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Renewable Energies in Kazakhstan: Current Status, Potential, Challenges, and Opportunities

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ABSTRACT

The Republic of Kazakhstan is one of the resource-rich countries and is proactively embracing the sustainable development goals (SDGs) via different strategies. The country has also pledged to achieve significant reduction in the emissions of greenhouse gases by 2030 relative to 1990 level. One of the key approaches to achieving these goals in this country is the development of renewable energies. The present study provides a comprehensive review of existing reports, data and research on renewable energy in this country by analyzing sources obtained from scientific databases, as well as reports and data from international institutions. The aim is to assess the potential and current status of various energy sources and to identify related opportunities and challenges. Among different sources, wind energy has the most significant potential to be used for power generation. This evidenced by the fact that half of the country's territory has an average wind speed in the range of 4–6 m/s. Solar energy also has acceptable potential for power generation, especially in the southern and central regions of the country with an annual potential in the range of 1300–1800 kWh/m^2. Additionally, other sources of energy possess acceptable potential and could serve both power generation and other purposes, such as heating. Challenges related to the development of these systems can include poor infrastructures, the need for investment and technical issues like grid balance. Overall, renewable energies offer the country promising alternatives to fossil fuels, with a variety of advantages including job creation, environmental protection, enhanced energy security.

1 | Introduction

The demand for energy has shown an increasing trend in recent decades owing to a variety of reasons including population growth [1], industrialization, urbanization [2], improvements in quality of life [3], and so on. Use of fossil fuels for the energy-related requirements leads to emission of greenhouse gases such as CO, CO_2, and NOx. On the basis of the data presented by International Energy Agency (IEA), Total Energy Supply (TES) in the world has increased from around 3.64×10^8 TJ to approximately 6.34×10^8 between 1990 and 2023 [4]. In the same period, electricity consumption in the world elevated from 10901.8 TWh to 28002.5 TWh [5] and total emission of CO_2 increased from 20540.3 to 34691.7 Mt [6]. Increasing demand for energy and particularly electricity in addition to its environmental consequence necessitate shifting towards cleaner alternatives. Several studies have shown that expanding clean energies, for examle, Renewable Energy (RE), is among the

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significant strategies for decrement of CO_2 emissions [7, 8]. REs, including geothermal, solar, wind and bioenergy are among the options applicable to provide energy requirements of human beings. These sources of energy are applicable for several purposes like power production, desalination and thermal comfort in buildings. In conjunction with the installation of RE technologies, improvement in the performance and efficiency of the current energy systems has been implemented to reduce the emissions of harmful gases for the environment and fuel saving. Furthermore, making use of carbon capture systems is another technique to decrement the emission of CO_2 due to the power generation (PG) from thermal power plants and industrial activities [9, 10].

Renewable energy systems (RESs) have been developed in various regions of the world in recent decades. As shown in Figure 1, electricity generation by the renewable energies has increased significantly in recent years and it is expected to continue growing in the future. The generated power by the renewable energies has increased from around 4194 TWh in 2010 to more than 9841 TWh in 2024 [11]. Electricity generation by use of RE sources is now one of the cheapest options in most regions of the world. The world weighted-average levelized cost of electricity (LCOE) by use of newly commissioned projects has significantly reduced in recent years. For instance, LCOE for solar PV in utility-scale has decreased by 85% between 2010 and 2020 and this value for concentrated solar power (CSP), offshore wind and onshore wind is 68%, 48% and 56%, respectively. Consequently, RE technologies are attractive options to being added to the capacity and attract investment [12]. Worldwide energy investment was set to exceed 3 trillion USD in 2024 and it was planned to allocate 2 trillion USD to clean energy systems and infrastructure. RESs, particularly the ones applicable for PG, has attracted remarkable investment. For instance, power sector investment in PV systems was planned to exceed 500 billion USD in 2024 [13]. According to Net Zero Emissions (NZE) scenario, yearly capacity additions of all RE sources in electricity generation would quadruple from 290 GW in 2021 to approximately 1200 GW in 2030 [14]. It should be expressed that in addition to the electricity generation, renewable energies can play key role for other purposes. For instance, different renewable energies such as solar, geothermal and biofuels could be used for heating. It is anticipated to have growth in share of renewables in heating demand in future. Modern renewable heat utilization is expected to increment by around one-third between 2022 and 2027, increasing the modern utilization of renewables for heating from 11.4% to 14% by 2027 [15]. Use of renewable energies for desalination and green hydrogen production are among the other applications of these energy sources that has been considered by scholars, policymakers and governments [16–18]. It should be noted that multiple energy renewable energy sources can be used, particularly through hybrid energy systems, to meet the human energy demand [19, 20]. These systems could be more reliable and have better stability compared with stand-alone energy systems. Hybrid energy systems are expected to play a key role in future power systems, as they are able to improve supply chain efficiency, enhance sustainability, and increase capacity of cleaner electricity generation [21].

In addition to the implemented or under-construction projects, there are several plans and policies to develop RESs in various countries and regions. For instance, the Kingdom of Saudi Arabia set ambitious goals for RE and planned to achieve 58.7 GW by 2030 [22]. In the 5th Strategic Energy Plan (SEP) of Japan, it is outlined that it is expected to increase the share of renewable energies in generation of power to 24% in 2030 [23]. In South Korea, according to the RE 3020 plans, a goal is set in order to produce 20% of the country's energy from renewable energies by 2030 and increment job creation related to these technologies [24]. For the MENA region, it is expected to have increase in the renewable capacity and reach around 150 GW by 2030 [25]. In European Union (EU), on 30th of March of 2023, a provision agreement was achieved for a binding target of a minimum 42.5% by 2030 [26]. Some of the Central Asian countries have plans to develop clean energy technologies in

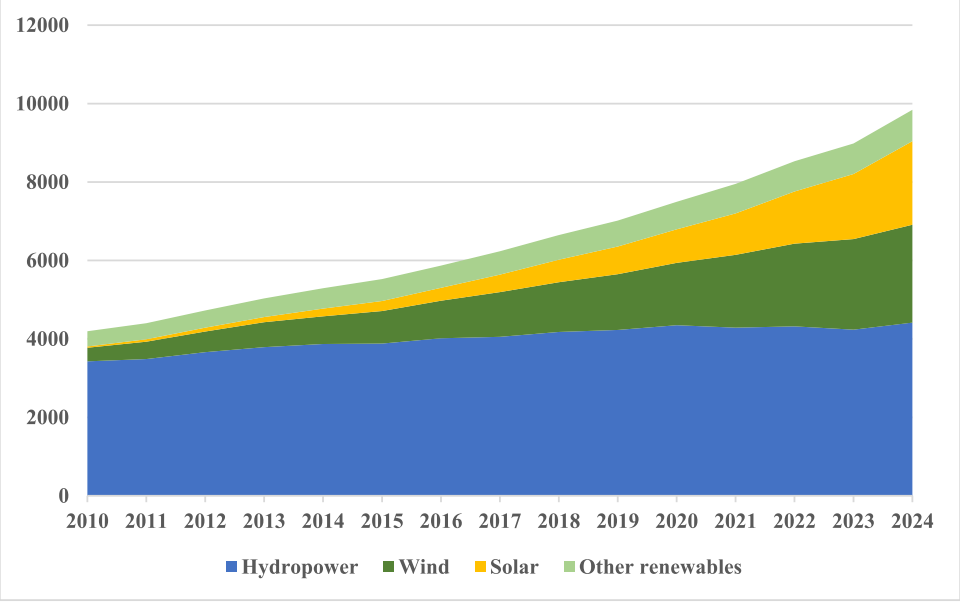


FIGURE 1 | Yearly electricity generation by the renewable energy sources between 2010 and 2024 [11].

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their countries. For instance, the government of Uzbekistan planned to a set a RE target of 4 GW wind and 4 GW solar power by 2026 while it is expected to reach further increment in their capacity by 2030 [27]. The National Development Strategy for Kyrgyz Republic for 2018-2040 plans to increase the renewable energies share in the total energy balance of the country by at least 10% [28]. In Tajikistan, majority of its electricity is generated by hydropower as a RE technology; however, the government has plans to diversify its electricity sources away from hydropower by considering other RESs namely wind and power aside from thermal power plants using coal [29].

Kazakhstan is another country in the Central Asia with several plans and policies to shift towards sustainable development. The energy system of this country is highly reliant on the fossil fuels and its emissions per unit of GDP is high in comparison with the world. In 2016, Kazakhstan ratified the Paris Agreement and, via its Nationally Determined Contribution (NDC), committed itself to reach a target of economy-wide decrease of emissions of greenhouse gases by 15% by 2030 compared with 1990 levels [30]. Moreover, Kazakhstan is engaged in the Sustainable Development Goals (SDG), which establish the roadmap to create more sustainable and better future for all [31]. The United Nations Country Team (UNCT) in Kazakhstan collaborates closely with the government bodies, private sector partners and civil society on adapting the Sustainable Development Goals (SDGs) to the country's specific context and to advance and implement the SDG agenda in the country [32]. The environmental impacts of energy production have become a central focus of the sustainable development agenda [33]. In this regard, there is high importance in development of REs in the country to accelerate the process towards sustainability. With adoption of the "Kazakhstan-2050" strategy, the country took its initial step toward reduction of carbon emissions [34]. The country has taken significant steps in its commitment to the RE and sustainable development. Based on the "Green Economy Concept", it is aimed to increase share of REs in electricity generation to 15% by 2030, making a shift towards more sustainable economic [35]. Some studies have considered use of REs and challenges related to policymaking; however, some of them are not updated and some others focused on the aspects that are different from the main concentrations of the present study. For instance, in 2016, an article was published on the energy systems of Kazakhstan and its potential related to green energy [36]. Compared with this study, present manuscript provides more updated data and considers the plans and policy designed in recent year for development of renewables in the country. In another study published in 2016 [37], the main focus was on the policy barriers and drivers associated with uptake of REs in Kazakhstan. The present study is different from the mentioned articles in presentation of update data, evaluation of different sources for power generation and provision of contemporary data on the status of energy systems and installed RE technologies. In 2020, Zhunussova et al. [38] published an article on challenges and prospects related to RE in Kazakhstan. In 2021, an article was published that focused on the challenges related to the governance and policy of REs in Kazakhstan [39]. In an article published in 2025 [40], CO_2 emissions, energy systems as well as mitigation policies in three Central Asian countries, namely Kazakhstan, Kyrgyzstan and Uzbekistan, were reviewed and discussed; however, there is no particular focus on the potentials of various RE resources. This article provides updated data that exhaustively assess the potential of REs in the country while also considering the opportunities and challenges associated with their development. Present paper addresses this gap by incorporating updated data and covering multiple aspects, such as plans and policies, the current status of various RE technologies, and the potential of different RE sources for exploitation. These elements constitute the main contributions and novelties of the present study. The main objectives of the current article are to:

