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REVIEW ARTICLE

A review of the current situation and challenges facing Egyptian renewable energy technology

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Abstract
Egypt is pivotal in the global energy transportation. It has committed to the Paris Agreement and presented its recognition of the necessity for international cooperation in tackling climate change. Despite these commitments, Egypt faces significant challenges in its energy sector. With the high domestic energy demands, the nation's crude oil reserve is projected to be depleted within the next 15 years. It is crucial to prioritize and focus on renewable energy technology and its utilization in the present and future frameworks of Egypt's energy by addressing these issues to maintain its strategic position in global energy markets. The study aims to examine Egypt's current energy landscape and assess its potential for adopting renewable energy sources. To meet the nation's electricity demands the study explores both the current state and future possibilities for renewable and sustainable energy in Egypt, taking into account plans from both the private and public sectors. The adoption of such strategies will guide the authorities of Egypt towards achieving the nation's renewable energy ambitions, including the 2035 energy strategy, with the ultimate goal of becoming a net-zero emissions nation. Egypt's renewable energy sector is largely underdeveloped and faces numerous challenges, despite it has abundant and varied resources. These challenges include barriers in manufacturing, political hurdles, economic constraints, and technological limitations. This study suggests several strategies for Egypt to optimize its utilization of renewable resources. The suggestions are made considering the existing energy policies and identifying potential obstacles in the deployment of renewable energy systems. This study would assist Egypt and other nations in establishing a clear path toward achieving the global objective of net zero emissions in the coming decades.

Keywords: Renewable energy; Energy technologies; Energy storage; Energy policy; Sustainable development; Egypt

Introduction

The exploitation of natural resources across the globe has escalated in recent years (Ridwan et al., 2023; Raihan, 2024a). That leads to severe environmental consequences, like global warming and climate change (Raihan, 2023a). In this regard, a major issue is the burning of fossil fuels, which represents around 80% of energy use globally (Raihan, 2023b; 2023c; 2023d). In this case, shifting towards renewable energy sources and improving energy efficiency can contribute to mitigating environmental deterioration (Ahmad et al., 2024; Raihan et al., 2022a; Raihan & Tuspekova, 2022a). This transition has the potential to reduce carbon emissions as well as to foster economic growth and environmental health (Voumik et al., 2022; 2023). Renewable energy sources generate electricity without burning fuels and offer a clean alternative to fossil fuel consumption (Ghosh et al., 2023). Hence, it reduces pollution and enhances the quality of life for humans, animals, and plants (Sultana et al., 2023). Policymakers could be inspired by the improvement in living conditions to increase investment in the renewable sector (Islam et al., 2023; Raihan & Bari, 2024). The United Nations has set the 2030 Agenda for Sustainable Development. That includes 17 SDGs, where goal 7 aims to significantly boost the proportion of renewable energy in the global energy mix for achieving a sustainable and environmentally friendly future. Egypt plays a crucial role in the context of the global energy sector owing to various factors, particularly its geographical location (Al-Maamary et al., 2017; Raihan et al., 2023a). Egypt is situated in North Africa and the Arab region, it boasts approximately 3000 kilometers of coastlines along the Aqaba, Red Sea, Gulf of Suez, and Mediterranean. Due to its strategic location, Egypt is placed at the nexus of Europe, the Middle East, Africa, and Asia (IRENA, 2018). Additionally, Egypt is home to vital transportation arteries including the Suez Canal and the Suez-Mediterranean Pipeline, bolstering its importance in the arena of global energy. Moreover, Egypt's heavy reliance on conventional energy sources contributed to the surge in CO_2 emissions within the nation (Abdallah & El-Shennawy, 2020). The electricity demand is escalating due to population growth, urbanization, economic expansion, industrialization, and energy subsidies. At present natural gas accounts for approximately 66% of the nation's overall electricity consumption whereas hydro energy and renewable sources contribute only 7% and 8% respectively (IRENA, 2018).

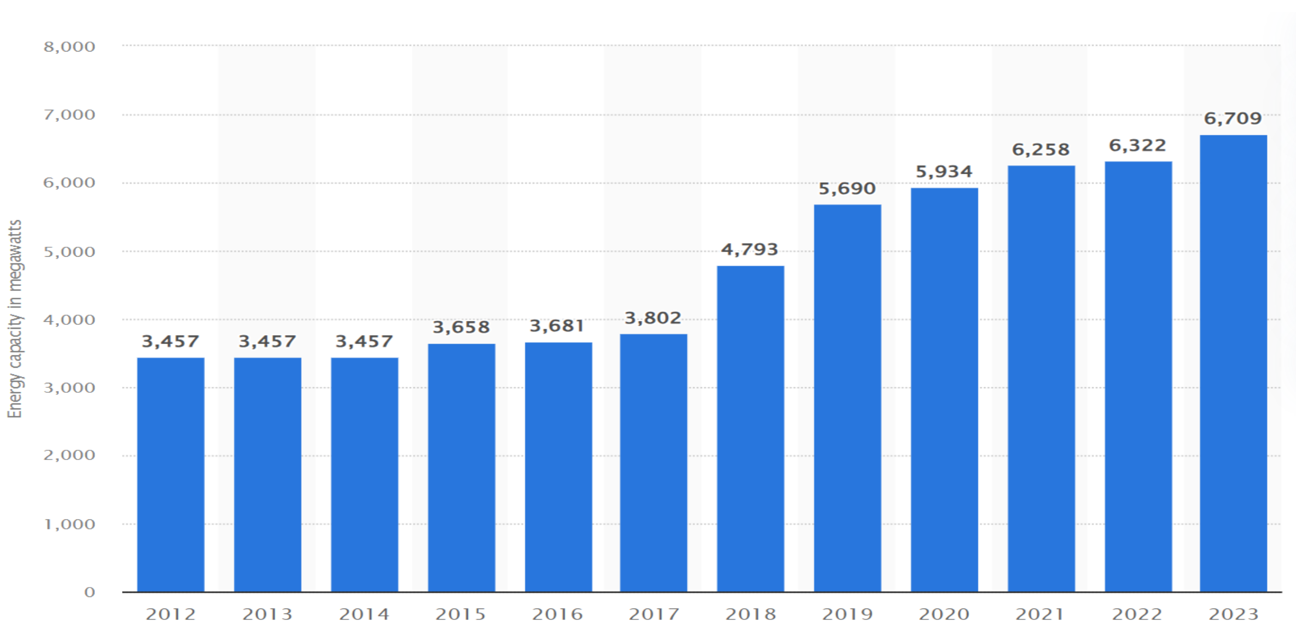

Figure 1. Total renewable energy capacity in Egypt from 2012 to 2023 (Statista, 2024a).

