (EI)	0.39, 0.59, 0.88	1, 1, 1	0.76, 1.31, 1.68	0.77, 1.32, 1.54
Economic benefits (EB)	2.12, 2.48, 2.21	0.71, 0.92, 1.56	1, 3, 1	1.31, 1.67, 1.53
Social acceptance (SA)	0.89, 1.49, 1.92	0.61, 0.88,1.31	0.49, 0.58, 0.	1, 3, 1
CR = 0.06				

$= (2.84 \times 1 / 22.07,\ 3.6 \times 1 / 16.86,\ 4.74 \times 1 / 12.99)$

$= (0.129,\ 0.214,\ 0.365)$

After calculating the values of SEi, we compared them and computed the possibility degree of $SEj=(xj,yj,zj) \geq SEi=(xi,yi,zi)$ by solving Eq. (8). Table 11 presents the values of $(SEj \geq SEi)$. We have now obtained the TFNs of four main indicators. After obtaining the SEi values, the possible degree of $SEj = (x, yj, zj) \geq SEi = (xi, yi, zi)$ is computed and compared by explaining equation (8). As mentioned earlier, the respective indicator results based on the process are presented in Table 12.

Then calculated the values of $(SEj \geq SEi)$, we find the minimum possible degree of $d'(i) = \min V(SEj \geq SEi)$, for $i = 1,2, 3, \ldots, k$.

d'(**Commercial potential**) $= \min V(SE1 \geq SE2,SE3,SE4)$
$= \min(0.82,0.82,1.00) = 0.81$

d'(**Environmental impacts**) $= \min V(SE2 \geq SE1,SE3,SE4)$
$= \min(1.00,0.92,1.00) = 0.81$

d'(**Economic benefits**) $= \min V(SE3 \geq SE1,SE2,SE4)$
$= \min(1.00,1.00,1.00) = 1.00$

d'(**Social acceptance**) $= \min V(SE4 \geq SE1,SE2,SE3)$
$= \min(0.85,0.82,0.82) = 0.92$

The weight vector is obtained as follows:

$W'=(0.92,0.88,1.00,0.92)T$

The weight vector was then normalized in the final step as follows: $W=(0.34,0.35,0.40,0.31)T$.

The final weights of environmental, commercial, economic, and social are 0.24, 0.25, 0.30, 0.21, respectively. These four criteria are ranked in order of preference as economic benefits > environmental impacts > commercial potential > social acceptance.

Table 12 – Values of $V(SE_j \geq SE_i)$

$V(SE_1 \geq SE_i)$	Value	$V(SE_2 \geq SE_i)$	Values
$V(SE_1 \geq SE_2)$	0.89	$V(SE_2 \geq SE_1)$	0.98
$V(SE_1 \geq SE_3)$	0.86	$V(SE_2 \geq SE_3)$	0.92
$V(SE_1 \geq SE_4)$	1.00	$V(SE_2 \geq SE_4)$	1.00
$V(SE_3 \geq SE_i)$	**Value**	**$V(SE_4 \geq SE_i)$**	**Value**
$V(SE_3 \geq SE_1)$	1.00	$V(SE_4 \geq SE_1)$	0.88
$V(SE_3 \geq SE_2)$	1.00	$V(SE_4 \geq SE_2)$	0.92
$V(SE_3 \geq SE_4)$	1.00	$V(SE_4 \geq SE_3)$	0.79

Different criteria priority weight for RES

The mentioned steps in 4.1 are applied to renewable energy sources considered as options to hydrogen production to evaluate the priority criteria. The renewable energy evaluation matrix of fuzzy assessment techniques has been used as a proxy under certain standards. The results in Table 13 clarifies the priority of renewable energy sources alternatives under each standard.

This study compares the four main criteria of environmental impact, business potential, social acceptance, and economic benefits under different standard conditions to see the secondary decision-making process. The results of this procedure are described in Tables 14–17.