- Present updated data on the energy systems of Kazakhstan to provide a comprehensive understanding of their characteristics.
- Assess the potential of different sources of RE for various applications, including power generation and heating.
- Assess existing plans and policies related to the development of REs in the country.
- Discuss the opportunities and challenges related to the development of RESs in the country.

The findings of the present study are applicable to the policymaker and scholars working on the development of REs to promote sustainability, particularly in Kazakhstan. Furthermore, the results of the present study can guide developers and investors in identifying opportunities and potential challenges, support educational programs, enhance social awareness, and provide a benchmark for regional comparisons by offering a valuable reference for other countries in the region, mainly the Central Asia, seeking to assess and develop their RE potential.

2 | Work Path of the Study

As mentioned, this article aims to review the status of renewable energies in Kazakhstan, evaluate the potentials of different energy sources, analysis of challenges and barriers towards development of RESs as well as providing opportunities and drivers. In this regard, an overview of energy system is Kazakhstan is presented. The data in that section are gathered from different sources such as International Energy Agency (IEA), the website of World Bank, and publications on the energy system analysis of the country. In addition to the data and statistics, policies and plans related to the use and development of renewable energies are provided in that section. Afterwards, the status of different renewable energies as well as their potentials in Kazakhstan are presented and discussed in the next section. To find appropriate sources to be included in this review article, several keywords like "Renewable Energy", "Wind Energy", "Solar Energy", "Geothermal Energy", "Bioenergy", "Hydropower" with "Kazakhstan" are used in different search engines such as Google Scholar, Web of Science and Scopus. It should be noted that the reliability of all the identified sources was verified by the authors to ensure they were published in reputable and reliable references. In Figure 2, co-occurrence map of the most frequently utilized terms based on the title and abstracts are presented. The references for the co-occurrence map are extracted from English resources on Scopus on the basis of two keywords, "renewable energy" and "Kazakhstan", and "AND" Boolean. This map is generated by

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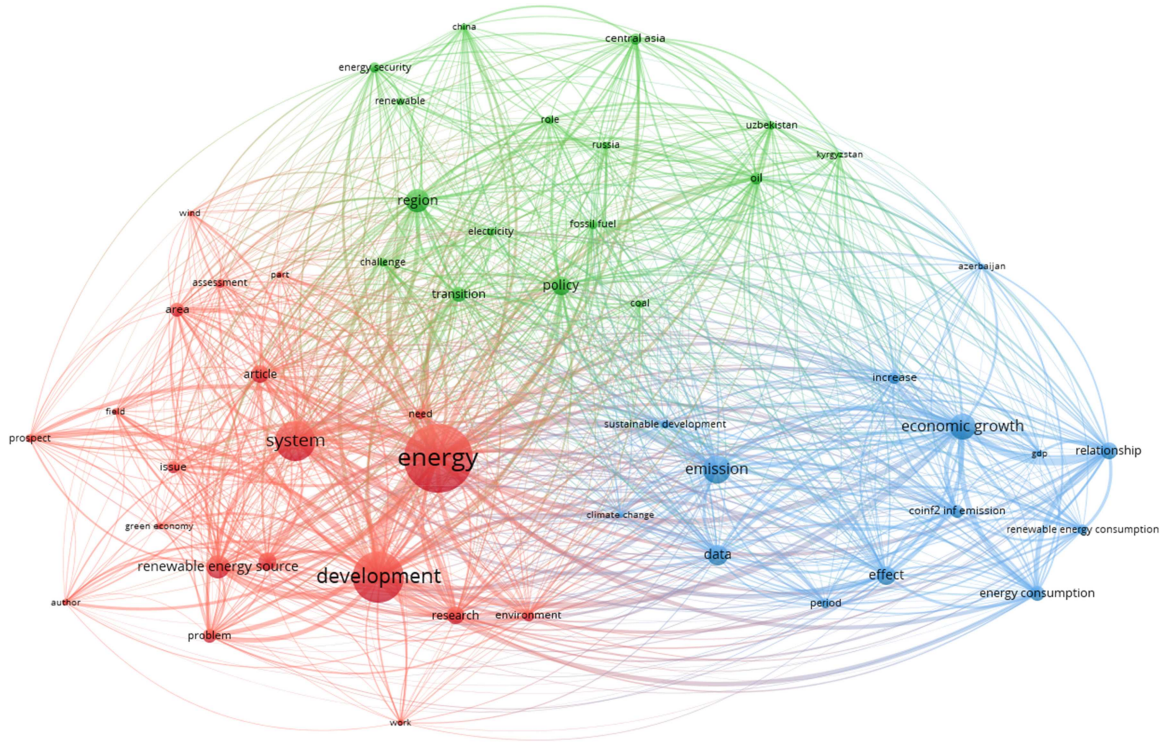


FIGURE 2 | Co-occurrence map of keywords from the abstract of the Scopus articles by consideration of "Renewable Energy" and "Kazakhstan" as the search terms.

use of VOS-viewer software. This figure represents the extent of terms simultaneously exists in the reviewed volume of the words in the selected articles. The network represents the link between the simultaneous terms, while the particular term frequency is presented by the size of the bubbles [41]. As it is shown, the term "energy" is utilized most frequently and is correlated with several other words. Furthermore, based on the dense network, it can be concluded that the mentioned terms are significantly interconnected with each other, except from the terms located much away from the cluster with dense network. It should be noted that this map is extracted in order to find the relevancy of the research articles in this field and some of them are used for review in this article.

The found the most relevant studies to the subject of the present article, found references in the initial stage were screened and selected. Afterwards, the key findings of the selected references were summarized to be reflected in this article. Subsequently, challenges and barriers for the development of renewable energies based on the studies for Kazakhstan and other countries are provided. In the next section, drivers and opportunities related to these systems are presented and discussed. Finally, conclusion section is provided based on the data, discussion and analyses presented in different parts of the paper. In Figure 2, a low chart is provided to summarize the work path of the present article.

3 | Kazakhstan Energy Systems

In this section of the present article, an overview of energy system of the country as well policy measures and plans are presented.

3.1 | Overview of Energy System

Republic of Kazakhstan is one of the countries in the Central Asia and the ninth-largest country in the world by the land area. In the period of 1990 to 2023, its population has increased from around 17,154,000 to approximately 20,330,000 [42]. In the same period, there was a significant growth in its economy and the GDP of the country increased from 26.93 billion current USD to 261.84 billion current USD [43]. Its economy growth is mainly attributed to the massive extraction and utilization of different fossil fuels and exporting them to the other countries [44, 45]. Kazakhstan heavily relies on the revenues of fossil fuel exports to develop and maintain its domestic economy and takes advantage of relatively low costs of energy to produce the exported goods [46]. Increase in both of the mentioned factors, population and economy, are key drivers for increment in the requirement for energy. This nation is a main producer of fossil fuels such as natural gas, crude oil, and coal, as well as a leading exporter of energy [47]. Coal, crude oil and natural gas exports of the country in 2023 were 593,526 TJ, 2,959,082 TJ and 290,364 TJ, respectively [48]. In 2022, the main importers of Kazakhstan's fuels were Italy, China and Netherlands [49]. According to the statistics, coal accounted for the largest portion of the country's Total Energy Supply (TES) in 2023, with natural gas being the second-largest source [50]. Shares of renewable energies in TES of the country is very low and it is far from its potential for use of these energy sources. In 2023, hydropower, biofuels and waste, and other renewable energies (solar, wind, and so on) 31,712 TJ, 1.871 TJ, and 20373 TJ, respectively, contributed to the TES, which stood at 3,099,821 TJ in that year [50]; however, the trend in share of renewable energies in TES of the nation is increasing and it is anticipated to have higher share in near future. In Figure 3, total CO_2

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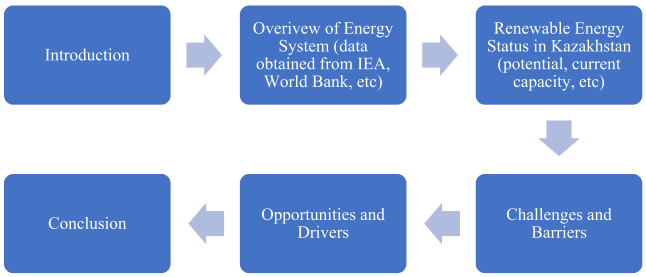


FIGURE 3 | Flow path of the present study.