Egypt holds a noteworthy position in the African region with the 8% production of renewable energy. Particularly solar energy has gained prominence as it contributed 1.9% of Egypt's total electricity production in 2020 (IRENA, 2021). In terms of solar energy production Egypt ranked second in Africa and thirty-first globally. The government of Egypt has planned to expand solar energy production by 3500 MW by 2027 (Shouman, 2017). Furthermore, Egypt has produced 1.44% electricity of its total electricity generation from wind energy which placed it third-highest renewable energy source (Samy et al., 2022). Across the Nile River, the Aswan High Dam is situated that generates 94% of the country's hydroelectric. Egypt ranks 4th in Africa in terms of hydropower capacity with a total of 2800 MW (Shouman, 2017). Also, Egypt holds great potential for both biomass and geothermal utilization in the near future, provided the government incentivizes investments through initiatives like Feed-in Tariff (FiT). This measure might further diversify the nation's energy mix and can reduce its CO_2 footprint in the long run. Figure 1 shows the total renewable energy capacity in Egypt from 2012 to 2023. Besides, Figure 2 presents the renewable energy mix in Egypt.

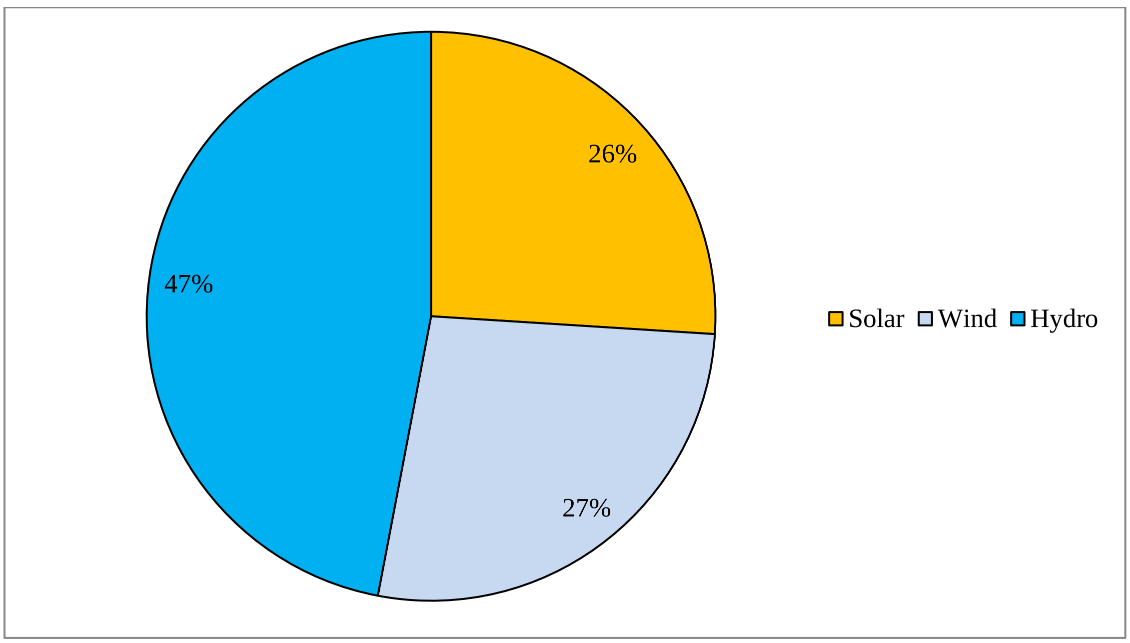

Figure 2. Renewable energy mix in Egypt.

Despite Egypt's immense potential in renewable energy, its current contribution to the African and Global markets remains relatively modest. Egypt boasts a crucial power generation potential as the concentrated solar power (CSP) technology offers an estimated 73,656 TWh/y and wind energy presents a potential of 7650 TWh/y (Shaaban et al., 2022). Other sources like photovoltaic panels (PV), bioenergy, geothermal, and hydropower contribute 36.0, 15.3, 25.7, and 80 TWh/y, respectively (Shaaban et al., 2022). Egypt's total installed power generation capacity in 2021 stood at approximately 59.5 GW, where renewable energy contributed only 10% of the total capacity (IRENA, 2022). These statistics provide evidence that the nation has yet to fully harness its renewable energy potential, despite its favorable geographical features, temperature, and wind speeds. Egypt has set an ambitious goal of deriving 42% of its energy generation from renewable sources by 2035 (IRENA, 2018). Egypt aimed to broaden its electricity generation sources by fostering the advancement of renewable energy technology. Figure 3 displays the intended composition of power generation in Egypt.

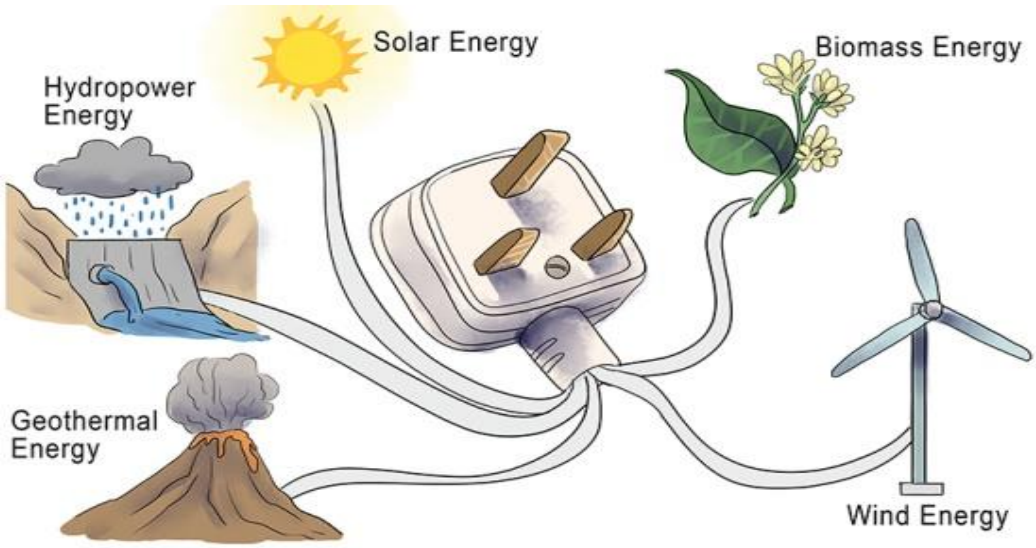

Figure 3. The planned mix of electricity generation in Egypt.