Alternative's criteria final weights for renewable energy sources

In order to get the final weight of each renewable energy, we multiply the standard priority weight by the standard priority weight of each renewable energy.

The scores of the four main indicators (economy, business, environment, and society) of renewable energy (wind, solar, biomass, and geothermal) based on the priority of the standard. Here, the commercial potential value of wind and solar energy is 0.29, the value of biomass energy is 0.26, and the value of geothermal energy is 0.16. Therefore, wind energy and solar energy are equally important to the commercial potential of Pakistan's hydrogen energy. From an environmental perspective, wind power has the highest score (0.27), followed by solar power (0.26). Geothermal energy has a score of 0.24, while biomass ranks last in terms of environmental impact with a score of 0.23. When using hydrogen energy, the economic benefit of renewable energy is led by biomass energy (0.28), followed by solar energy and wind energy, with a score of 0.27. Here, geothermal is ranked last in economic returns with a score of 0.17. Biomass is the main source of hydrogen energy conversion, which is recognized by the society after a score of 0.31, followed by solar energy (0.30). The importance of wind energy and geothermal energy to social acceptance is relatively low, with scores of 0.24 and 0.16. In this case, total wind energy resources from renewable energy are relatively more suitable for hydrogen energy production in Pakistan, followed by solar energy and biomass energy, considering mainly four aspects [27,35,36].

Table 13 – Fuzzy assessment of renewable energy sources alternatives within commercial Criteria.

	Wind	Solar	Biomass	Geothermal
Wind	1, 1, 1	0.82, 1.11, 1.48	0.88, 1.28, 1.32	1.12, 1.41, 1.65
Solar	0.78, 0.89, 1.24	1, 1, 1	0.77, 1.31, 1.88	1, 1.51, 1.67
Biomass	0.62, 0.82, 1.23	0.62, 0.81, 1.32	1, 1, 1	1.31, 1.68, 1.23
Geothermal	0.67, 0.68, 0.88	0.62, 0.71, 1	0.52, 0.57, 0.97	1, 1, 1
CR = 0.01				

Table 14 – Fuzzy assessment of RES alternatives within environmental impact standards.

	Wind	Solar	Biomass	Geothermal
Wind	1, 1, 1	0.87, 1.41, 1.77	0.72, 0.88, 1.42	0.81, 1.09, 1.43
Solar	0.62, 0.81, 1.11	1, 1, 1	0.82, 1.22, 1.61	0.91, 1.31, 1.82
Biomass	0.81, 1.11, 1.61	0.71, 0.89, 1.29	1, 1, 1	0.58, 0.79, 1.22
Geothermal	0.81, 0.89, 1.31	0.61, 0.80, 1.23	0.91, 1.19, 1.71	1, 1, 1
CR = 0.01				

Table 15 – Fuzzy assessment of renewable energy sources alternatives within economic benefits criteria.

	Wind	Solar	Biomass	Geothermal
Wind	1, 2, 1	0.78, 1.31, 1.79	0.71, 0.82, 1.32	0.82, 1.51, 1.88
Solar	0.61, 0.71, 1.21	1, 1, 1	0.71, 1.11, 1.51	1, 1.71, 1.51
Biomass	0.81, 1.31, 1.71	0.71, 1, 1.51	1, 1, 1	1.21, 1.70, 1.41
Geothermal	0.48, 0.68, 1.11	0.39, 0.59, 1.11	0.39, 0.72, 0.89	1, 1, 1
CR = 0.00				

Table 16 – Fuzzy assessment of renewable energy sources alternatives within social acceptance criteria.

	Wind	Solar	Biomass	Geothermal
Wind	1, 1, 1	0.59, 0.89, 1.41	0.50, 0.69, 1.21	0.83, 1.31, 1.56
Solar	0.72, 1.1, 1.71	1, 1, 1	0.71, 1.17, 1.73	1.1, 1.62, 1.94
Biomass	0.89, 1.42, 1.98	0.71, 0.88, 1.52	1, 1, 1	1.31, 1.79, 2.62
Geothermal	0.72, 0.74, 1.22	0.42, 0.49, 0.88	0.41, 0.62, 0.92	1, 1, 1
CR = 0.00				

Table 17 – The important significance weight criteria of renewable cause.