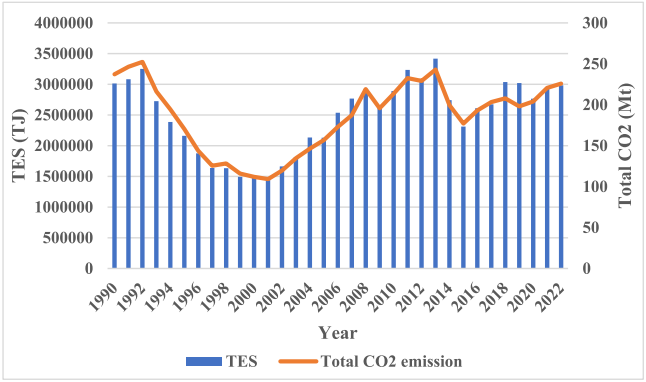


FIGURE 4 | Total CO2 emission and TES between 1990 and 2022 [50, 53].

emissions arising from fuel combustion as well as TES between 1990 and 2022 are presented. It can be seen that in general, increase in the TES leads to higher emissions of CO_2. It is mainly due to the fact that the main sources of energy supply in Kazakhstan are fossil fuels.

Thermal power plants have the key role in electricity generation of Kazakhstan and the main source of fossil fuel used in the thermal power plant is coal. In 2023, 66,291 GWh of the country's electricity was generated by coal and it was followed by natural gas with 32,328 GWh. In 2023, exported 60.2 million USD electricity and imported 236 million USD, mainly from Russia (235 million USD) that was followed by Kyrgyzstan (1 million USD) [51]. RE sources have been used for PG in the country; however, its share was very low compared with fossil fuels. In 2023, among RE sources, shares of hydropower, wind, solar PV and biofuels in electricity generation were 8809, 3786, 1872, and 1 GWh, respectively [52]. In Figure 4, share of renewable energies in power generation of the Central Asian countries in 2022 is compared. It can be seen that in comparison with the other countries in the Central Asia, except Turkmenistan, share of renewable energies in power generation sector of Kazakhstan is lower. Significant contribution of renewable energies in power generation of Kyrgyzstan and Tajikistan is due to high potential of hydro energy and use of this energy source for power generation. Industry sector is the main consumer of electricity in Kazakhstan that was followed by commercial and public services, and residential sector, respectively [54].

Since 2020, the residential sector has been the largest contributor to Total Final Consumption (TFC). The residential sector's share of TFC has risen significantly in recent decades, surging from 83,450 TJ in 2020 to 615,525 TJ in 2023 [55]. One of the most important reasons behind the significant energy consumption in residential sector of Kazakhstan is its weather condition and requirement for heating. In most regions of Kazakhstan, heating season lasts over 6 months and the annual mean temperature in the country ranging from 2°C in the northern regions to 13°C in the southern regions [56]. In spite of regional variations, space heating is required across the entire country, particularly in cold months [57]. In Figure 5, monthly mean temperature in 2022 for three cities in Kazakhstan is represented. It should be noted that these cities are located in distinct regions of the country. Astana is near the north of country, Aktau is located on the Caspian Sea coast, west of the country, and Almaty is at the southeast mountains foot [57]. It can be seen that winters in Kazakhstan is severe and high heating load is required for thermal comfort. Results of household survey in 2018 showed that 30% of households in Kazakhstan utilize coal and/or firewood. Furthermore, it was found that fuel utilization by household is significantly dependent on the regions due to the different in climate, shares of types of housing and accessibility of infrastructure. In urban regions, 46% of detached houses and 5% of apartment utilized solid fuels; however, in rural areas it was 68% and 31% for detached houses and apartments, respectively [62].

3.2 | Policy and Plans Towards Development of Renewable Energies

It is appeared that Kazakhstan is the most capable country of RE deployment among the Central Asian economies in terms of generation scale and diversity of the sources [63]. In Figure 6, the countries in the Central Asia are compared based on the five scored indicators in RE encompassing multi-dimensional facets of regulations and policies. It can be seen that Kazakhstan has higher overall score compared with the other countries in this region; however, its score in heating and cooling renewables and transport renewables is zero. In this part of the paper, the policies and plans for development of REs in Kazakhstan are provided with more details and description.

For improvement of RE integration, policymakers should consider a mixt of short-term and long-term strategies. By creating robust regulatory policies which stimulate the use of REs, for example, feed in tariffs as well as tax incentives, government could make sustainable energies more economically attractive [67]. Recently, some policies and plans have been considered by the government to shift towards sustainable development and increase in share of REs in the energy mix of the country. Republic of Kazakhstan is part of EU$Energy Program, that is an initiative concentrated on the policymaking, evidence-based type, for the sector of energy [47]. Kazakhstan has consistently advanced its dedication to RE and climate initiatives via forward-thinking national policies and engaging in global agreements related to environment protection. A key development in this direction was adaption of a law on Supporting the Use of RE Sources (in 2009), that established a comprehensive regulatory foundation to facilitate and promote RE development via the nation [68]. The 2013 Concept to the Transition to a Green Economy sets target to generate 50% of the country's electricity from renewable or alternative sources of energy, that can include nuclear energy. Moreover, it calls for 15% and 40%

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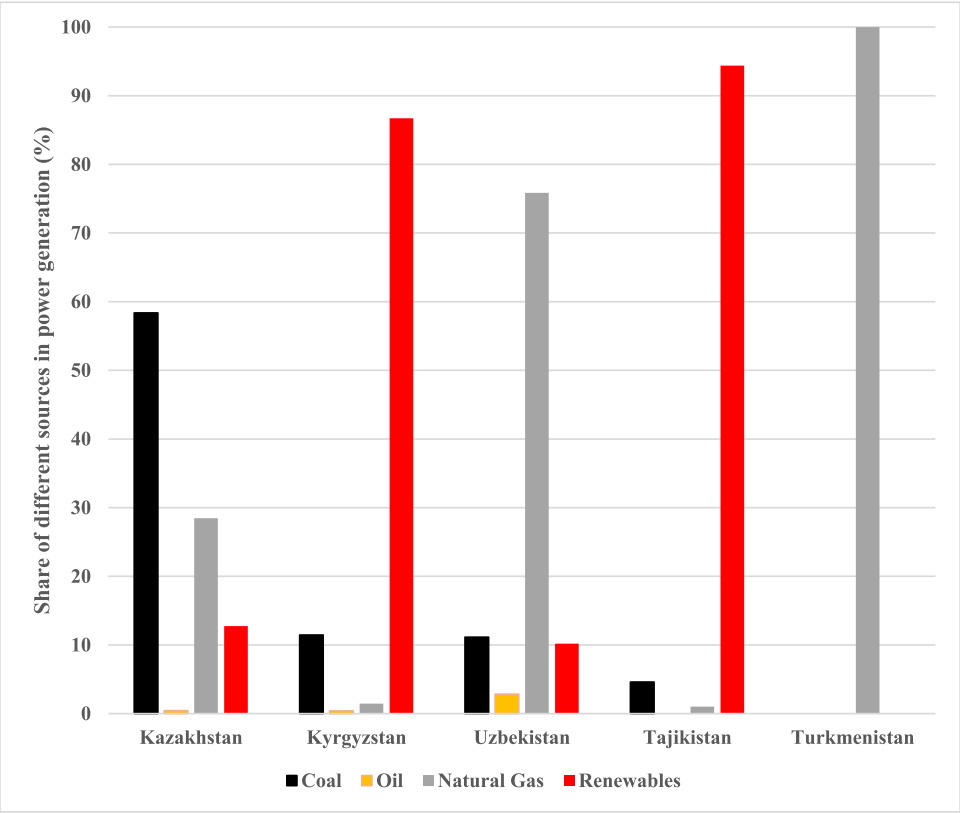


FIGURE 5 | Shares of different sources in power generation of the Central Asian countries in 2023 [52–61].

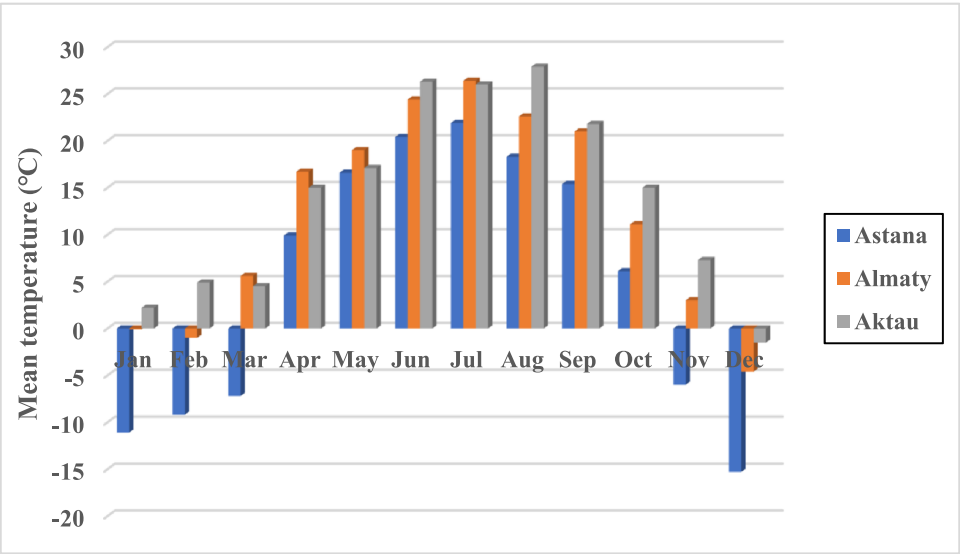


FIGURE 6 | Monthly mean temperatures in three cities of Kazakhstan in 2022 [64–66].

decrease in the emissions of CO_2 by 2030 and 2050, respectively [69]. In 2014, via close partnership with the European Bank for Reconstruction and Development (EBRD), Kazakhstan implemented a support mechanism on the basis of feed-in-tariff (FIT). This mechanism provided the investors of REs with highly attractive tariffs and guaranteed 15-year purchase agreement, that significantly accelerated development of REs in the country. Again in 2018, in collaboration with EBRD and USAID's power Central Asia Program, the country introduced RE auctions. These aimed to reduce price as well as more control over the scale and location of new facilities. RE auctions led to significant decline in tariffs for both solar and wind power [70].