To maximize the renewable energy potential in Egypt, several studies have explored different facets of renewable energy technologies. Khalil et al. (2010) outlined an action plan aimed at fostering the development of innovative materials. Besides focusing on solar, wind, and biomass energies, local components are designed to boost the competitiveness and efficiency of renewable energy systems in Egypt. El-Kholy and Faried (2011) present a strategy to manage the energy demand of Egypt through renewable resources such as hydro, biomass, solar, and wind energy. A study conducted by Ibrahim (2012) investigated the solar and wind energy potentials in Egypt. Jamel et al. (2013) provided insight into the integration of solar thermal technologies with unconventional power generation systems in various countries, including Egypt. Moreover, Aliyu et al. (2018) have conducted a comprehensive review study of renewable energy development in Africa. The study had a specific emphasis on Egypt and Nigeria, covering hydropower, solar, wind, and biomass energies. Furhermore, the study conducted by Obukhov and Ibrahim (2017) analyzed the renewable energy potentiality in Egypt, specifically in wind and solar energies. However, renewable energy sources such as wave and tidal, nuclear, bio, geothermal, and renewable desalination systems still have not received sufficient attention in previous studies. Some of these neglected energy sources should be within Egypt's potential future energy frameworks. Elshamy et al. (2022) explored the challenges and opportunities for integrating renewable energy systems in Egyptian building stocks. Although Salah et al. (2022) provided a comprehensive review of renewable energies in Egypt, the study lacks updated information. Consequently, a study gap exists in the current literature regarding the status and challenges of Egyptian renewable energy technology, particularly concerning the latest statistical data. This study seeks to address the existing research vacuum by analyzing the current state and challenges of renewable energy in Egypt.

Solar Energy

Egypt is renowned as a nation of the "sun belt". The nation possesses a formidable solar energy capacity of 1,856 MW, which contribute approximately 68.5% of its total renewable energy capacity in 2023 (Statista, 2024b). Figure 4 presents the total solar energy capacity in Egypt from 2012 to 2023. For an average of 9 to 11 hours daily, the sun is gracing Egypt's skies. It benefits from abundant direct solar radiation ranging from 2,000 to 3,000 kWh/m^2/year (Ghali & Ibrahiem, 2023). The Global Solar Atlas projects Egypt's solar energy potential at an impression of 74 billion MWh annually. That surpasses its current electricity production. Hence, Egypt has emerged as a prime candidate across the globe for harnessing solar energy for both power generation and thermal heating applications (IRENA, 2018). In Egypt, the diverse applications of solar photovoltaic (PV) systems have been found since the early 1980s. Applications include lighting, pumping, commercial advertising, desalination, and cold storage, with additional usage in remote areas for emergency roads and navigation lighting (IRENA, 2018). That further, underlines its substantial potential for PV panel deployment across its territories. The highest potential locations are around the Red Sea coast and Upper Egypt cities such as Luxor, Aswan, Hurghada, and Asyut, as indicated in Figure 5.

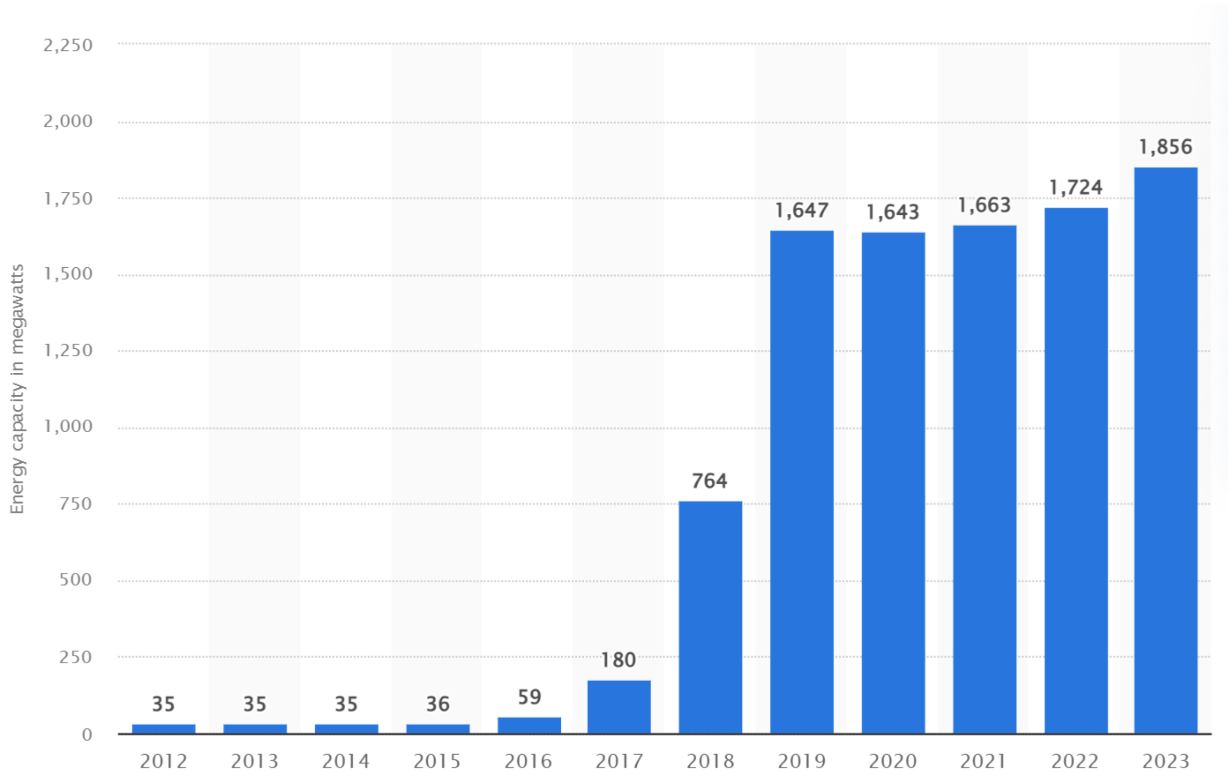

Figure 4. Total solar energy capacity in Egypt from 2012 to 2023 (Statista, 2024b).

In Egypt, 29 prime locations have been identified by the NASA renewable energy resource website for photovoltaic (PV) plants due to abundant solar radiation year-round. An energy production of 26.35 GWh per year and an average capacity factor of 30.9% is boosted by these sites (El-Shimy, 2009). Moreover, the profitability of constructing PV plants at any of these locations is confirmed by a financial analysis. Similarly, a study conducted by Sultan et al. (2018) explored the technical feasibility of establishing 100 MW PV power plants at 27 locations in Egypt. For large-scale PV installations their finding pinpoints Southeast Egypt, along the Red Sea coast, and the Eastern Nile River region as optimal sites. Carbon emissions could be reduced by 75,442 tons annually through the implementation of a 100 MW solar plant. Shouman (2017) provided insight into the electrification efforts in rural areas that lack centralized power access, the study emphasizes solar electricity as a viable solution. This study revealed that installing a 1kWh PV system is more cost-effective compared to relying on diesel generators for residential electricity in rural settings. Additionally, Sadeq et al. (2020) conducted a study by comparative analysis of PV technology potential across four locations in Egypt including Hurghada, Aswan, Alexandria, and Cairo. Aswan emerged with the highest yield and capacity factor of 2062 kWh/kWp per year and 24% respectively (Sadeq et al., 2020). Aswan has the shortest simple payback period (4.3 years) and the lowest levelized cost of energy (0.56 EGP/kWh).

