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Geothermal and wind energy: Sustainable solutions for Pakistan's energy economics

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Abstract. The need for green energy sources like wind farms and geothermal energy has increased along with the world's energy requirements. These developments offer reliable and clean energy with significant economic advantages, particularly for trade deficit countries like Pakistan. Geothermal and wind energy development reduces dependency on imports of fossil fuels, generates employment, and helps mitigate climate change. Pakistan struggles to meet its energy needs and economic targets like many other developing countries. Therefore, National research priorities should integrate geothermal and wind energy storage and discover relevant resources. This article summarizes how geothermal and wind energy technologies might support economic development objectives and promote sustainable energy production. The technological and financial possibilities, challenges, and opportunities, as well as the present and future of these technologies, are considered in the case study. In Pakistan, laws and policies are being established to promote renewable energy development. For example, the Alternative Energy Development Board is the public authority that encourages and enables the growth of renewable energy. This study proposes regulations to stimulate the use of renewable energy sources, promote private investment, and foster a favorable atmosphere for their growth.

Keywords: Geothermal, Wind energy, Sustainability, Energy economics, Feasibility, Energy policy.

1 Introduction

Global energy demand has increased by many folds with technological advancements. On the other hand, the need to reduce carbon emissions has increased interest in renewable sources. Geothermal and wind are two major sources that could help solve these problems [1]. Pakistan struggles to meet its energy needs and economic targets like many other developing countries [2]. This study explores the feasibility of shallow geothermal and wind energy technologies, which can be adopted as long-term sustainable techniques to fulfill energy demands and stabilize the economy. By looking at the current state of these technologies, their benefits, and the problems that need to be solved, this study aims to highlight the possibilities of using green energy sources in Pakistan [3].

Several studies have been conducted on Pakistan's geothermal energy potential, exploring its possibilities for sustainable energy generation. Shuja [4, 5] correlated tectonic and geologic features with surface manifestations of geothermal activity in areas such as the Chagai volcanic arc and its extension to Iran. Bakht [6] and Alam *et al.* [7] concluded that commercial exploitation of geothermal fluids is possible. Ahmad and Rashid [8] and Abbas *et al.* [9] highlighted national-level issues and challenges related to geothermal energy in Pakistan. Younas *et al.* [10] and Mehmood *et al.* [11] explored the geothermal energy potential for electric power generation. Other studies, such as Kazmi and Sheikh [12] and Shah [13], focused on designing hybrid energy systems and exploring different renewable energy sources. These studies help understand the potential of geothermal energy in Pakistan for sustainability and economic development [14].

Pakistan's limited fossil fuel resources and struggling economy restrict the large-scale import of fossil fuels that directly impact the energy crises. Therefore, renewable energy development is a potential solution to the current energy crisis. The country has high wind energy potential along its 1100 km long coastline [15]. Studies have shown that wind energy is a cost-effective renewable resource that can help meet energy demands and reduce dependence on imports [16–18]. Wind-generated power can also be used to produce renewable hydrogen, fuel cars, and other forms of transport, reducing the burden on oil and gas resources [19]. Pakistan's wind power generation capacity is increasing, with a cumulative capacity of around 2118 MW

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Table 1. Summary of the estimated electricity for the fiscal year 2019–2020 [30, 56].

Energy source	Installed capacity (MW)	Electricity production (GWh)
Thermal (oil, gas, coal)	24,826	116,904
Hydropower	9389	38,811
Renewable (wind, solar, biomass)	2414	4418
Nuclear	1360	9078
Imported	3150	23,721
Total	41,139	193,932

installed and commissioned [18, 30]. However, efforts are needed to harness wind energy effectively and overcome the energy crisis [15–18].

Pakistan possesses a long coastal belt with significant renewable energy potential [20]. Wind energy is a cost-effective solution to meet energy demands and reduce dependence on imported fuels [21, 22]. Efforts are underway to explore the wind and solar potential across coastal megacities [20]. A fully integrated renewable energy atlas has been developed to provide wind and solar power potential and cooling demand for the country [23]. While Pakistan faces challenges in transitioning to renewable energy, the potential benefits include reduced toxic gas emissions and a move towards a green economy [22]. Several studies offer valuable insights into the technical and economic feasibility of wind energy projects in Pakistan, as well as the effectiveness and benefits of existing wind farms in the country [24–29].

According to the Pakistan Energy Yearbook 2020 [30], the estimated total electricity demand in Pakistan for the fiscal year 2019–2020 was 136 TWh.

Table 1 and Figure 1 show that thermal power facilities are the primary source of electricity generation, followed by hydropower and imported electricity. Renewable energy sources, such as wind, solar, and biomass, contribute a small proportion of electricity production [30].