Kazakhstan's 2015 Nationally Determined Contribution (NDC) indicates that emissions of greenhouse gases decrements would be reached by carrying out the Green Economy Concept and related legislative acts aimed to promote the key infrastructure modernization and the production base, on the basis of energy-efficient systems. The NDC provide the key laws that intend to

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provide proper conditions for the RESs and efficient technology adoption [71]. As an ambitious goal, it is planned to reach climate neutrality by 2060 [45]. In 2020, the government announced its commitment to achieving carbon neutrality by 2060. The country's updated NDC indicates ambitious climate goals, that includes 25% reduction in the emissions of greenhouse gases by 2030 relative to the levels in 1990. In order to reach this goal, Kazakhstan aims to promote integration with global technology transfer mechanisms, encourage financing related to the climate investment, engage in global research collaboration, foster the development of innovative clean technologies and promote initiatives to build domestic expertise [72]. It is also planned to reduce subsidies of fossil fuels as an effective motivation for transition to alternative energy sources with zero or low emissions. In 2021, subsidies of fossil fuels amounted to around 6% of the country GDP. The government has decided to implement reform and slowly phase out the mentioned subsidies. As a part this reform, some initiatives such as "tariff for investment" program have been introduced in order to facilitate transition to energy infrastructure modernization [73]. These subsides can be one of the obstacles for the development of alternative clean energy systems. As well as subsidy management, the government has signed some contracts and agreements for installation of new RESs. For instance, in 2023-24, the government of Kazakhstan signed a deal with some flagships companies to develop wind energy project with 3 GW capacity integrated with energy storage technologies [70]. As well as construction of new plants, rehabilitation of current RESs, particularly hydropower plants, is supported by the government and financed by international organization like the World Bank to make the plant, Almaty Hydropower Plant, safe, efficient and reliable [74].

Aside from power sector, development of REs for other purposes has been considered in the policies and plans of the government. In 2019, Kazakhstan's Ministry of Energy requested technical assistance from Asian Development Bank (ABD) to develop new legislative framework for heating sector. This framework is essential for creating a balanced and transparent regulatory system, setting clear goals, and creating an exhaustive plan for increasing use of REs as well as enhancing energy efficiency standards in the heating sector [75]. Another plan in the country based on use of REs is Green Hydrogen Production (GHP). Kazakhstan considers green hydrogen as key driver in its transition towards a sustainable and low-carbon economy. With the abundant RE sources, particularly wind and solar, the country plans to become a leading producer and exporter of green hydrogen. This energy carrier would play key role in achieving the country's goal of carbon neutrality by 2060. In this regard, there is a target in the country to install at least 10 GW of electrolyzer and 10 GW of RESs dedicated to production of hydrogen by 2040. The ambitious plan for the development of GHP plants requires considerable investment and it is anticipated to attract up to 11 billion USD in hydrogen energy sector by 2040 [76].

4 | Renewable Energy Status in Kazakhstan

There are various RE sources with applicability for thermal comfort, PG and other purposes. In this section, the utilization of five types of REs including solar, wind, geothermal, hydropower and bioenergy in Kazakhstan are considered and analyzed. In the following subsection, each of them is discussed separately.

4.1 | Solar Energy

Solar energy is one of the most attractive RE sources regarding its availability in different regions of the world. It is one of the most abundant and cleanest energy sources in the world and play a key role in shifting towards sustainability [77]. This RE source is applied for different intentions like heating [78], electricity production [79], cooking [80] and desalination [81–83]. In case of electricity generation, it is possible to directly convert solar radiation to power by use of solar PV modules [84, 85]. Solar PV modules can be used both in stand-alone or hybrid configurations to generate power [86]. The performance of these technologies is under the impact of a variety of factors [87, 88]. In addition to the characteristics of the PV module, solar irradiance and temperature are two the most important factors in their performance. Effect of these factors on the output of the PV cells can be expressed according to Equation (1) [89, 90]:

$$E_{PV} = P_{STC}[1 + \beta_p(T_{cell} - T_{STC})]\frac{H_t}{H_{STC}}, \quad (1)$$

where T_{cell} and T_{STC} refers to the surface temperature of the cell under real working conditions and standard conditions, respectively. β_p, H_t and H_{STC} are the power temperature coefficient and global solar irradiance incidents on the surface of the module at actual and standard test conditions, respectively. In Equation (1), P_{STC} is the rated power of a PV module at standard test condition. In addition to solar PV technology, solar radiation thermal energy content could be used to drive thermal cycles to produce power [91, 92]. Based on the report by Ministry of Energy, in 2022, the generated electricity by use of solar PV modules, as the only solar technology used for PG in Kazakhstan, was 1899 GWh [93]; however, this can be significantly increase due to the high potential of country. Annual solar potential of the country is highly dependent on the region. In the southern and central regions is in range of 1300–1800 kWh/m^2, while this value for the western and northern regions is in range of 1000–1500 kWh/m^2 [94]. Solar energy potential of Kazakhstan in a year is estimated to be 2.5 TWh, that corresponds to an area of around 10 km^2 of solar cell with overall efficiency of 16% [95]. As shown in Figure 7, southern region of the country has high potential for PG by PV modules. The estimated LCOE based on the use of solar energy is 5.7 USc/kWh [97].

Aside from PG, solar energy in Kazakhstan could be applied for heating, particularly in district heating systems. There is a well-developed district heat heating systems when it comes the cities of the country. The total share of households in the cities connected to district heating system is 63.6% [57]. There is a plan to introduce solar energy into the district heating system of the country. In addition to the district heating systems, it is possible to use solar heating technologies as proper systems for heating, particularly in rural regions. Although it may seem that use of solar technology without subsidy is not cost-effective in

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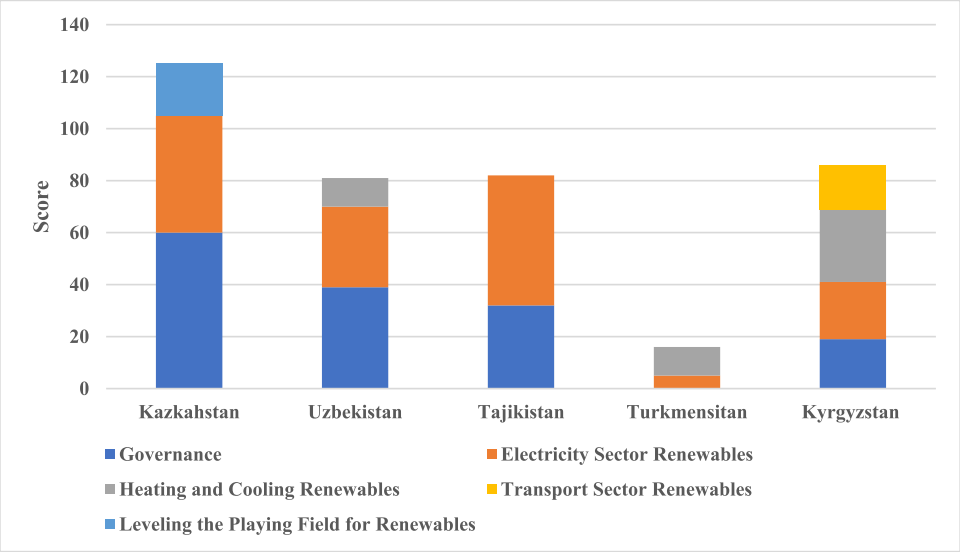


FIGURE 7 | Comparison of the Central Asian countries based on scored indicators in RE encompassing multi-dimensional facets of regulations and policies in 2023 [96].

Kazakhstan, according to the results of a study by Absemetov et al. [98] on a solar water heating system in Astana, implementation of this system for private households could bring environmental and economic benefits to Kazakhstan in case of competing with the heating systems using electricity. It should be noted that by elimination or reduction of subsidy on electricity or fossil fuel, making use of solar heater can be more feasible. Due to the variations in seasonal demand for heat in Kazakhstan, utilization of substantial capacities of storage units is required [99]. Another practical use of solar energy in the country is its application for GHP. As mentioned, there are some plans to develop REs, particularly solar and wind energy for GHP by use of these energy sources and electrolysis technology.

According to the evaluation potential of solar energy in Kazakhstan, it can be stated that this energy source is applicable for PG and other purposes in the country; however, its potential is higher in the southern regions of the country and use of solar systems in these areas would be more feasible. In the northern parts of Kazakhstan, the potential of solar energy is very low and other use of other energy sources with higher potential is more feasible. In comparison with other energy sources, solar energy has some advantages such as scalability and modularity that makes it appropriate for different applications from small-scale residential systems to large-scale systems. Moreover, rapid deployment of solar systems compared with other REs is another advantage of this energy source that make it attractive to be developed in the country. Another advantage of this energy source is its applicability for different purposes like PG, cooling, heating and desalination.

4.2 | Wind

Wind is another type of RE sources with applicability for PG by means of wind turbines. Generated power by the wind is influenced by some factors; however, characteristics of the wind turbine and wind speed are among the most important ones. A wind turbine energy yield at any time could be calculated according to Equation (2) [20].

$$P_t = \begin{cases} P_{\text{rat}}\left(\frac{V_t - V_{\text{cut-in}}}{V_{\text{rat}} - V_{cut-in}}\right) V_{\text{cut-in}} < V_t < V_{\text{cut-off}} \\ 0 \quad V_t \le V_{\text{cut-in}} \text{ OR } V_t > V_{\text{cut-off}} \end{cases}. \tag{2}$$

In Equation (2), P_t and P_{rat} refer to the wind turbine energy yield at any time and the rated power, respectively. V_{rat}, $V_{\text{cut-in}}$ and $V_{\text{cut-off}}$ refer to the rated, cut-in and cut-off wind speed, respectively, and V_t is the speed of wind at the time t at the hub level of the wind turbine [20].