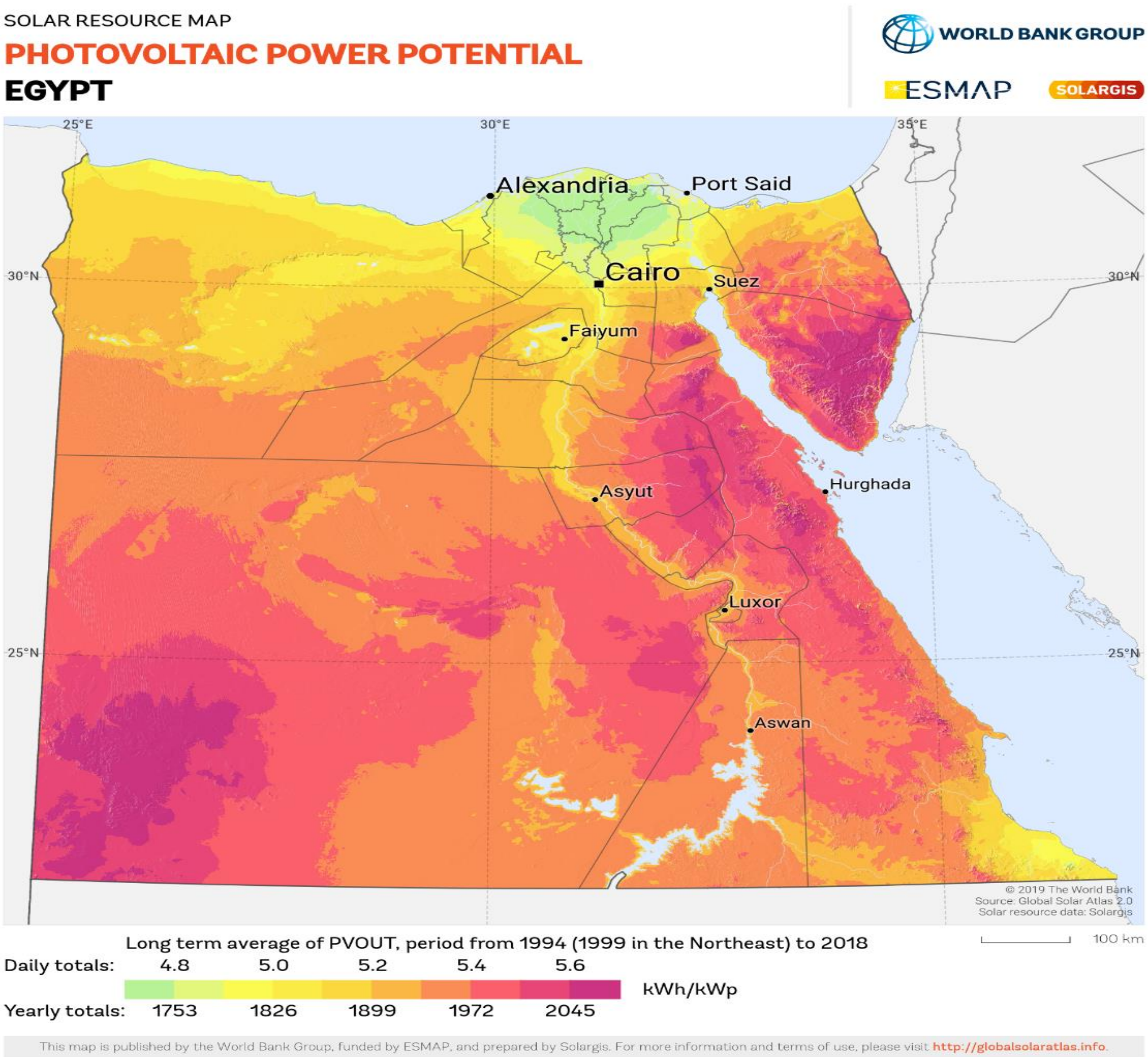

Figure 5. Photovoltaic power potential in Egypt.

Gabr et al. (2020) have investigated the economic viability of installing rooftop grid-connected photovoltaic (PV) systems on residential buildings in Egypt. The study has suggested that the payback period could significantly be shortened and could enhance the cost saving on electricity bills through the optimization of the size of the PV system to enhance household energy demands. The study of Sadeq and Abdellatif (2021) introduced an online tool for pre-sizing grid-connected PV systems. Utilizing this innovation users can easily assess the feasibility of PV systems in various locations. It has potentially boosted public interest and adoption of solar energy without the necessity for expert advice. Moreover, to address Egypt's power shortages the government has been actively implementing PV technology through utilizing them for straightforward applications like streetlights. In Egypt, the rapid advancement of solar PV distribution technology is supported by numerous ongoing projects allowing industries and businesses to integrate small-scale PV systems that will significantly reduce energy expenditures. At present Egypt boasts over 125 solar PV installations. It generates around 9000 MW of power which contributes to the reduction of approximately 9 tons of CO_2 emissions annually (Egypt-PV, 2021). Interestingly a considerable portion of the land suitable for PV technology falls within desert areas. It indicates the vast potential for future electricity production initiatives if the government continues to launch new projects in these areas. For two significant solar projects, feasibility studies have been completed recently by the New and Renewable Energy Authority (NREA) in Egypt. These studies were done in the Hurghada and Kom Ombo regions where photovoltaic plants are situated and designed to produce 20 MW and 26 MW, respectively (IRENA, 2018). It is projected that these plants will generate about 32 GWh and 42 GWh of electricity annually and will contribute to reducing CO_2 emissions by around 40,000 tonnes (IRENA, 2018). Furthermore, another significant project is Benban Solar Park in Aswan which comprises 41 individual solar power plants situated. It is managed by several independent entities under the oversight of the NREA, also it has a collective capacity of 1.8 GW. Infinity Solar has developed a 50 MW plant at the initial stage of this expansive initiative feature. This project started operating in March 2018 and reached completion in 2019. This specific installation is now producing over 4 TWh annually. Hence, it is preventing 2 million tonnes of CO_2 emissions each year (Ritchie and Roser, 2020).