Sources	CP	SA	EB	EI
Solar	0.31	0.22	0.23	0.32
Geothermal	0.18	0.29	0.19	0.19
Biomass	0.21	0.17	0.29	0.26
Wind	0.32	0.32	0.29	0.23

Techno-economic analysis of wind-generated renewable hydrogen production

When Pakistan's demand for hydrogen for zero-emission vehicles increases, there will be no zero-emission vehicles. In contrast, all provinces of Pakistan add intensity of gasoline consumption in rural and urban areas. Table 18 shows that the total demand for gasoline in all provinces is 14.6 billion kilograms. On the other hand, the demand for H2 (1 billion kilograms) 4.88 billion kilograms of renewable hydrogen requires a fleet equivalent to the country's 14.6 billion kilograms of gasoline [94]. Further, Punjab's potential demand for renewable hydrogen is 4.54 billion kilograms. In addition, provinces with the potential to produce wind energy have almost no possibility of hydrogen missions, mainly the coastal areas of Baluchistan and Sindh and the areas inland Sindh. Gasoline consumption in urban areas is almost 3.2% lower than average gasoline consumption, and gasoline consumption in rural areas is almost 6.66% higher than average gasoline consumption. The following findings are consistent with the conclusions drawn by Ref. [95]. Similarly, LDV H2 needs 6.63 billion kilograms (kg/year). The price of renewable hydrogen fluctuates between USD 0/kg and USD 5/kg, with an increase of USD 0.1/kg. When the minimum price of hydrogen exceeds USD2.99/kg kgH2, the production of renewable hydrogen increases and the price of hydrogen will increase. The price of hydrogen is between $ 05/kg, the average price of the sites included in this study is $ 4.3/kg, and the market prices for KE and wind power come from potential data. In contrast, economically, in Pakistan, since the marginal price of renewable hydrogen is US $ 3.92/kgH_2, it is beneficial for

Table 18 – Price of renewable hydrogen.

Price in $	Sites
$0.0874/kWh	Electricity price of Baghan site
$0.0878/kWh	Electricity price of Nooriabad site
$0.0884/kWh.	Electricity price of Golarchi site
$0.0872/kWh	Electricity price of DHA K site
$4.304/kg-H2	Electricity price of all sites
$4.30–$4.80/kg	Supply price of hydrogen at all sites

Other sites: DHA Karachi, Baghan and Golarchi.

electricity. The difference between the different sources of the renewable energy cost curve shows that the profitability of focusing on the penetration of renewables is lower than focusing solely on decarburization.

Renewable hydrogen and electrification pathways have comparable energy cost systems. In 2050, the total cost of the two lines will be about 29% higher than that of the national energy cost system, and the gap between the two will be less than 1%. However, in these cases, the cost structure is quite different. The path dependence on crude oil is highly dependent on crude oil imports. Until 2016, Pakistan's import dependence remained between 70% and 72%. In Pakistan, fuel prices range from US $ 2.27 to US $ 2.756 per gallon (the highest fuel price in Norway is US $ 7.08 per gallon). Due to rising acquisition costs, the average cost of green hydrogen has increased. To become a competitive fuel for electric vehicles, the cost of hydrogen is between $ 4–5 per kilogram. Due to extreme energy shortages and the world's most vulnerable atmosphere, the cost of using hydrogen in Pakistan may be higher (US $ 5.30/kg to US $ 5.80/kg). According to Table 18, when the level of carbon emission reduction increases, the gap between the cost curves will widen. In terms of carbon emission reduction, the profitability of focusing on renewable energy targets is more than 20% lower than focusing on ambitious emission reduction targets. In this case, there is no excess electricity because the grid can be accessed when needed. In the case of the national grid\/wind turbines, the largest excess electricity is generated by wind turbines, accounting for 35.2% of the total excess electricity generated, avoiding 883 kg of CO2 emissions per year.