Economic evaluation and investment quantification are essential for assessing the viability and potential returns of Pakistan's geothermal and wind energy projects. It also requires considering the local energy market dynamics, government incentives and policies, and the availability of financing options. The power sector circular debt is a major issue in Pakistan's energy economics; it is reported to be Rs. 2.6 trillion (9.3 billion US$) by the end of October 2023; power generation by imported fossil fuels is the key element for such an economic crisis [31]. The World Bank conducted a Variable Renewable Energy (VRE) study in 2020. As per the study outcome, the enhancement and implantation of VRE is a win–win situation for the country, and if VRE targets are met as per expectations, up to 5 billion $ could be saved in terms of fossil fuel imports [32]. Developing geothermal and wind energy projects in Pakistan requires collaboration among stakeholders, including private and industrial investors, government agencies, and local communities. The government must facilitate the provision of permits and create a supportive regulatory framework for renewable energy projects. The Alternative Energy Development Board facilitates renewable energy development and attracts private investment. Collaboration with international organizations, such as the World Bank and the Asian Development Bank, can also provide financial and technical assistance for project implementation. The World Bank has provided 100 million $ for developing the Sindh solar energy project, while it committed to finance 425 million $ for the National Transmission Modernization Project. Turkish firm M/s Zorlu also intends to establish a 100 MW solar power project at a 13% return on Equity. Three Gorges South Asia Investment Limited has developed a 100 MW wind power plant in Sindh province with a direct foreign investment of 150 Million US$; the project has been operational since 2018.

2 Policies on renewable energy

For many years, Pakistan has struggled with an energy shortage. The country is sensitive to price changes due to the current energy mix's heavy reliance on imported fossil fuels, contributing to environmental deterioration. A shift to renewable energy is now more important than ever to alleviate the energy issue, reduce its carbon footprint, and fulfill its international climate change commitments. With an emphasis on expanding solar, wind, hydro, and biomass resources, the Government of Pakistan's current policies and plans (refer to Tab. 2) on renewable energy seek to boost the percentage of renewable energy in the total power generating mix to 30% by 2030 [33, 34]. Incentives for foreign investment, support for off-grid renewable energy options, the creation of a council to oversee policy implementation and coordination with stakeholders, as well as initiatives to raise public awareness of renewable energy advantages and advance energy efficiency, are also included in these policies [33–35].

2.1 Existing policies

See Table 2.

2.2 Proposed policies

Additional regulations might be beneficial to realize the potential of renewable energy and ensure its sustainable growth. The proposed policies and regulations (mentioned in Tab. 3) are significant upgrades to the current ones since they tackle major obstacles to developing renewable energy in Pakistan, including funding, grid stability, and innovation. Additionally, they offer a more thorough framework

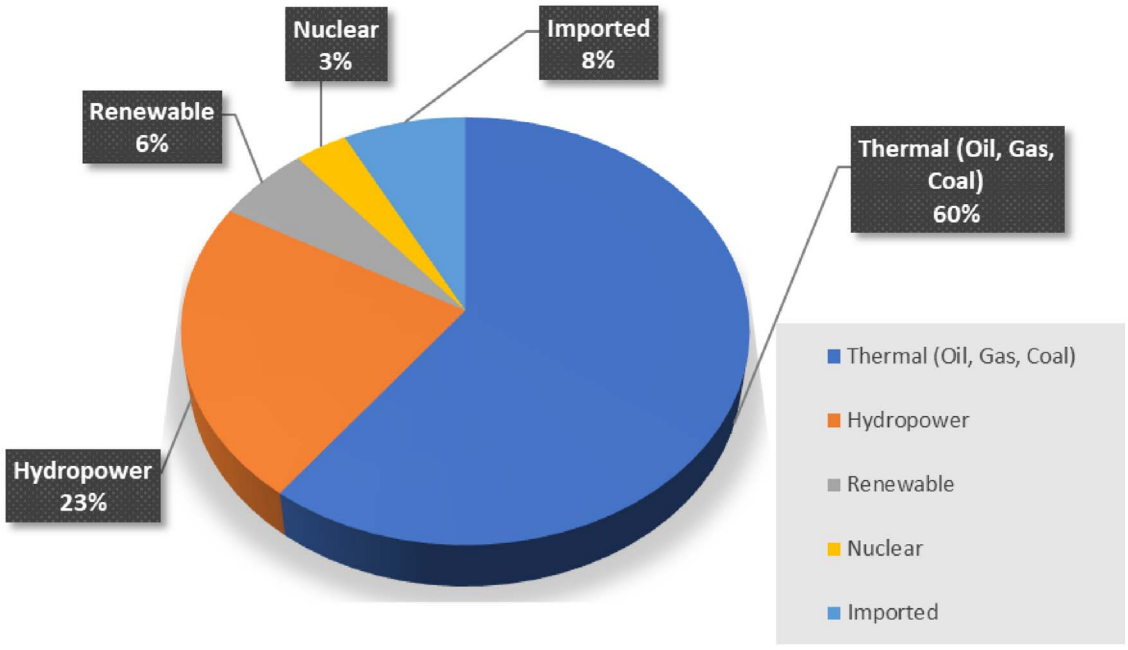

Figure 1. Total electricity production [30, 56].

Table 2. Existing policies of the government of Pakistan on renewable energy.