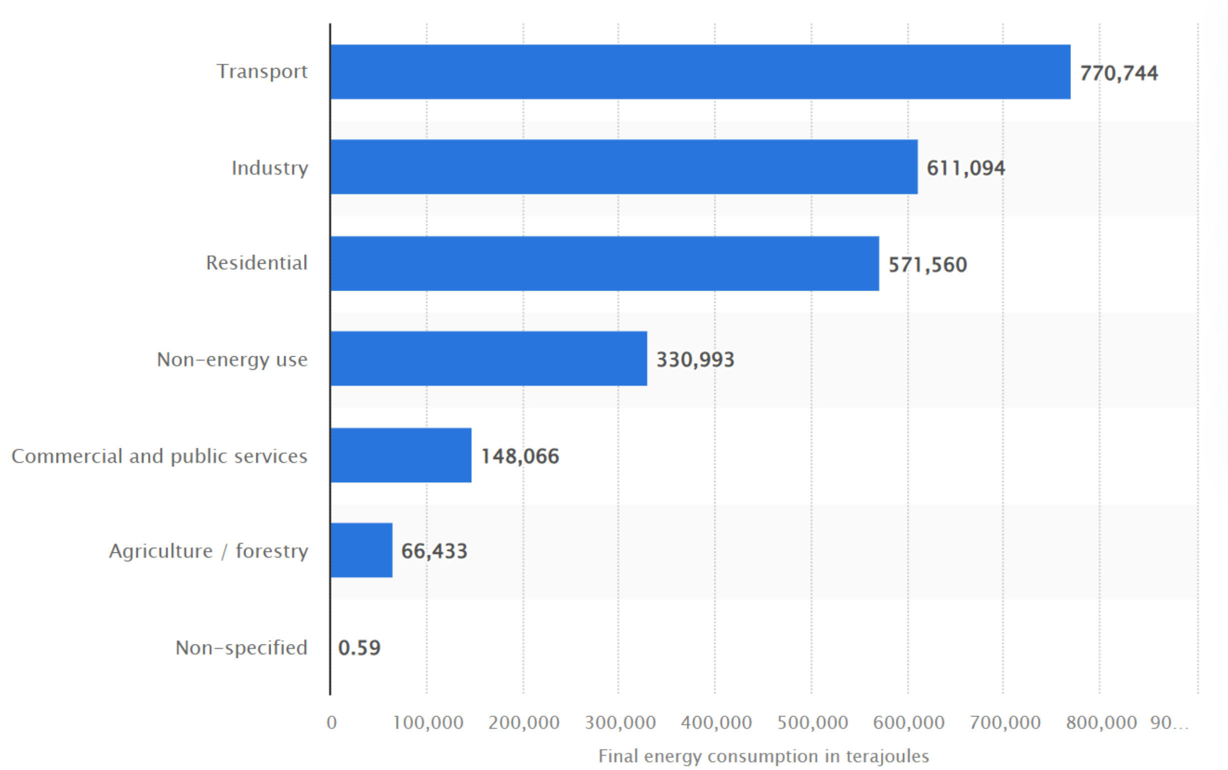

Figure 6. Total final energy consumption in Egypt in 2021, categorized by sector (Statista, 2024c).

In 2021, the transportation industry in Egypt accounted for the highest energy use, at 770,744 terajoules (Figure 6). Furthermore, the industrial sector consumed around 611,094 terajoules. Residential energy usage ranked third, totaling approximately 571,600 terajoules (Statista, 2024c). Reliance on traditional energy sources like electricity, diesel, and natural gas can be reduced as Solar water heating (SWH) systems present a crucial opportunity. Particularly, Egypt possesses the capacity to harness approximately 16 PJ per year for industries such as chemical, food, textile, and agriculture (Sharma et al., 2017). These operations require temperatures under 100 degrees Celsius over an area of 4.6 million square meters (Sharma et al., 2017). Studies have revealed that solar water heating and cooling systems are viable in cities like Aswan, Kharga, Asyout, Cairo, and Matruh. These systems are economically sound based on life cycle saving as well as environmentally beneficial. The study conducted by Reda et al. (2016) has shown the environmental advantages of utilizing solar-driven cooling systems in residential settings. For example, it is possible to reduce CO_2 emissions from 1062 kg CO_2eq per kWh when using natural gas to just 193 kg CO_2eq per kWh in Assiut. It exhibits that in Egypt solar heating can play a potential role in the residential energy landscape by mitigating conventional energy use as well as carbon emissions (Reda et al., 2016). Consequently, energy-efficient and integrated renewable energy-built environments require thorough investigation and implementation (Elshamy et al., 2022).

About 75% of global desalination capacity is represented by the Middle East and North Africa (MENA) region (Maftouh et al., 2023). It is predicted that by 2050 the global water shortage might be up to 155 billion cubic meters per year (Ghosh, 2021). In this respect, Egypt is particularly vulnerable due to its current water scarcity issues caused by inadequate resource management. In Egypt, 7.3 million individuals lack access to safe water, with 5.8 million residing in rural regions and 1.5 million in urban locales. In rural regions, around 12 percent of the population resides in residences lacking water system connectivity, whereas in urban areas, this figure is 4 percent (UNICEF, 2024). For addressing this the government of Egypt has initiated desalination projects (Elsaie et al., 2023). Where solar-powered systems emerging as a sustainable solution given the nation's substantial potential for concentrated solar power (32 GW) also its extensive coastlines along the Mediterranean and Red Sea. A significant number of studies focused on the evaluating effectiveness of various solar desalination technologies in Egypt. The study conducted by Mohamed (2020) provided a detailed multi-criteria analysis. The study has assisted in identifying the best locations for these facilities, considering factors like solar intensity, access to transport, topography, land use, characteristics of saline water bodies, and population density. The analysis of this study determined a larger proportion of western desert and coastal zones of Egypt as a prime candidate for establishing solar desalination plants. 24.6% territory of Egypt specifically, covering over 240,000 square kilometers near saline water sources, was deemed highly suitable (Mohamed, 2020). The moderately suitable territory is 17% while the rest of the area is seen as having low suitability. Moreover, regions like Asuit, Sohag, Aswan, Qena, ElKharga Oasis, and Toshka in the upper side of Egypt have been identified as having high potential for groundwater desalination using solar technology (Salim, 2012). The above-discussed initiatives present the growing emphasis on sustainable methods to mitigate water scarcity challenges in Egypt and beyond.

Wind Energy

Egypt prides itself with a significant amount of wind energy supply specifically in the Sinai Peninsula and around the Gulf of Suez. Due to the consistently high speeds of wind, Egypt is one of the best across the globe. The average wind speeds between 8 and 10 meters per second at 100 meters above ground level, coupled with vast uninhabited desert areas. Across the different parts of Egypt several studies have been conducted to assess the wind energy potentiality, and these exhibited substantial resources available. In 2023, Egypt gained a wind energy capacity of 1,890 megawatts, which represents approximately 28.2% of its total renewable energy capacity (Statista, 2024d). Figure 7 presents the total wind energy capacity in Egypt from 2012 to 2023. To boost wind energy development, the government of Egypt has implemented supportive measures for private developers. Incentives such as elimination of customs duties on wind energy equipment, providing special land access policies, and promoting the build, own, operate model for projects. Besides, the Egypt government aimed to produce 7.2 GW in 2022. Figure 8 presents the map of wind energy potential in Egypt.