Due to the rise of new natural gas and wind energy sectors, Pakistan\u2019s import dependence dropped to 70% in 2016 and 69% in 2017. Analysis of the system efficiency at the nominal stack current shows that the efficiency of the electrolysis system is 57%, while the highest efficiency alkaline system is 41%. He pointed out that hydrogen production is about 20% lower than the manufacturer's nominal flow rate. If the nominal flow rate is reached, the system efficiency will reach 50%. In addition, Pakistan is also an oil importer. Compared with total oil imports, Pakistan's total oil imports are 25%.

Discussion

Next, biomass has a recent score of 0.975, solar energy is classified third with a score of 0.756, but this is consistent with [51]. The geothermal energy efficiency score of Pakistan is 0.662, indicating that it has minimum efficiency as RES for hydrogen production. The renewable energy of hydrogen is a sustainable and reliable future supply for globalization, and several countries have hydrogen energy technical purposes on their horizon. For this purpose, the source of wind energy is considering the best option for the production of hydrogen energy from Pakistan. The sun and biomass are the second source of energy available based on previous preference standards. However, geography can be considered as a minimum selection for this purpose. Therefore, it is necessary to correct the most efficient size as a wind to make the energy intervention of hydrogen in Pakistan. Biomass can use hydrogen as the second-best option in this regard. The results of this study can help choose the best option for the future hydrogen economy for renewable energy sources available. This study is based on the empirical data of Pakistan, and experts have provided their advice on local languages. After all, economic conditions, resource capabilities, and social-political conditions are very different between countries. However, this can address other similar areas and studies. This task can also help perform the technical evaluation of a particular technician based, or you can find the best available way to develop Hydrogen Base energy.

Hydrogen can also be supplied by low-temperature tank trucks, or it can be liquefied and transported through pipelines. Pipelines are only profitable in large batches or short-term operations but are rarely used to maximize the efficiency of hydrogen by-products. Since the load is very complex (4000–4500 kg), liquefaction will allow more efficient transportation of renewable hydrogen produced in trucks over long distances. In addition, there is considerable inconsistency in the prices of hydrogenation and dehydrogenation reactors. For example, Teichmann calculated that the hydrogenation reactor cost was slightly higher than the dehydrogenation reactor cost, while xxx estimated that the reactor cost was closer [96]. Think that dehydrogenation reactors are more expensive, although Reu also thinks so. If Pakistan implements green hydrogen energy production, it can reduce its daily demand for crude oil by 600 billion barrels. In this regard, the existing carbon dioxide emissions of 166,298,450 tons must be assessed. In the case of traditional power terminals, changes in demand levels will make market power costs extremely unstable, causing additional difficulties for companies that rely on their transmission. Energy costs make renewable hydrogen from wind energy increasingly attractive. In addition, the electricity bill generated by K-Electric has less impact. The marginal price of green hydrogen produced by wind is US$4.30/kgH2. Therefore, due to the improvement in sales, the annual demand for renewable hydrogen generated by wind energy has increased over time, allowing the construction of more wind power plants, thereby increasing the production capacity of renewable hydrogen generated by wind energy.

Conclusion and policy implications

In this research, four main steps are used to choose the most appropriate renewable energy source (RES) in Pakistan for generating hydrogen. We weight all criteria using the Fuzzy-

AHP MCDA method. In addition, the study measured the production of renewable hydrogen and its cost using first-class engineering models and Levelized costs of energy. Based on the outcomes of the fuzzy analytic hierarchy process, we found that the weight of biomass energy is 0.062, the second-highest, and geothermal energy weighed the lowest at 0.038. From an environmental impact point of view, the result determined wind energy to be the best source of renewable energy for the production of green hydrogen.