Policy	Description
Renewable energy share	Aim to increase the share of renewable energy in the total power generation mix to 30% by 2030.
Indigenous resources	Focus on developing solar, wind, hydro, and biomass resources.
Foreign investment incentives	Incentives for foreign investment in the renewable energy sector, including tax exemptions and facilitation of land acquisition.
Off-grid solutions	Encouragement of off-grid renewable energy solutions to provide electricity to remote and rural areas.
Development fund	Establishment of funds to provide financing for renewable energy funds and projects.
Net metering promotion	Encouragement of net metering to promote the adoption of rooftop solar systems.
Renewable energy council	Establishment of a council to oversee policy implementation and coordinate with stakeholders.
Public awareness	Measures to increase public awareness of the benefits of renewable energy and promote energy efficiency.
Skilled workforce	Focus on developing a skilled workforce through training and capacity-building programs.
Environmental sustainability	Focus on ensuring environmental sustainability and minimizing the negative impact on local communities and ecosystems.

for promoting renewable energy and guaranteeing sustainable growth. By implementing these measures, Pakistan may maximize its enormous renewable energy potential, lessen its reliance on imported fossil fuels, and support international efforts to address climate change.

3 Geothermal energy

Geothermal energy is the energy contained beneath the Earth's surface that can be used to generate electricity or for direct heating and cooling. Geothermal systems are typically divided into two categories: shallow and deep. Shallow geothermal systems utilize heat energy near the surface. In contrast, deep geothermal systems tap into high-temperature reservoirs several kilometers deep. Many scientists and engineers have studied and used the Canadian well technique as a passive technique for heating or cooling a dwelling [36], as shown in Figure 2. This type of system cannot provide the heating and cooling requirements for comfort in the winter and summer; instead, the local climate highly influences it. The EAHE (Earth–Air

Table 3. Proposed policies related to renewable energy.

Policy	Description
Feed-in tariff	Guarantee of a fixed price for electricity generated from renewable sources to incentivize the development of renewable energy projects.
Renewable energy targets	Set renewable energy targets for each province to ensure an even spread of renewable energy development.
Energy storage	Promotion of energy storage solutions to address the intermittency of renewable energy sources and ensure grid stability.
Research and development	Funding of renewable energy research and development initiatives to promote innovation and improve the efficiency and cost-effectiveness of renewable energy technologies.
Green financing	Promotion of availability of green financing options, such as green bonds and loans, to support renewable energy projects and make them more financially viable.
Carbon pricing	Consideration of implementation of carbon pricing mechanism to put a price on greenhouse gas emissions and encourage the transition to renewable energy sources.
Distributed generation	Consideration of providing incentives for distributed generation, such as rooftop solar systems, to promote the adoption of small-scale renewable energy solutions and reduce strain on the grid.

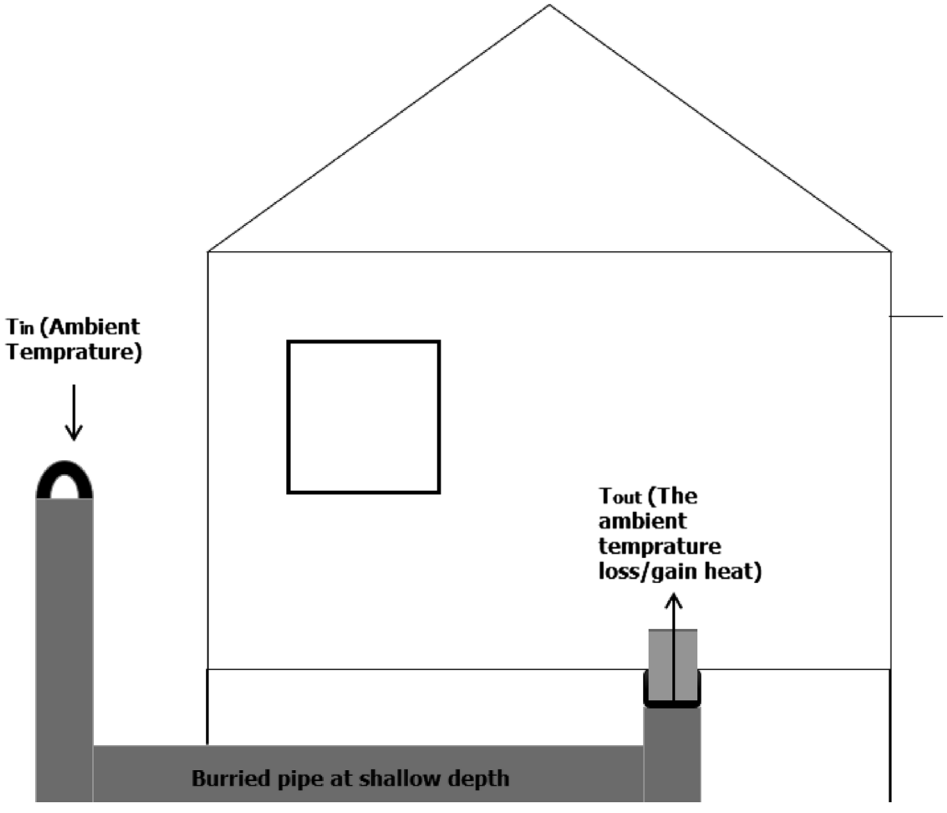

Figure 2. A schematic illustration of the Canadian well-design.