In 2022, electricity generation by wind energy in the world incremented by 265 TWh, up to 14%, achieving 2100 TWh. After solar PV, wind energy has the highest growth among the RESs usable for PG [100]. It is anticipated to reach further increase in the installation of wind turbines for PG to reach the goals of sustainable development in the world. There is high potential for wind energy in Kazakhstan; however, power production by this technology has not been well developed. Electricity generation by use of wind source in this country increased from 3 GWh in 2012 to 2319 GWh in 2022 [93]; however, there is much more potential for electricity generation by use of this energy source in Kazakhstan. There is enormous potential for wind energy in Kazakhstan as half of this territory has a mean speed in the range of 4–6 m/s [101, 102]. In a study by Jianzhong et al. [33], 42 locations in the country were evaluated based on different factors like yearly wind speed, availability of wind energy, and four kinds of potential for wind PG namely technical, gross, economic and emission. In their study, the country was divided into three electricity generation zones as represented in Figure 8. They reported that production of wind power is economically viable in power-deficient southern regions, specifically, Saryzhas, Djungar, Taraz and Zhuzimdyk in cases of height lower than 50 m above the ground level. For cases of heights above 50 m, the most proper regions for PG by use of wind energy in northern, central and western parts of the

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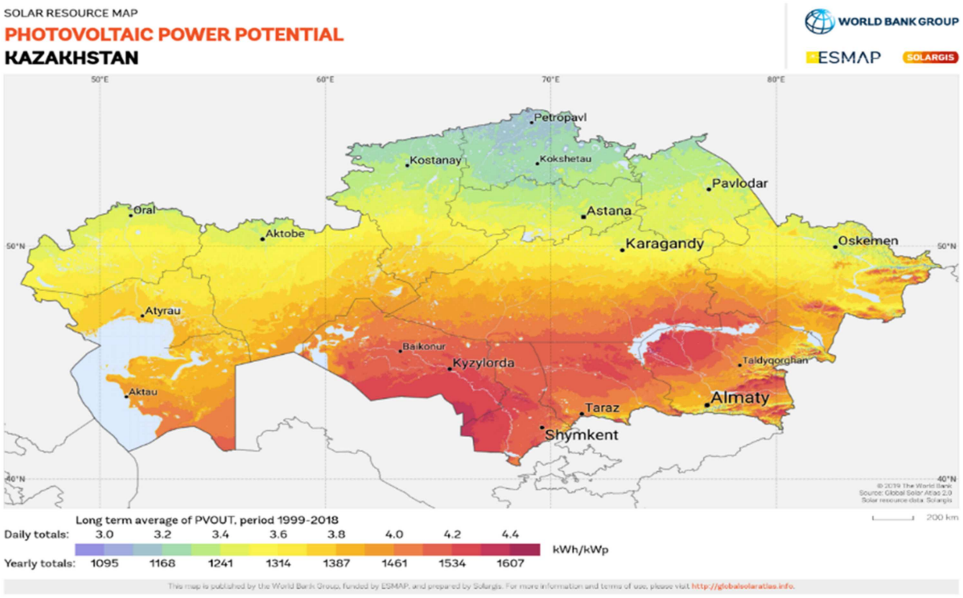


FIGURE 8 | PV power potential in Kazakhstan (Solar resource map © 2021 Solargis, used under CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0/)) [103].

country are Tarabagatay corridors, Central, Northwestern and Caspian. In Table 1, the mean speed of wind in different regions of the country is represented. It is approximated that wind energy potential that can be economically developed is around 760 GW [101, 102]. According to the Doctrine of Achieving Carbon Neutrality by 2060, the country's projected supply of electricity would be higher than 200 TWh/year [97], this means huge capacity of wind turbines must be installed in future to reach this goal. Recently, some funds have been allocated to boost shares of wind turbines in PG sector by increasing the capacity of wind turbines in Kazakhstan.

Based on the assessment of wind energy in Kazakhstan, it is concluded that the potential of this energy source is significantly high and can be applied for PG in large scales with affordable cost. Capsian region, northern and central Kazakhstan as well and south-eastern and southern parts of Kazakhstan have the highest potential of wind energy. These regions should be prioritized for the installation of upcoming wind farms to develop economically and technically feasible systems. Another interesting and applicable idea for development of wind energy is integration of wind turbines with other systems like reverse osmosis desalination systems to provide fresh water since the government is pursuing desalination projects in the western coastal region along the Caspian Sea. The use of wind-powered desalination in the coastal region of the Caspian Sea is both practical and feasible owing to the scarcity of freshwater, the availability of saline water, and the high potential of wind energy in the area.

4.3 | Geothermal

Another RE source with applicability for different purposes, mainly heating and PG, is geothermal energy. This energy is derived from the generated and stored thermal energy in the earth. The heat (H) stored in a specific volume in the subsurface can be calculated based on Equation (3).

$$H = V\left((1-\varphi)\rho_m c_{p,m,T_r} + \varphi\rho_f c_{p,f}\right).(T_r - T_{\text{ref}}), \quad (3)$$

where φ, ρ and $c_p$are porosity, density and heat capacity, respectively. Subscripts m, and f refer to the rock matrix and pore fluid, respectively. T is the temperature and subscripts r and ref refer to th te reservoir and reference, respectively [104, 105].

The energy is reachable by heat transfer from the rocks to the surface either via the natural cracks, boreholes and faults [106–108]. There are different classifications for geothermal systems. Based on the nature and geological settings, the majority of geothermal resources and associated reservoirs in Kazakhstan are sedimentary type. These types of geothermal resources are found in several major sedimentary basins of the world. These systems are formed owing to the existence of permeable sedimentary layers exist at great depths (> 1 km) and higher than mean geothermal gradients (> 30°C/km) [109]. Estimated geothermal energy potential in Kazakhstan is 97 billion ton oil equivalent (toe) which reveals its significantly high potential [97]. Geothermal resources with good potential have been found in the southern regions of the country. These resources hosted in sedimentary basins and include Arys sub-basin in Syr-Daria basin and Ily basin that hosts Zharkent and Almaty sub-basins [109]. The most concentrated geothermal areas are the Ustyurt-Buzashin as well as Mangyshlak basins in the southwest of the country and the West-lly (Almaty) and East-lly (Zharkent) basins that are located in the southeast region of Kazakhstan. The highest levels of extractable energy per basin belong to Syrdarya and Pre-Irtysh basins, owing to their particularly large surface areas [110]. In Table 2, density of geothermal resources in sedimentary basins of the country is represented. It should be noted that the majority of geothermal resources in Kazakhstan are low or medium temperature type and are competitive for heating rather than large-scale PG; however, small-scale power plants in combination with heating systems can be

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TABLE 1 | Mean wind speed in different regions of the country developed by the authors in [33] (used under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/)).