Although it is determined that solar energy has a very low impact on the environment, it is found that the weights of wind and solar resources are 0.068 and 0.065, respectively. Geothermal energy gains 0.060, while biomass is the least environmentally friendly energy source with a weight of 0.058. On the contrary, biomass energy is economically more beneficial than other renewable energy sources. Under the economic efficiency standard, biomass has scored 0.084. Solar and wind power each have the same weight of 0.081. Geothermal weighs the least at 0.051. The social acceptance of biomass is significantly higher than wind energy and geothermal energy, but slightly higher than solar energy. The weight of biomass is 0.065, and under social acceptance, the weight of solar energy is 0.063. Wind with a weight of 0.050 ranks third, and geothermal is last with a weight of 0.034.

The current research has evaluated wind energy potential for its economic viability and capability for generating renewable hydrogen and launching a clean fuel. The results of the research can be generalized for decisions makers in countries similar to Pakistan in their environment, climate, economic and energy characteristics. There are different electrolytic tank systems to produce hydrogen through an electrolytic phase. If the lowest price of hydrogen exceeds US$2.99/kg kg-H2, the demand for green hydrogen also increases. However, the prices of sustainable hydrogen limits in Pakistan are US$3.92/kg-H2, making it commercially beneficial. In addition, because of the effectiveness of the hydrogen transformation mechanism, it is estimated that wind energy can produce approximately 0.85.5 billion kg of Pakistan, which can satisfy the demand of 22% of the country.

It is concluded that renewable hydrogen costs US$1/kg kg-H2 and US$4/kg kg-H2 respectively, according to the findings., which implies a significant increase in the production of renewable hydrogen leading to a decrease in the demand for hydrogen. The results are not considered. In addition, the inexpensive renewable hydrogen monetary value (e.g., US$2/kg) has an effect on the demand for renewable hydrogen. The hydrogen output produced by wind power per year is dependent. The electrolyzer device functionality in power conversion ability will have a great impingement on the quantity of reproducible wind-generated hydrogen. According to the results of the survey, an electrolytic tower device with 75% energy effectiveness.

Independent Power Producers (IPPs) are the primary figures in the supply chain in Pakistan, whether in the public or private sectors. As a result of the merge, WAPDA has had four GENCO distribution entities since 2012. There are three rental power projects to select from.

The loss of distribution is found in the range of 9.47%–33.40%, and the DISCOs cannot achieve the objective of the loss of NEPRA, and the improvements compared to the previous year. As indicated by the fact that the program was started, another problem is the lack of organized and integrated policy decisions. A scheme that was found impossible midway through the project. Due to geopolitics, despite its significant hydropower capacity, it was not given priority. No technological adaptation abused local capital, and after signing the MOU for thermal plants, the China Pakistan Economic Corridor is now responsible for all projects.

Policy implication

In the process of globalization, renewable hydrogen power is considered a sustainable and secure energy resource for the future. Countries are now more determined and focused on developing the technology required for hydrogen energy. Pakistan may produce renewable hydrogen using its plentiful renewable energy. Hydrogen energy technology will have a great effect on the latest energy dilemma and future energy security in Pakistan. To achieve this ambitious goal in Pakistan, it must use the most efficient renewable energy to develop hydrogen, and wind energy has proven to be the most appropriate resource. Biomass, on the other hand, may also be used for hydrogen treatment. However, geothermal energy, on the other hand, has not yet to be developed as a viable hydrogen-producing alternative.

The outcomes of this research can help decision maker choose the best option for the future hydrogen economy. However, these results are only applicable to Pakistan since experts provided advice in Pakistani. Other factors differ from one country to another such as, economic status, resource capabilities, and socio-political situations. Therefore, the two-stage MCDM methodology used in this study can be applied to the same type of research in other countries or regions. It can also be used to specify the optimal alternative solution from renewable energy resources to generate hydrogen and evaluate the technologies used in this process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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