Heat Exchanger) system can readily meet the cooling demand during the hot season. Still, only partially the heating load during the winter season with cold climates is the opposite for countries with hot climates.

Numerous studies have investigated the economic and technical viability of geothermal systems in Pakistan. Geothermal systems can vary in cost depending on size, location, and complexity. However, as a rough estimate, the initial costs of implementing geothermal systems can range from $1 million to $5 million or more, depending on the scale and scope of the project [37]. In addition to the cost, the training required for specialized technical expertise in geothermal systems can also vary. As an approximate figure, it is not uncommon for individuals to undergo

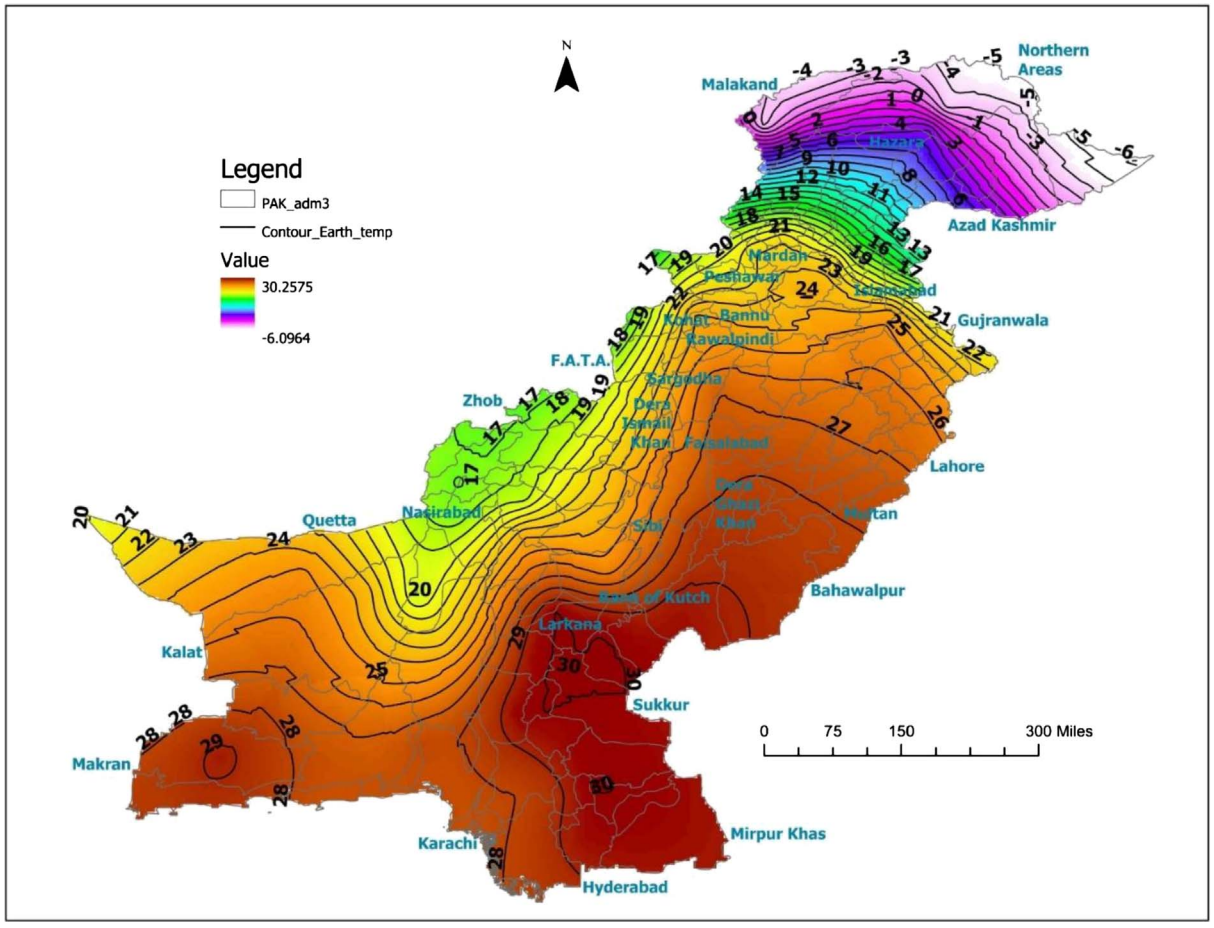

Figure 3. Mean annual Isotherms of Earth temperature based on 36 years of data [39].

training programs or acquire relevant qualifications over 2–5 years to develop the necessary skills and knowledge in geothermal technology and its applications [38].