Zone/Location	Winter		Spring		Summer		Autumn		Mean annual (V)	
	50 m	100 m	50 m	100 m	50 m	100 m	50 m	100 m	50 m	100 m
Zone I										
Aktau	6.5	8.5	6.5	8.5	5.5	8.0	6.5	8.0	6.25	8.25
Aktobe	6.0	9.0	6.5	8.5	5.0	7.5	5.5	8.5	5.75	8.38
Atyrau	6.0	8.0	6.0	8.0	6.0	8.0	6.5	8.5	6.13	8.13
Emba	5.5	8.0	6.0	8.0	5.0	7.5	5.5	8.0	5.50	8.00
Fort Shevchenko	6.5	9.5	6.0	8.5	5.0	7.5	6.5	8.5	6.00	8.50
Kandyagash	6.0	9.0	6.0	8.5	5.0	7.0	5.5	8.5	5.63	8.25
Karabatan	5.0	8.0	5.5	7.5	5.0	7.5	6.0	7.5	5.38	7.63
Kulsary	5.0	7.0	5.5	7.5	5.0	7.0	5.0	7.0	5.13	7.13
Makat	5.0	7.0	5.5	7.0	5.0	7.5	5.0	7.0	5.13	7.13
Shalkar	5.0	7.0	5.5	7.5	5.0	7.5	5.5	7.5	5.25	7.38
Uralsk	5.5	8.0	5.5	7.5	4.5	6.0	5.0	7.0	5.13	7.13
Zhanaozen	6.0	7.5	6.5	8.0	6.0	8.0	6.5	8.0	6.25	7.88
Zone II										
Arkalyk	6.0	8.0	6.0	7.5	5.5	7.0	6.0	8.0	5.88	7.63
Astana	6.5	5.5	6.5	8.0	5.5	7.0	6.0	8.0	6.13	7.88
Atbasar	5.5	7.5	5.5	8.0	4.5	6.0	5.0	7.5	5.13	7.25
Ekibastuz	5.5	7.5	5.0	7.0	4.5	6.5	5.5	7.5	5.13	7.13
Erementau	6.0	8.5	6.0	7.5	5.5	7.0	6.0	8.0	5.88	7.75
Karaganda	5.5	7.5	5.0	7.5	4.5	6.5	5.5	7.5	5.13	7.25
Karkaralinsk	6.0	8.0	5.5	7.5	5.0	7.5	60	8.0	5.3	7.75
Kokshetau	5.5	7.5	5.5	8.0	4.5	6.0	5.0	7.5	5.13	7.25
Kostanay	6.0	8.5	6.0	8.5	5.0	6.5	6.0	7.5	5.75	7.75
Pavlodar	5.0	7.5	5.0	7.0	4.5	6.0	5.0	7.0	4.88	6.88
Petropavlovsk	4.5	6.0	4.5	6.0	4.0	5.5	4.5	6.0	4.38	5.88
Schuchinsk	5.5	7.0	5.5	75	4.5	6.0	5.0	6.5	5.13	6.75
Stepnogorsk	5.5	7.5	5.5	7.0	4.5	6.0	5.0	7.0	5.13	6.88
Urzhar	6.5	7.5	6.0	8.0	5.5	7.5	6.5	8.5	6.13	7.88
Zhezkazgan	5.5	8	5.0	7.5	5.0	7.5	5.0	7.5	5.13	7.63
Zone III										
Akbakay	6.0	8.0	6.0	7.5	5.5	7.5	6.0	7.5	5.88	7.63
7. Aralsk	5.0	6.5	6.0	7.5	5.5	7.5	5.0	7.0	5.38	7.13
Chilik	6.0	8.5	6.0	9.0	5.0	8.0	6.0	9.0	5.75	8.63
Djungar	8.0	9.5	7.5	8.0	7.0	8.0	8.0	9.0	7.63	8.63
Kapshagay	6.0	7.5	5.0	7.5	5.0	70	5.5	7.5	5.38	7.38
Karakur	7.0	8.0	6.5	7.5	6.0	7.5	7.0	7.5	6.63	7.63
Kordai	7.0	9.0	6.0	8.0	5.5	7.5	6.5	9.0	6.25	8.38
Kyzylorda	5.0	6.5	5.5	7.0	5.0	7.0	5.0	7.0	5.38	6.88
Mirny	5.5	7.0	5.0	7.0	5.0	6.5	5.5	7.0	6.88	6.88
Sarkand	6.0	7.5	5.0	7.0	5.0	7.0	5.5	7.5	5.38	7.25
Saryzhas	7.5	8.0	6.5	8.0	6.5	8.0	7.0	8.5	6.88	8.13
Taldykorgan	6.0	8.0	5.0	7.0	5.0	7.0	5.5	7.5	5.38	7.38
Taraz	7.0	9.0	6.0	7.5	6.5	8.0	7.0	8.5	6.63	8.25
Zharkent	7.5	10.0	6.0	8.0	5.5	7.5	8.0	9.5	6.75	8.75
Zhuzimdyk	8.0	8.5	7.5	8.5	7.5	8.5	7.5	9.0	7.63	8.63

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TABLE 2 | Geothermal resources density in sedimentary basins of Kazakhstan (toe/m^2) (Reproduced from [111]).

Sedimentary basins	Temperature zones (°C)					Total
	< 20	20–40	40–60	60–90	> 90	
Prikaspiy	0.27	0.15	1.75	1.26	1.4	4.83
Ustyurt-Buzashin	0.02	0.11	0.63	3.22	7.49	11.47
Manguyshlak	0.04	0.10	0.31	3.36	8.47	12.28
Aral	0.03	0.21	1.35	4.34	0.60	6.53
Syr-Daria	0.18	0.41	0.52	0.52	1.01	2.64
South-Torgay	0.33	1.27	1.14	0.48	—	3.22
North-Torgay	0.22	0.18	—	—	—	0.40
North-Kazakhstan	0.11	0.39	—	—	—	0.50
Teniz	0.09	—	—	*	—	0.09
Shu-Saysuy	0.16	0.61	1.17	1.87	2.04	5.85
West-Iliy	0.16	0.27	0.52	6.56	2.03	9.54
East-Iliy	0.15	0.58	1.37	4.62	7.77	14.49
Balkhash	0.26	0.75	0.61	—	—	1.62
Alakol	0.13	0.82	1.34	—	—	2.29
Zaisan	0.03	1.01	1.28	—	—	2.32
priirtysh	0.02	0.24	0.80	1.04	1.86	3.96
Average	0.14	0.47	0.98	2.73	3.63	7.95

considered to make them more economically feasible [111]. In 2019, it was reported that the geothermal heating costs in the country is comparable to several countries; however, they were higher compared with the existing prices of the energy in Kazakhstan [110]. Although geothermal energy has not been used for PG in the country till now, there are some facilities that mainly use this energy source for heating. For instance, in Zharkent area, hot water for geothermal sources is applied for fish farming, heating of greenhouses, schools and hotels, in addition to bathing facilities [110]. As another example, Kaplanbek geothermal filed, in the vicinity of Chimkent, is applied for supply of hot water for residential sector [112]. It should be noted that use of relatively new technologies like Organic Rankine Cycles (ORCs) for electricity generation from low- and medium temperature geothermal sources could be an attractive option for the country since there is considerable untapped potential for PG in the country. As an example, Abdlakhatova et al. [113] reported that geothermal wells in the Zharkent basin have an approximated potential of 10.5 TWh/year, that could address around 82% of the regional electrical energy deficit. total potential production from wells located in the Zharkent basin

Based on the reports and studies on the evaluation of geothermal energy resources potential in Kazakhstan, it can be concluded that this energy source could be considered to be developed in the country, particularly for heating purposes. As well as heating, it can be used for small-scale PG in combination with heating system to be feasible in term of economy. Although there are few facilities for use of geothermal energy in the country, mainly for heating, there is much more opportunities to develop these systems based on geothermal energy in the country to accelerate shifting towards sustainability.

4.4 | Bioenergy

Bioenergy refers to energy sources derived from the organic material which makes up plants, known as biomass. Biomass energy is applicable for different purposes like heating, cooking, generation of power, steam and liquifying biofuels [114]. These materials contain carbon absorbed by plants via the process of photosynthesis [115]. Production of biofuels has remarkable incremented in the recent decades with the aim of environment protection and improvement of energy independency [116]. Biofuels and waste have demonstrated significant potential to provide clean energy in different regions of the world [117, 118]. Depending on the type of the biomass, for example, municipal waste or residues in agriculture, as well as the generated biofuel, the extracted energy can be different [119, 120]. In 2022, total final consumption of biofuels and waste in Kazakhstan was 1521 TJ [93]; however, there is much more potential for development of these energy sources in this country. According to a study by Askarova et al. [121], there is annual production potential of 3.726×10^7 tons of residual biomass that can be capable for energy production of 466.74 PJ per year. Animal, agricultural and municipal solid waste are accessible for energy production in Kazakhstan on the basis of combustion systems, but animal waste with 61.02% and agricultural wastes with 38.34% shares have the highest theoretical overall potential. In Table 3, theoretical potential energy from different biomass residues is represented. It should be noted energy from biomass sources can be co-fired for slight substitution of coal with biofuels in the thermal power plants which would result in decrement in emissions of greenhouse gases. The highest share of residues in the country is found in the northern regions of Akmola, Kostanay and northern provinces that was followed by the eastern and southern regions. Livestock distribution across the country is affected by climate, that influences the

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TABLE 3 | Theoretical potential of different biomass types in Kazakhstan [121] (used under CC by 4.0 (https://creativecommons.org/licenses/by/4.0/).

Biomass type	Theoretical potential energy (PJ/year)	Total energy percentage (%)
Agricultural crop residues	174.23	37.12
Animal wastes	284.82	60.69
Municipal solid waste	10.28	2.19

availability of grass. Consequently, livestock are majorly concentrated in the eastern, northern and southern provinces, while the western and central regions have fewer livestock [122]. The municipal wastes are mainly produced in the large cities of the country like Almaty and Astana. All of these biomass types have considerable potential for energy production.

Bioenergy can be developed in rural regions of the country to supply their requirements, particularly for heating and cooking. United Nations Development Program (UNDP) Kazakhstan evaluated potential of biofuel production for requirements of the country's rural areas. It was reported that the potential production volume of fuel briquettes from wood waste is 147,500 tonnes and from straw is up to 3,500,000 tonnes per annum, that is equivalent to burning of coals with mass of 2,940,000 tonnes [123]. In addition to use of biomass in rural areas and as alternative fuels for PG, it is possible to utilize some types of biomass for GHP. In a study [124], potential GHP by use of available biomass resources, namely livestock waste and agricultural crops in 14 regions of Kazakhstan was presented. They reported that by use of agricultural waste, it is possible to produce green hydrogen with total amount of 432 tonnes/km^2/year. Yearly GHP by use of livestock waste is 5262×10^{-6} tonnes/km^2/year. According to these data, it can be stated that biomass resources in Kazakhstan are applicable for production of hydrogen as a clean energy source. Aside from the mentioned applications, biofuels are applicable in transport sector. Ethanol and biodiesel have been widely utilized in various regions of the world to make the transportation sector cleaner and reduce the emission of greenhouse gases. This idea, use of biofuels in transportation, should be considered for Kazakhstan.

Based on the gathered data on the potential of bioenergy in the country and reported evaluations, it can be stated that there is considerable potential for use of bioenergy in the country for PG, heating and cooking in residential sector, transport sector and hydrogen production. Depending on the type of bioenergy and the local requirements, the most appropriate usage can be different.