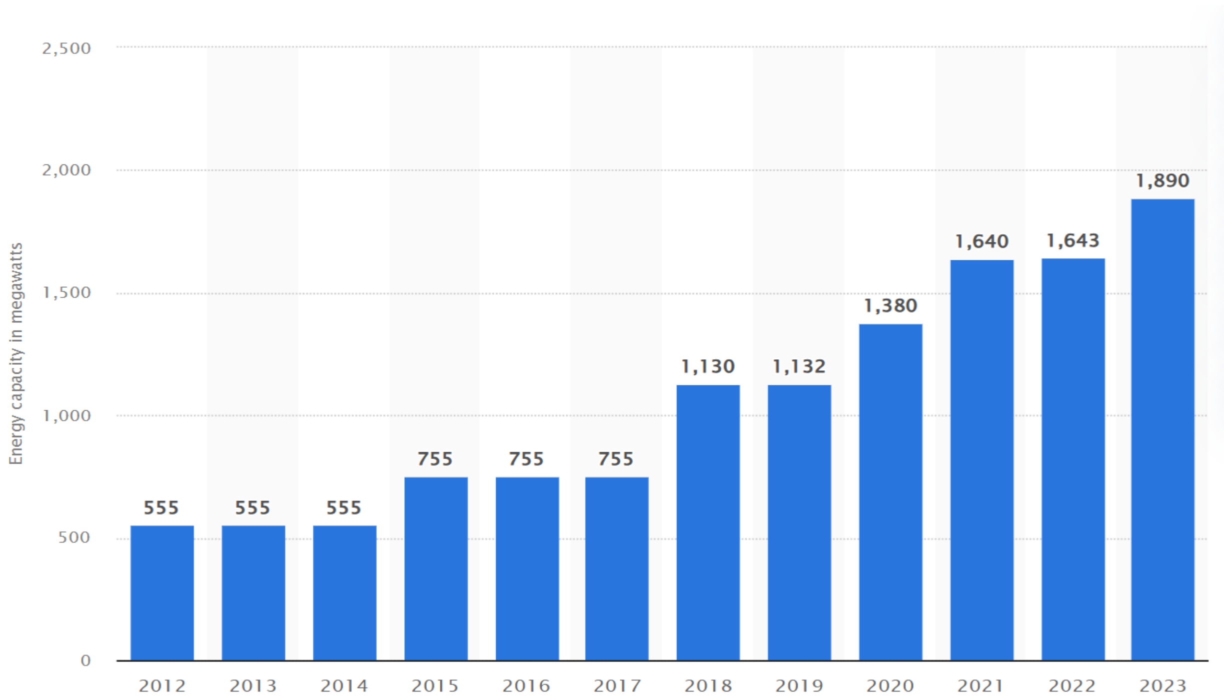

Figure 7. Total wind energy capacity in Egypt from 2012 to 2023 (Statista, 2024d).

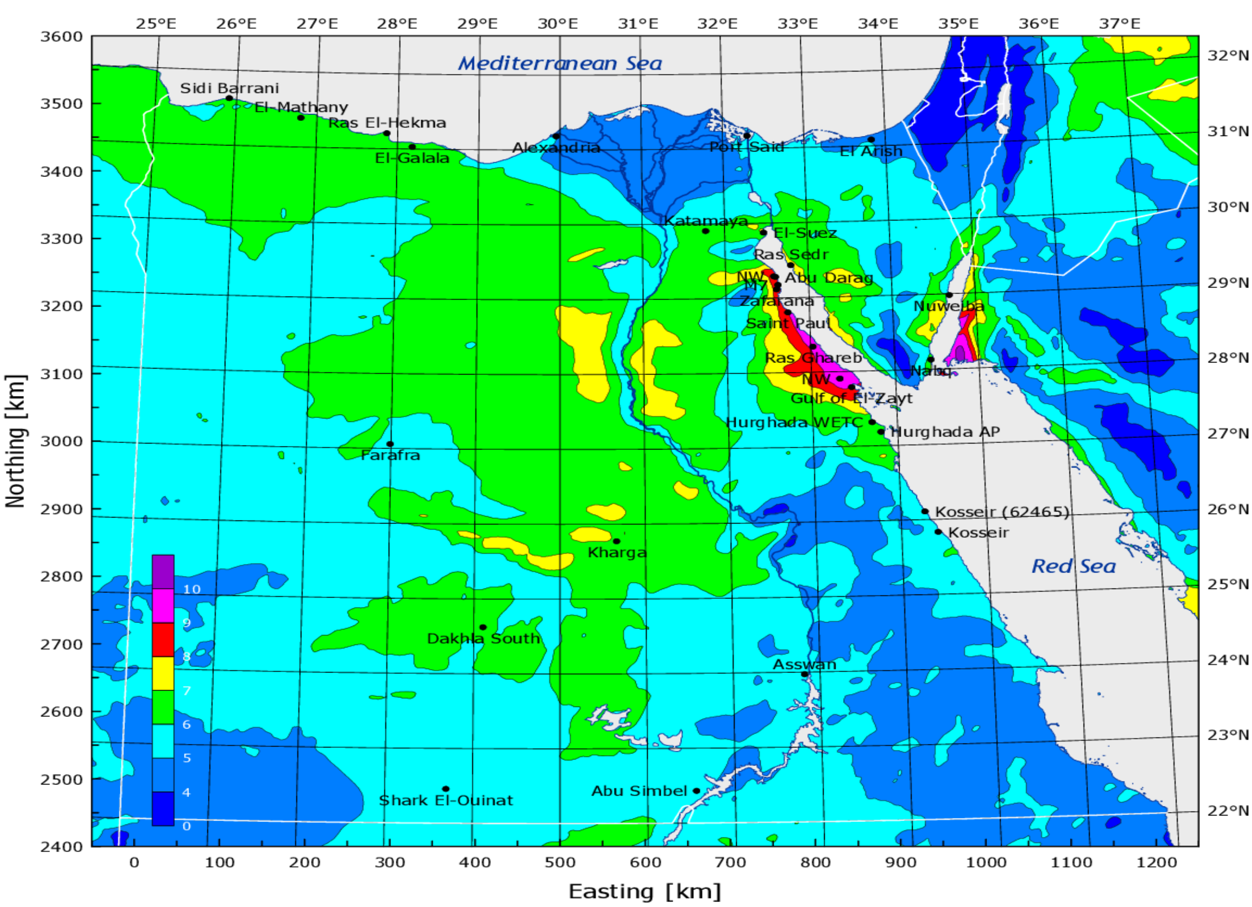

Figure 8. Wind energy potential in Egypt

Numerous research has explored the feasibility of establishing wind energy facilities in Egypt that are supported by detailed wind maps. Hamid (2011) has conducted research focusing on identifying cost-effective locations for wind farms using a Geographic Information System (GIS) integrated with a multi-criteria decision support system. Also, this research suggests that about 30% of the territory of Egypt is viable for wind energy development. Particularly, in this study wind energy characteristics were analyzed at Marsa Matruh, El-Suez, and El-Kharjah. These sites exhibited average annual wind speeds between 4.6 and 5.5 meters per second at a height of 20 meters, with energy outputs ranging from 638 to 1127 kWh/m^2 (Hamid, 2011). Besides, this study extended to another fifteen locations, including both coastal and inland areas such as Hurghada, Zafarana, and Aswan. The finding of the study consistently revealed that coastal regions along the Mediterranean and Red Seas, along with some inland areas like Aswan and Cairo, hold significant potential for wind power generation (Mahdy & Bahaj, 2018).