Employing geothermal systems encounters substantial hurdles, such as high initial costs and the need for specialized expertise. With the appropriate policies and investments, geothermal energy could be a promising source contributing to the production of sustainable energy and economic development. There have been effective applications showing that this technology has the potential to provide sustainable energy solutions. The Tattapani geothermal power facility in Azad Jammu and Kashmir is one example of a power plant that powers more than 6000 households in the area. This power plant produces 1 MW of energy utilizing thermal springs as a heat source [15]. The Tattapani geothermal power station is Pakistan's first grid-connected geothermal power facility. It is a prototype for upcoming national geothermal ventures [39–41].

Mean annual Isotherms of Earth's surface demonstrate the capability of geothermal technologies to provide sustainable energy solutions to Pakistan (Fig. 3) [40]. Additional investments and policy support are needed to accelerate the adoption of geothermal systems in the country. Geothermal energy could be a prospective renewable energy source for Pakistan with the right policies and investments, contributing to the generation of sustainable energy and economic growth.

Previous studies on geothermal energy in different locations and soil conditions by the author investigate the temperature variation with the soil depth. Assessments of cooling and heating in several climatic conditions have been made (Refer to Fig. 4) [41]. One study assessed the geothermal system for a single pipe system, and the inlet and outlet temperatures were recorded for a year [42, 43].

In the study case, the temperature gain and loss for a shallow geothermal system at 4.0 m depth comprising medium sandy soil was observed.

The top soft/loose superficial soil has been ignored. As shown in Table 4, soil profiles of different soils consistent with the workable depth of 3–15 m have been adopted [44]. The inlet temperature (Tin-S5) of the air entering the system and the outlet temperature (Tout-S5) of the air leaving the system are shown in Figure 4.

Its relatively constant temperature differential (T) between the inlet and outlet temperature demonstrates the system's consistency and dependability. The system's year-round capacity to deliver heating and cooling highlights its adaptability and applicability for various applications.

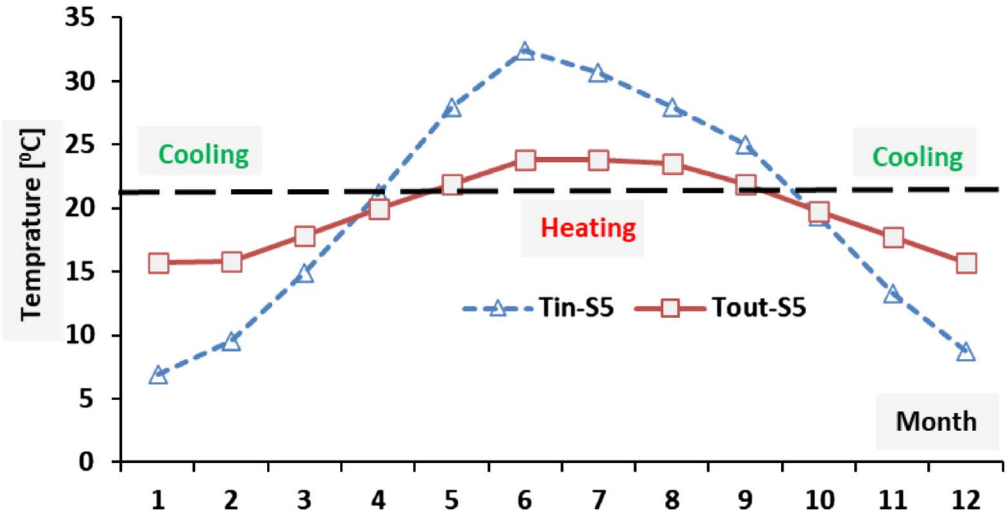

Figure 4. Inlet and outlet temperature time history.

Table 4. Geotechnical and thermal properties of islamabad soil.

Case	Density ρ (g/cm^3)	Porosity n (%)	Thermal conductivity k (W/mK)	Heat capacity Cv (MJ/m^3)	Thermal diffusivities α (m/s)
1	1.4	43	1.18	3.2	3.7×10^{-7}
2	1.64	42	0.92	2.6	3.5×10^{-7}
3	2	40	0.78	2.3	3.4×10^{-7}
4	1.53	40	2.5	2.4	1.0×10^{-6}
5	1.62	38	2.5	2	1.2×10^{-6}
6	1.69	36	2	1.7	1.2×10^{-6}

The shallow geothermal system employing medium sandy soil appears to be operating effectively overall, and it is a promising technology for supplying heating and cooling sustainably and effectively [45].

4 Wind energy

Pakistan is an optimal location for wind energy development due to its extensive open terrain and longer coastline. The wind is extreme along the country's southern coasts, making them ideal places for wind turbine installation. Systems for wind turbines range from modest, off-grid applications to extensive grid-connected power facilities. The economic and technical viability of wind energy has been the subject of several findings. Shami *et al.* [46, 47] conducted a feasibility analysis of the wind energy potential and observed that wind energy is a possible option for electricity generation in the region.

The 50 MW Jhimpir Wind Power Plant in Sindh is one such example. The plant was commissioned in 2013 [48]. The 52.8 MW Sapphire Wind Power Plant, commissioned in 2017 and with a capacity of 52.8 MW, is another successful example [49–51]. These wind power facilities have decreased Pakistan's reliance on fossil fuels and helped meet the expanding energy demands. However, implementing wind energy systems in Pakistan presents obstacles, such as the intermittent nature of wind energy and the need for utility infrastructure to support large-scale wind power plants.