4.5 | Hydropower

Hydropower is an energy form engendered by flowing water. It is possible to utilize turbines to harness the energy that is generated by the flowing water and turn it into electrical power [125]. In Kazakhstan, hydropower has significant contribution to electricity generation. In Figure 9, generated electricity by use of hydropower

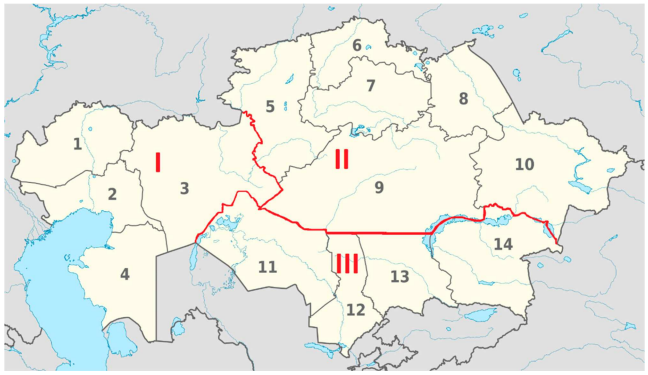


FIGURE 9 | PG zones in Kazakhstan according to [33] (used under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/)).

technology in this country between 1990 and 2023 is represented. Although the overall trend is increasing, there were some fluctuations in PG by hydropower technology. It is estimated that technical feasibility of hydropower in Kazakhstan is 62 billion kWh/year [97]. It should be noted that resources of water in Kazakhstan are not uniformly distributed and the majority of the resources are located in the eastern regions. For example, Irtysh River and Balkhash-Alakol basins in the northeast and east regions of the country contribute to around 75% of generated surface water resources, while there is water shortage in southwestern and western regions of the country [126]. The main river basins in the country are the Balkhash-Alakol basin, the Syr Darya river basin, the Chu-Talas-Assa basin, the Nura-Sarysu basin, the Irtysh River basin, the Tobol-Torgai basin, the Ishim River basin and the Ural-Caspian basin [126, 127].

Till 2022, there were 15 large-scale hydropower stations, higher than 50 MW, with overall capacity of 2.25 GW in the country [128]. In addition to the large-scale plants, there are several small and medium-scale projects and these types of projects are more popular due to reliability, low-cost and being environmentally-friendly [129, 130]. Some plans have been designed to further develop hydropower plants with different scales in Kazakhstan. One of these projects is Tentek with capacity of 480 MW and it is anticipated to initiate its commercial operation in 2029. Kerbulak is another project with 50 MW capacity located in the southern region of the country and it is expected to become online by 2028. Shelek Hydropower Plant-29 in Almaty is the other project which is expected to start its commercial operation by 2027. Koksay with capacity of 17.84 i.e. planned in Jambyl and it is expected to get commissioned by 2025. KazHydro HPP is the other one i.e. anticipated to start operation by 2027 [131]. Addition of these plants to the existing hydropower plant would elevate share of this RE source in the PG of the country. In comparison with the other RE sources, hydro energy has higher contribution to the TES of the country; however, there is much more potential for exploitation of this energy source for PG.

5 | Challenges and Barriers Related to Renewable Energy Development

In the previous section, current status of different RESs and the targets for development of these systems in future in addition to

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the potential of various RE resources were represented and discussed. In spite of existence of several plans for development of RESs and significant increase in their usage in recent years, their penetration is still low, just 2% of total primary energy in 2023 [132]. The development of RE systems across different regions of the world faces some challenges that have been reported in various studies [133]. Some of the most important barriers and challenges related to development of these energy systems in Kazakhstan are presented and discussed in this section. One of the most important challenges is requirement for considerable investment to accelerate development of RESs in the country. In spite of considerable potentials of RE sources in Kazakhstan and political will behind the development of clean energy technologies, utilization of renewable energies, for example, solar, is not widespread yet which can be attributed to the inbuilt inertia in the energy system of the country, lack of regulatory incentives for investment of private sector as well as uncertainties related to the economic return [134]. To solve this issue, it is required to facilitate national investment by involvement of private sector and attract international investment. According to the findings of a study, investors are concerned with the lack of consistency and several gaps in the structure of governance [39]. These issues must be settled to encourage them to invest more on the RESs and related infrastructures. Technical issues related to the irregular nature of some renewable energies like solar and wind can cause reliability reduction of the systems. In a study by Temirgaliyeva and Junussova [135] published in 2020, it was reported that the country lacks sufficient infrastructure for balancing its supply of power on the regional level. Furthermore, electricity sector has limited flexible generation capacity and, in practice, depends significantly on parallel operation with the Russian power system to manage imbalances and maintain stability of frequency [69]. Fast growth of renewable energies in the country would causes serious challenges for the operators of energy management which is not possible to be simply resolved by consideration of smart-grid technologies or utilization of conventional thermal power plants as regulating units. To alleviate these problems, storage units or hybrid energy systems can be also utilized; however, the cost of electricity storage unit is significantly high which would reduce economic attraction of these technologies. In order to reduce the cost and enhance economic feasibility, optimization methods should be implemented to determine the optimal size and configuration of hybrid energy systems with based on the required load and the constraints [136, 137].

Social awareness is one of the important factors in facilitating and promoting the development of renewable energy systems within a community. It, along with related aspects of adoption of renewable energy, has been widely studied by various scholars due to its significant importance [138–140]. Low social awareness about the benefits of RESs is another challenge in the country. Karatayev et al. [37] reported that insufficient awareness of clean and sustainable energy systems for power generation in addition to combination of poor education and social poverty in communities are among the society-related barriers for evolve of renewable energies. Education can play key role in improving awareness about renewable energies and their advantages and benefits. It is suggested that awareness can be enhanced by educational programs, both in supplementary

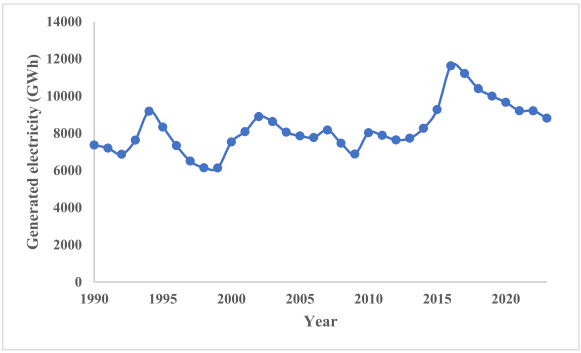


FIGURE 10 | Generated electricity by hydropower in Kazakhstan between 1990 and 2023 [143].

education and school curricula, by developing training programs for engineers, workers, managers, designers, among others. Insufficient expertise is another barrier for development of renewable energies in Kazakhstan [141]. To resolve this issue, universities have key role. Several universities in Kazakhstan, for example, Al-Farabi, Almaty University of Power Engineering and Telecommunications, Nazarbayev University, Yessenov University, Astana IT University, and so on, have developed their research activities on RESs and sustainability concepts in recent years; however, there is much more potential and human capacity in the educational system of the country in field of renewable energies. In addition to schools, universities and academic institutions, media could play key role in enhancement of social awareness regarding the advantages of renewable energies [142]. As well as social awareness, it is crucial to improve social attraction of RESs. For this purpose, economic tools would be significantly effective. Huge paid subsidies for fossil fuels by the government decrease attraction of RESs in term of economy for consumers. As shown in Figure 10, the value of fossil fuel subsides in Kazakhstan is significant and totally it was around 35 billion USD in 2022 for gas, oil, coal and electricity [144]. In order to solve the issue related to the cost-effectiveness of RESs, it is needed to enhance economic attraction of these technologies for consumers by implementation of some financial policy measures like tax deduction [145]. Another issue is associated with the characteristics of the country and its weather conditions which hinders development of some RE source in some parts of the country, for example, solar energy in the northern regions due to low potential of solar energy and possibility of ice and snow accumulation causing in efficiency reduction, and so on. To resolve the issues related to the installation location of RE facilities, it is recommended to use practical methods such as multi criteria decision making approaches to discover the most feasible technology and site locations [146]. Moreover, conducting a sensitivity analysis is useful, as it provides deeper insight into the relative importance of different parameters and improves the robustness of the process of decision-making. Carbon lock-in, poor prospects of employment, stranded assets, out of date technologies, isolate regional supply chains from global markets, inappropriate infrastructures and technologies, losses related to transmission and business environment with high risk are among the other challenges associated with the growth of RESs in Kazakhstan that are reported in different studies [36, 147, 148].

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6 | Opportunities and Benefits Related to Renewable Energy Development

Despite the existence of some challenges and barriers for the development of RESs in Kazakhstan, there are plenty of opportunities and benefits for evolution of these systems. These most important opportunities and drivers can be related to the environmental aspects. One practical way to reduce emissions of greenhouse gases, particularly CO_2, is developing RESs since they have significantly lower carbon footprint [149]. Studies in different countries have shown considerable potential of renewable energies for emission reduction. For instance, for case study of China, it was reported that for every 1% increment in the development of RE, carbon emission intensity reduces in range of 0.028%-0.043% [150]. Emission reduction exploration is necessary for Kazakhstan and the acceptance of Paris Agreement marks an important milestone for this country. In accordance with this agreement, Kazakhstan has pledged to reach an unconditional goal of decreasing greenhouse gas emissions by 15% and a conditional goal of a 25% decrement by the year 2030, relative to 1990 levels [151]. Implementation of RE projects and replacement of coal-fired thermal power plant with cleaner technologies, for example, wind turbines and solar PV, would be worthwhile for significant reduction in the emissions of the country. Consideration of the environmental damage due to the emissions of greenhouse gases, particularly CO_2, leads to more economic feasibility of clean energy technologies compared with the fossil fuel-based systems [120]. Considering the costs related to environmental damage caused by CO_2 emissions, in addition to the mitigating effects achieved via the use of renewable energy, would result in a reduction in both the simple payback period (SPP) and the LCOE of renewable energy–based systems, as presented in Equations (4) and (5) [20, 120, 152].

$$\mathrm{LCOE} = \frac{\left(\frac{r(1+r)^n}{(1+r)^n - 1}\right) \times C_c + C_{O\&M} - C_{\mathrm{CO_2}}}{8760 \times E_t}, \tag{4}$$

$$\mathrm{SPP} = \frac{C_I}{(C_{\mathrm{ener}} + C_{\mathrm{GHG}}) - C_{\mathrm{O\&M}}}. \tag{5}$$

In Equation (4), C_c, $C_{\mathrm{O\&M}}$ and $C_{\mathrm{CO_2}}$ refer to the capital cost, operation and maintenance cost and environmental damage cost due to the emissions of CO_2, respectively, and E_t is the generated power by the systems (8760 refers to the operating hours in a year), r is the annual inflation rate and n is the lifetime of the system. In Equation (5), C_I is initial investment cost, C_{ener} refers to the annual energy income or saving and C_{GHG} denotes the revenue from GHG reduction.

As well as PG, REs offer an opportunity to modernize the heating system of the country and make it more sustainable. Heat generation in the country is highly dependent on coal as the main source, accounting for 342,211 TJ out of a total 386,227 TJ in 2023 [153], which causes significant emissions. Currently, the heating system of country is now reliant on outdated and inefficient fossil fuels systems and infrastructure and focusing on development of REs, such as geothermal and biofuels, in this sector would environmentally beneficial (Figure 11).

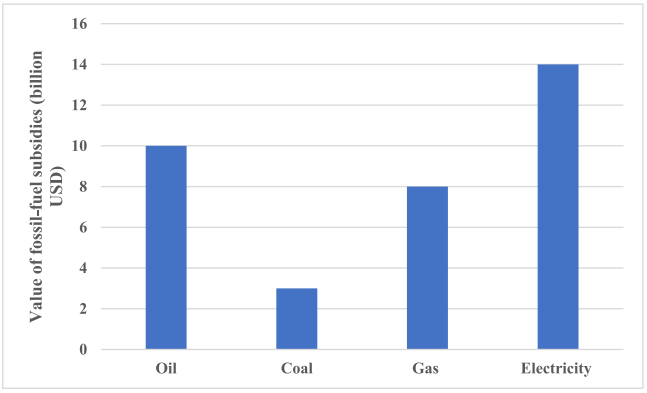


FIGURE 11 | Values of fossil fuel subsidies in Kazakhstan in 2022 [144].

Besides the environmental advantages, growth of RESs would be beneficial in term of economy which is another motivation for the country to shift towards REs [34]. According to an analysis, it is reported that clean energy added approximately 329 billion USD to the world economy in 2023, representing 10% of world GDP growth [154]. The main economic benefits of the using renewable energies are job creation, decrease in cost of energy, reduced reliance on imported sources and long-term stability of economic. Harnessing local RE resources leads to stabilization of prices and guarantees secure long-term supply of energy, particularly for the countries with high reliance on energy import [155]. Moreover, investments in renewable energies would stimulate economic growth via increasing private and public sector funding in development of infrastructure and innovative technologies [156]. Kazakhstan is highly dependent on fossil fuels exports and fuel saving would provide higher capacity of exports. Furthermore, as it was mentioned, the country is net importer of electricity and development of RESs, particularly for PG, would provide an opportunity to reduce electricity import and even enable the country to increase its electricity export. Moreover, by developing renewable energy systems in the country for power generation, it would be possible to increase national income through electricity exports, particularly to Kyrgyzstan, which is facing a power shortage. In addition, development of RE will result in remarkable job creation in the country. Investment in renewable energies offers significant scope for providing employment opportunities. Considerable employment potential related to the development of project, installation and construction of RE technologies exist. According to a report provided by IRENA and ILO [157], RE employed 16.2 million people both indirectly and directly in 2013. It is announced that it is planned to implement 72 energy projects, including 32 RE projects, in Kazakhstan by 2030. These projects would lead to creation of 41,000 jobs and approximately 6000 of them will be permanent positions [158]. Another factor that can make the economic benefit of RESs more sensible is carbon taxing. Consideration of carbon pricing, including carbon taxing, make the development of renewable energies more feasible in term of economy; however, since the country's competitive advantage is low energy prices for the production of export goods, this factor could result in an increase in the price of goods as a negative economic consequence. In this regard, carbon taxing must be implemented with comprehensive study and careful consideration.

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TABLE 4 | Total installed cost, capacity factor and LCOE trends of different RE technologies, 2010 and 2023 (adapted from [168]).

	Total installed Costs (2023 USD/kW)			Capacity factor (%)			LCOE (2023 USD/kWh)		
	2010	2023	Percent change(%)	2010	2023	Percent change(%)	2010	2023	Percent change(%)
Bioenergy	3010	2730	−9	72	72	0	0.084	0.072	−14
Geothermal	3011	4589	52	87	82	−6	0.054	0.071	31
Hydropower	1459	2806	92	44	53	20	0.043	0.057	33
Solar PV	5310	758	−86	14	16	14	0.460	0.044	−90
CSP[a]	10453	6589	−37	30	55	83	0.393	0.117	−70
Onshore wind	2272	1160	−49	27	36	33	0.111	0.033	−70
Offshore wind	5409	2800	−48	38	41	8	0.203	0.075	−63

[a]CSP: Concentrated Solar Power.

As well as economic and environmental benefits, there are some other benefits and opportunities, particularly in term of energy security. This term, energy security, refers to uninterrupted and continuous energy availability to a particular region of country [159]. Energy security remains a persistent issue for numerous countries across the globe [160]. Several items, including energy diversification, affordability, acceptability and availability impact the level of energy security in a country [161, 162]. Resource-poor nations like European countries are interested in long-term agreements with the fossil fuels exporters in order to guarantee supply of fuel uninterruptedly to meet their economy requirements; while, resource-rich countries have better position since they own fossil fuels to meet their need. However, these countries are dependent on the changing prices of fuels in addition to political uncertainties in different parts of the world [160]. Several studies have reported favorable impact of RE development on energy security [163]. Development of these system would respond to the energy security challenges related to availability, reliability, resilience and affordability [164–166]. One of the reasons for enhancement of energy resilience is the country is that the majority of these technologies are decentralized, which decrease the effects arising from terrorist attacks and technological malfunction that can severely disrupt the electricity grid of a country [164]. Kazakhstan experienced slow strategic diversification and modernization of infrastructure. The nation has started incorporating RE sources, demonstrating its dedication to broadening its energy mix [161]. In term of energy affordability, for the conventional technologies such as thermal power plants, both operational and front-end cost are significant. Making matters worse, prices of fossil fuels are sensitive to external market volatility and the trends is increasing [164, 167]; while, the main costs related to the RE technologies are tied to the investment cost in initial stage, and these upfront costs have reduced significantly [164]. In Table 4, total installed cost, capacity factor and LCOE of different renewable technologies are presented. It can be seen that there is reducing trend for the costs of bioenergy, solar and wind systems which make them more attractive for consumers. Energy availability is another criterion evaluated for assessment of energy security and refers to the availability of adequate supply to satisfy the demand [164]. Although Kazakhstan is a resource-rich country and there are several fossil fuels resources, development of RE can further enhance energy availability. Energy diversification is another criterion for assessment of energy security. By development of RESs and increment in the exploitation of RE sources, the energy system of the country would be more diversified and this index will enhance in the country. As well as the benefits and opportunities in term of energy security, development of renewable energies in the country and implementing research and development activities would provide some opportunities for the academic societies. For instance, universities can develop their collaboration with the industries and companies working on these systems and train experts and researchers in this field of science. In recent years, some universities such as Yessenov university established cooperation with a European project developer and Kazakh-German University (DKU), to train high-class specialists for the project on the GHP in Mangystau region [169]. Similar programs and collaboration could be established at other universities to train more local experts and develop academic researches.

7 | Conclusion

Kazakhstan, as a rapidly developing nation with high potential in RE resources, is at a pivotal point in advancing sustainable development. The commitment of the nations to the SDGs highlights the importance of expanding use of REs in order to decrease emissions of greenhouse gases. However, challenges persist due to the lack of comprehensive evaluation of potential of RE, current utilization status and related issues. This study is conducted to provide detailed overview of RE sources, their utilization, and the associated plans and policies in the country. The most important findings are outlined as follows:

- There are considerable potentials for different RE sources in the country and can be developed for variety of intentions like power generation and heating.
- Among different RE sources, wind energy has the highest potential and it is estimated that the potential of this energy source that can be economically developed is approximately 760 GW.
- As well of power generation and heating, REs can be applied for GHP as promising technologies. The government has ambitious plan to develop GHP systems by use of solar and wind technologies.
- Geothermal resources in the country are more feasible for heating rather than PG due to their characteristics and specifications. Moreover, these resources can be used for small-scale PG in combination with heat system to be more economically feasible.

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- Bioenergy can be used for heating and cooking purposes in rural areas as well as PG as alternative fuel source.
- The main barriers for development of RES in Kazakhstan are requirement for huge investment, inappropriate status of infrastructures, low social awareness, lack of expertise, gap in policies and huge subsidies of fossil fuels.
- It is recommended to develop research and development activities, allocate financial incentives, attract both private and foreign investment to accelerate development of RES in Kazakhstan.

Author Contributions

Lyailim Taizhanova: writing – original draft, investigation, project administration. **Akhmetov Berik:** conceptualization, supervision, funding acquisition. **Samal Syrlybekkyzy:** writing – original draft, validation, resources. **Shynar Baimukasheva:** writing – original draft, validation, data curation. **Symbat Koibakova:** validation, writing – review and editing. **Nurkhat Zhakiyev:** writing – review and editing, validation, visualization. **Mohammad Alhuyi Nazari:** writing – review and editing; writing – original draft, supervision. **Mohamed Salem:** supervision, writing – original draft, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Declaration of AI Assistance

The authors did use AI tools (ChatGPT and DeepSeek) to support readability and enhance the flow of the writing, but all ideas, content, and conclusions are entirely their own.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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