Wind energy has tremendous potential in the southern region, specifically in Mirpur Khas, Hyderabad, Karachi, Makran, and Quetta, as seen by the wind contours in Figure 5. The average yearly wind speed is between 4.2 and 5 m/s. An average of 36 years' worth of data is used here. Therefore, it is suggested that onshore wind turbines be placed at a height of 120 m [14, 16, 24, 52, 53].

With the appropriate policies and investments, wind energy is a promising renewable energy source contributing to sustainable energy generation and economic growth.

5 Synergies between Geothermal and Wind Energy

The complementary characteristics of geothermal and wind energy make them appropriate for integrated applications in Pakistan. Geothermal systems are highly dependable and can provide a constant heat source. Wind turbines are intermittent but can generate significant energy if installed appropriately. Integrating these technologies

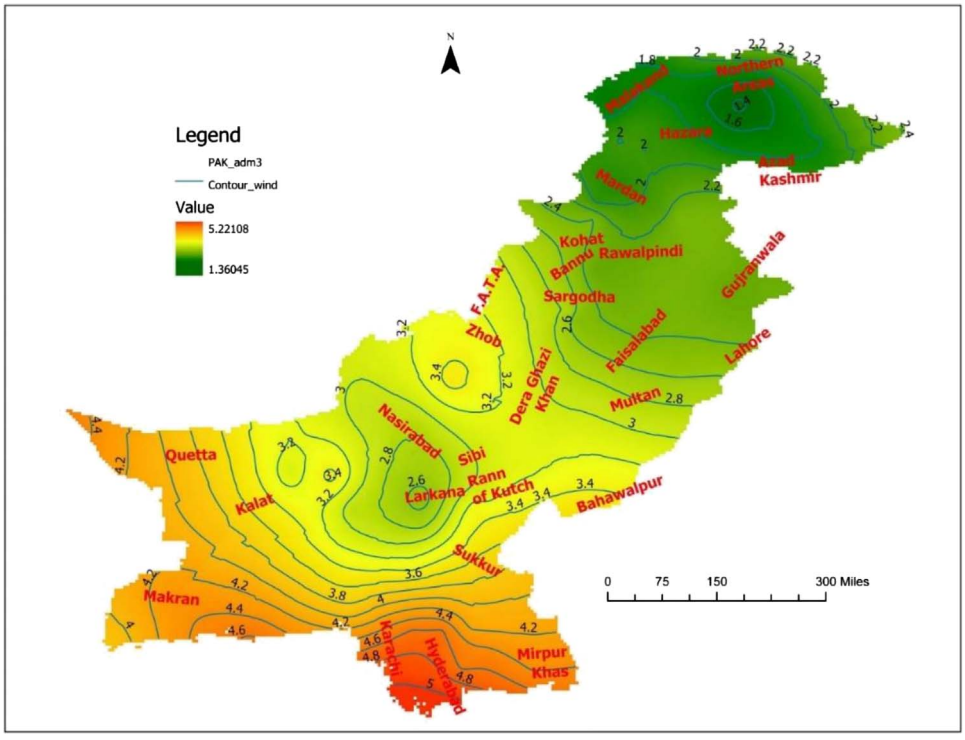

Figure 5. Mean annual wind speed contours based on 36 years (10 m height from ground).

enables the developing of a more dependable and cost-effective energy system. During periods of low wind speed, for instance, the subsurface geothermal system can provide a reliable source of heat energy to supplement the electricity produced by wind turbines. Similarly, excess electricity produced by wind turbines during high wind speeds can be used to power geothermal heat exchangers, which can then be used for space heating and cooling [54].

Pakistan has numerous possible applications for integrated subsurface geothermal and wind energy. These systems can, for example, provide electricity and heating/cooling to off-grid communities in remote locations with limited grid infrastructure. Moreover, these systems can give district heating/cooling and electricity to buildings in urban areas, thereby reducing reliance on fossil fuels and carbon emissions [7]. Nevertheless, the current production of these technologies contributes only to 6% of the total energy production, with an estimate of about 2036 MW from wind and only 400 MW from geothermal (refer to Fig. 6).

Additional research and development are required to optimize the design and operation of these systems. With appropriate policies and investments, integrated shallow geothermal and wind turbine systems could substantially contribute to sustainable energy generation and economic growth.

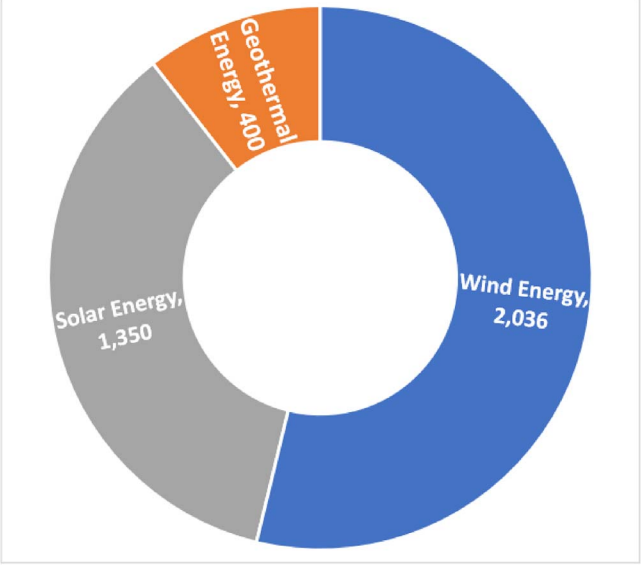

Figure 6. Renewable energy mix of Pakistan [56, 57].

6 Economic and environmental GAINS

Geothermal and wind energy have the potential to economically reduce Pakistan's dependency on imported fossil fuels, which account for a sizable component of the energy mix. By producing power from homegrown renewable sources, Pakistan may increase its energy security and lessen its reliance on uncertain international energy markets. Developing geothermal and wind energy programs may also create jobs and boost local economies.

From an environmental point of view, geothermal and wind energy can assist Pakistan in achieving its climate change mitigation goals. Both energy sources have low operational greenhouse gas emissions, lowering the power's

Table 5. Economic and environmental benefits of geothermal and wind energy.

Renewable energy source	Economic benefits	Environmental benefits
Geothermal	– Job creation – Reduction in fossil fuel imports – Investment opportunities	– Clean and renewable energy – Improved air quality and public health – Reduction in greenhouse gas emissions
Wind	– Job creation – Economic development in remote coastal areas – Development of new industry	– Clean and renewable energy – Improved air quality and public health – Reduction in greenhouse gas emissions

carbon footprint. The extraction and burning of fossil fuels, which can have adverse environmental effects such as air pollution, land degradation, and water contamination, can be reduced by employing geothermal energy. The use of geothermal and wind energy can also benefit the environment indirectly. For example, wind turbines can minimize the amount of water needed to produce energy, which is in short supply in many parts of Pakistan.

Pakistan gains substantial economic and environmental advantages by adopting geothermal and wind energy, as highlighted in Table 5. By decreasing dependence on imported fossil fuels, creating new job opportunities, and mitigating the impact of climate change, these energy sources can promote sustainable energy production and foster economic growth within the country.

7 Challenges and opportunities

Several technical and regulatory obstacles must be resolved to actualize the utmost potential of shallow geothermal and wind energy in Pakistan. The intermittent nature of wind energy and the requirement for energy storage solutions to ensure a constant and dependable energy supply represent a significant technical challenge. In addition, wind turbine installation and maintenance can be difficult and complex. Technological awareness is needed to install even small geothermal systems. Regulatory obstacles must be removed to facilitate the adoption of these technologies. It is also noteworthy that large-scale projects may not be practical in some areas due to a lack of utility infrastructure. Investors may combat ambiguity without definite laws and regulations. International organizations may, for example, offer technical support and training to increase local capacity. Collaboration between the public and commercial sectors can also help remove regulatory obstacles and create an environment that encourages investment. Table 6 shows a summary of the challenges and opportunities.

Although there are challenges in Pakistan when it comes to integrating geothermal and wind energy technology, nevertheless, there are many chances for cooperation and capacity building.

Table 6. Summary of the challenges and opportunities.

Challenges
– Intermittent nature of wind energy
– Need for energy storage solutions
– Complex installation and maintenance of wind turbines
– Technical know-how required for geothermal systems
– Limited availability of suitable geothermal resources
– Lack of well-defined renewable energy laws and regulations
– Lack of utility infrastructure for large-scale wind projects
Opportunities
– Cooperation and capacity building through international support
– Technical support and training for local capacity building
– Collaboration between public and commercial sectors for regulatory facilitation
– Potential for sustainable energy production in Pakistan
– Contribution to global climate change mitigation
– Economic and environmental advantages of renewable energy

8 Potential for renewable energy sources

Wind, hydropower, solar, geothermal, and biomass are renewable sources with significant potential in Pakistan. The 2019 Alternative and Renewable Energy Policy [1] estimates the following renewable energy resource potential (refer to Tab. 7 and Fig. 7) [55].

- Wind energy: 50,000 MW.
- Solar energy: 2.9–3.2 kWh/m^2/year.
- Small hydropower: 6000 MW.
- Geothermal energy: 100 MW.
- Biomass energy: 1200 MW.

To realize this potential, Pakistan must employ a variety of initiatives, including:

- Wind Energy Projects: Pakistan has much potential for wind energy, especially in northern and coastal regions. Pakistan must implement large-scale wind energy projects, such as wind farms, employing cutting-edge wind turbine technology to exploit this potential.

Table 7. Estimated renewable energy in Pakistan [30, 58, 59].

Energy source	Estimated potential	Current production	Percentage of total energy mix
Wind	50,000 MW	2036 MW	5.2%
Geothermal	3000 MW	1 MW	<1%
Solar	2900–3200 kWh/m^2/year	1350 MW	3.5%

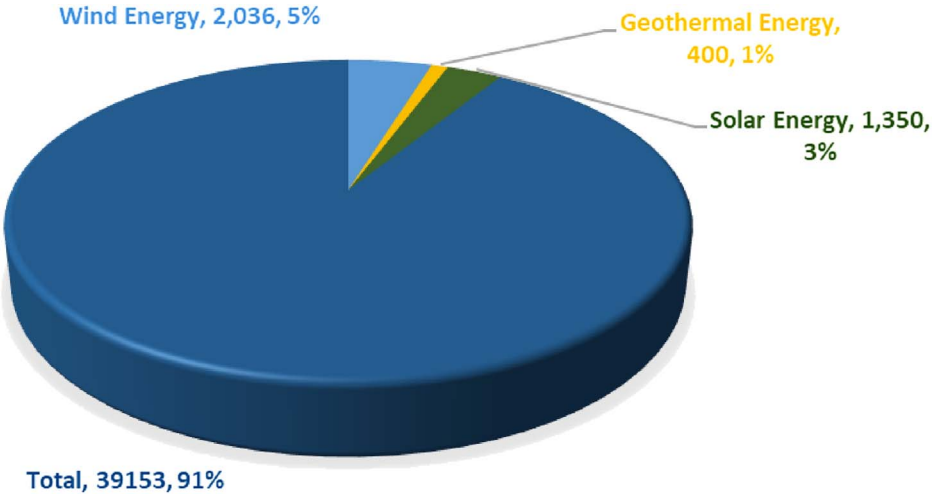

Figure 7. Current production of energy in Pakistan [32, 58, 59].

Table 8. Potential and cost of geothermal and wind energy.

Renewable energy	Estimated potential (MW)	Estimated cost (USD/kW)	Estimated total cost (USD billion)	Estimated sources and funds needed
Geothermal	100	2500–4000	0.25–0.4	• Public and Private Investment,
Wind	60,000–100,000	1000–1500	60–150	• International Financing Institutions and • Carbon Markets

- Pakistan is a good place for solar power since it has one of the world's highest solar irradiation levels. Pakistan must create expansive solar energy projects, including solar parks, that use photovoltaic and concentrated solar power technology.
- Pakistan, particularly in its northern parts, has considerable hydropower potential. Pakistan must implement small-scale hydropower initiatives, such as run-of-river and storage hydropower plants.
- Geothermal Projects: Northern areas have some potential for geothermal energy. To use this potential, Pakistan must launch small-scale geothermal projects, such as direct-use geothermal systems for space heating and ventilation.
- Biomass Projects: Pakistan has significant potential for biomass energy, particularly from urban and agricultural solid waste. Pakistan must launch small-scale, neighborhood-based biomass projects, such as biogas plants and waste-to-energy facilities.

Pakistan has significant potential for renewable energy sources; various renewable energy initiatives must be implemented to realize this potential, as shown in Table 7.

Estimated sources and funding for these initiatives include public and private investment, international financing institutions, and carbon markets. The estimated total cost for renewable energy initiatives in Pakistan ranges from USD 60 billion to USD 150 billion, as mentioned in Table 8.

9 Conclusion

Although there are obstacles to adoption, the technical and economic viability of these technologies in Pakistan demonstrates that there is room for collaboration and capacity building. Pakistan has sufficient potential and sources for developing renewable energy, which must be utilized for economic development and sustainable energy production.

It can join global efforts to combat climate change through investments in research and development.

The country may overcome technical and regulatory hurdles and achieve the full potential of these technologies by establishing rules and regulations, offering technical assistance, and collaborating between the public and private sectors. Pakistan can have significant benefits, including reducing its dependence on fossil fuel imports, creating indigenous industries, and combating climate change using geothermal and wind energy.

Further investigation of geothermal and wind energy systems and expanding storage solutions are recommended for future research and development. Accompanying research is required to identify and indicate potential resources and optimize the installation and operation of geothermal and wind energy systems.

In conclusion, implementing geothermal and wind energy can significantly add to sustainable energy and economic growth.

Conflict of interest

The authors declare that they have no competing interests that could influence the interpretation or presentation of the results reported in this manuscript.

Data availability statement

Upon request, we are ready to provide the necessary data and materials to support the findings of our study.

Author contribution statement

Each author contributed significantly to the study's conception, design, data collection, analysis, and interpretation. The specific contributions of each author are as follows: Muhammad Tayyab Naqash: manuscript writing, review, study conception, design, data collection, analysis and interpretation. Qazi Umar Farooq: review, study conception, data collection. We confirm that all authors have read and approved the final version of the manuscript and agree with its submission. No part of this manuscript has been published or is under consideration for publication elsewhere.

Ethics approval

This study adheres to the ethical principles established by our institute.

Consent to participate

Consent was obtained from all participants involved in the study. They were informed about the purpose of the study, the potential risks and benefits, and their rights to withdraw at any point without consequences.

Consent for publication

We have obtained consent for the publication of individual data, images, or any other identifiable information from all participants included in the study.

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