Tidal Energy

Egypt's tides hold a huge amount of stored energy that could be utilized to produce hydroelectric energy from the Red Sea. In Egypt, Alexandria is one of the biggest cities with wave energy that has a comparatively large standard deviation of 5 kW/m and is confined to values less than 2 kW/m (Shehata et al., 2017). Compared to the summer, the average wave power was observed to be greater between December and March. It is connected to a great degree of variability, which could be derived from the fact that the mean wave energy (10 kW/m) in the winter season is over five times that of the sea (Zodiatis et al., 2014). The Southern Mediterranean reservoir on the Egyptian coastline, located between the Nile Delta and Libyan borders, holds a wave power of 36003 kWh/m, wave magnitudes from 1 to 4 m, a time duration of 4 to 8 s, and a substantial energy of 3.35 kW/m and 6.8 kW/m over the summer and winter seasons (Shehata et al., 2017). Egypt has two additional coastlines: 1200 km along the Red Sea's Gulf of Suez and 650 km along the Red Sea's Gulf of Aqaba. These beaches are part of the 1150-km coastal area around the Mediterranean Sea (Amin et al., 2020). Shehata et al. (2017) carried out comparative research on several wave turbine designs according to the factors that are relevant to Egypt's northern shore. They demonstrated that under a sinusoidal wave with a periodic time (ts) of 6 s, an effective turbine can produce up to 2.2 kW. After this, in the context of Egypt at Alexandria, El-Geziry and Radwan (2012) conducted research on tidal and surge elevations. They found that the tidal elevation varied from 11.12 to 10.57 cm, with a mean value of 0.001 cm. In the case of surge fluctuations, it varied from 14.64 to 87.15 cm, and the mean value was 50.66 cm. The potential of wave power in Egypt can be utilized to produce small amounts of energy, though it appears that the average wave energy on Egyptian shores is not as promising as the large potential in coastal zones along the ocean. Generating energy for business purposes and local communities near coastal areas can both benefit from this.

Hydropower

The Nile River, which provided trustworthy, fertile soil for grain growth and ensured the establishment of a vast business connection with neighboring civilizations, was essential to the development of the Egyptian civilization. The river is the main source of hydroelectricity for numerous African countries, including Egypt. When the Aswan High Dam was established in the late 1960s and beginning 1970s, it was capable of decreasing the impact of the yearly flooding while meeting about thirty percent of the country's energy requirements thanks to its 13,545 GWh yearly hydropower generation rate (Salman & Hosny, 2021). In Egypt, hydroelectric is the most developed green power technology. Egypt has a hydroelectric potential of approximately 50,000 GWh annually, which is technically possible. The country had a 2,832-megawatt hydropower-producing capacity as of 2022 (Statista, 2024e). This confirmed 44.8% of the nation's overall green energy potential. Figure 9 presents the total hydropower energy capacity in Egypt from 2012 to 2023. The country gets approximately 9% of its power from hydroelectric. The nation has hydroelectric potential; however, this is dependent on the Nile River's stream, upstream demands, and irrigation needs (Ahmed et al., 2023). Egypt's hydropower output fell by approximately 6% in 2021–2022, to 13,800 GWh from 14,700 GWh in 2020–2021. The implementation of several maintenance programs, which need the outrage of units, is the primary reason for the reduction. Egypt has four primary hydropower-producing hubs: the Aswan Low Dam, the Esna Dam, the Aswan High Dam, and the Naga Hamady Barrages. The biggest hydropower project in Egypt, Gabal Alattaqa, which is situated at Attaqa, Suez, has an ability of 2400 MW and was put into service in 2022.

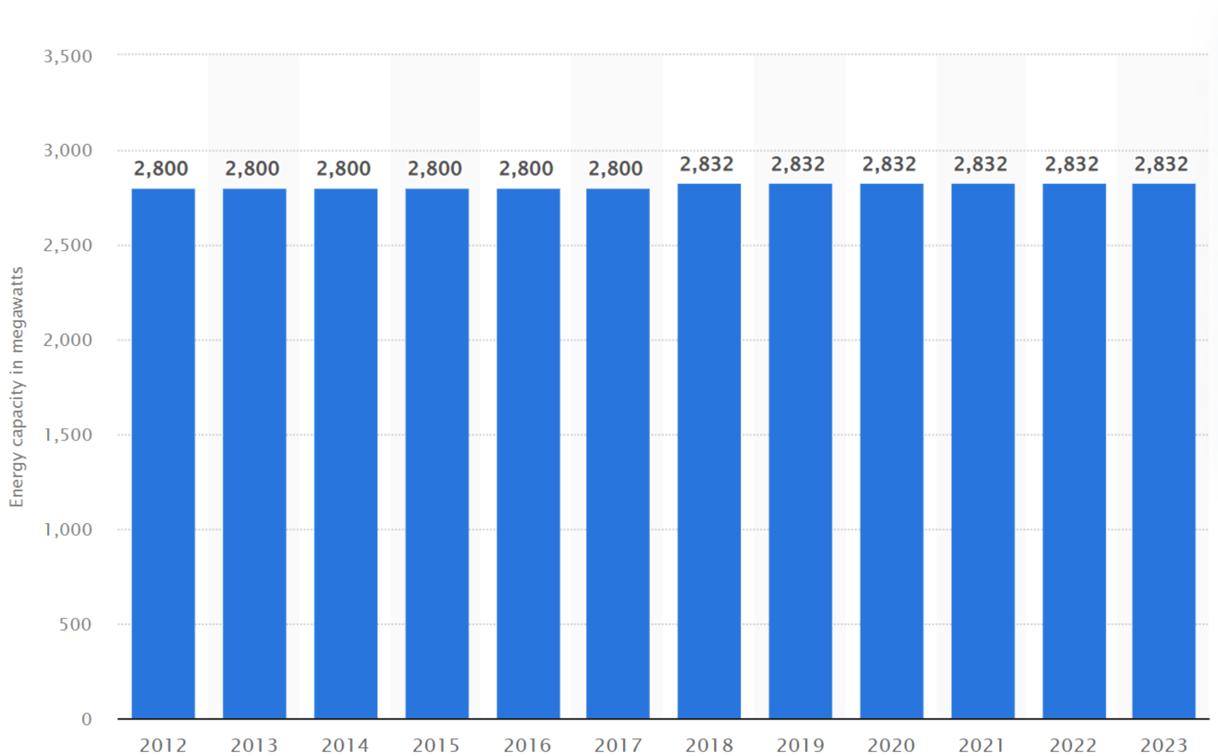

Figure 9. Total hydropower energy capacity in Egypt from 2012 to 2023 (Statista, 2024e).

The Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile has several potential impacts on Egypt's High Aswan Dam (AHD), including:

- Reduced water inflow: During the first impoundment of the GERD, water inflow to the AHD reservoir will be reduced. In the long term, the inflow will be affected by flow regulation and evaporation losses from the GERD (Negm & Abdel-Fattah, 2019).
- Reduced energy output: The annual energy output from the AHD is expected to be reduced by around 12% during the filling stage and 7% during the operation stage (Mulat & Moges, 2014).
- Decreased water loss: Water loss at the AHD due to evaporation is expected to decrease by 22% (Mulat & Moges, 2014).
- Water shortage: Some fear that the GERD's capacity could reduce Egypt's water share, which could lead to a water shortage (Matthews & Vivoda, 2023).
- Economic crisis: A water shortage could cause a significant economic crisis for Egypt.
- Loss of jobs: A water shortage could lead to the loss of jobs in Egypt (Matthews & Vivoda, 2023).

Bioenergy

In 2023, Egypt's bioenergy capacity reached 131 MW (Statista, 2024f). Figure 10 presents the total bioenergy capacity in Egypt from 2012 to 2023. In the power sector of Egypt, biomass and bioenergy have potential quality and can assist the country in achieving its goals of using green power sources. Enhancing energy demand in Egypt can be met by biomass derived from crop scraps. Egypt normally produces twenty million tons of agricultural waste per year and makes them raw biomass materials. From them, 11,000 GWh of green energy can be produced, which meets the 5.5% energy requirements of the country (Abdelhady et al., 2021). Sustainable biomass makes up a sizeable piece of the overall potential electricity supply (44.6%), next to city solid waste (41.7%), due to its several volumes and comparatively large energy potential. Particularly, rice waste makes up roughly 61.5% of the overall power capacity of all harvested biomass leftovers. It is capable of recovering power in various forms, including biogas, syngas, bioethanol, and bio-oil. Potential power generation from agricultural waste and solid wastes can decrease crude oil need by 19% (IEA, 2024).

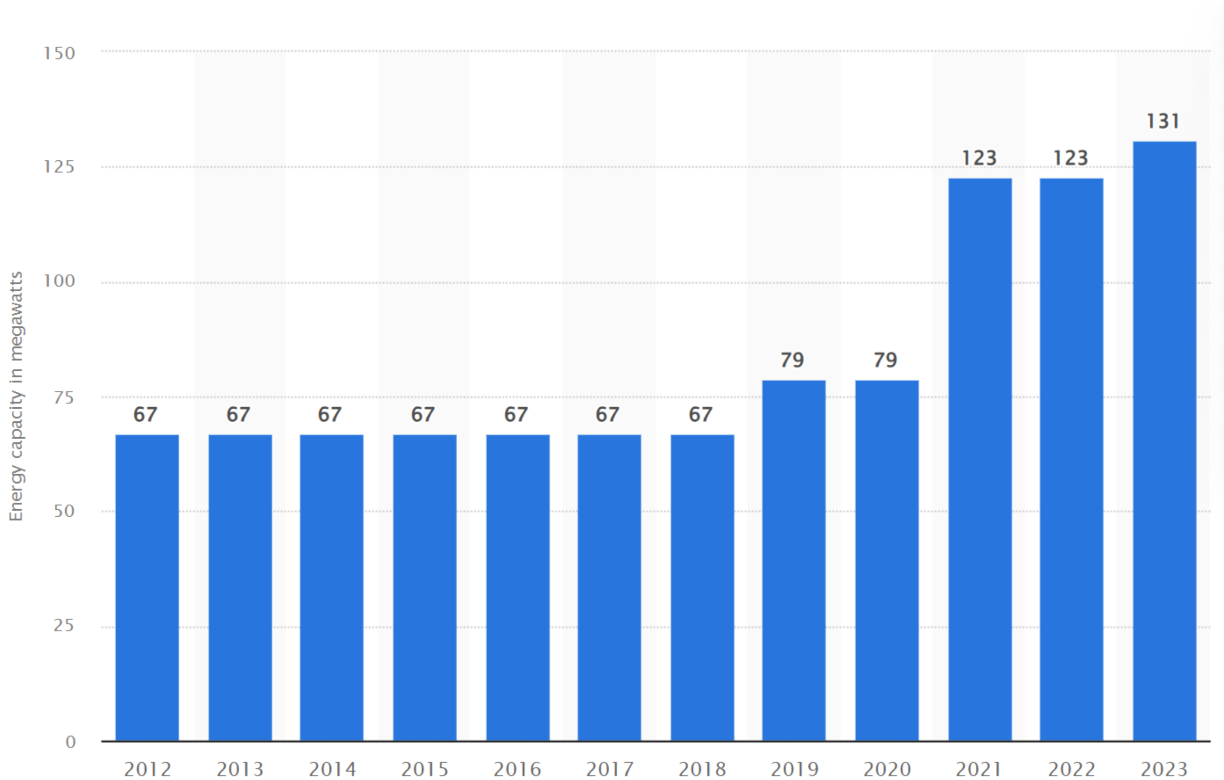

Figure 10. Total bioenergy capacity in Egypt from 2012 to 2023 (Statista, 2024f).

The Sustainable Power Authority stated in its annual report that they produced 4.7 M kWh of energy from 11.5 MW of set-up biomass (IRENA, 2018). In terms of economics, a biomass energy station may be quite competitive with traditional energy plants and other sustainable energy sources. Farmers may use modest biogas machines to generate fertilizer for their crops and clean, renewable energy. If the governing body can modify the legal framework in the fields of politics, finance, technology, and institutions to assist biomass and draw in foreign capital, the country's biomass electricity sector will prosper. To promote the consumption of biomass electricity in Egypt, the government must eliminate obstacles related to its utilization.

Geothermal

Geothermal functions within Egypt are known to exist in several locations, such as thermal deep wells and tiny hot springs that are visible at the surface level. It is expected that some areas will be identified as geothermal hubs, including the Red Sea, Gulf of Suez, Gulf of Aqaba coastlines, and the Western Desert's hot springs and thermal deep wells (Lashin, 2015). According to measurements from boreholes, initial heat transfer values show that geothermal gradients range from 42 to 175 mW/m^2. Figure 11 illustrates the optimal sites for the extraction of geothermal energy in Egypt. The Gulf of Suez's eastern and western borders are home to thermal springs ranging in temperature from 51 to 70°C (Stellae Energy, 2024).

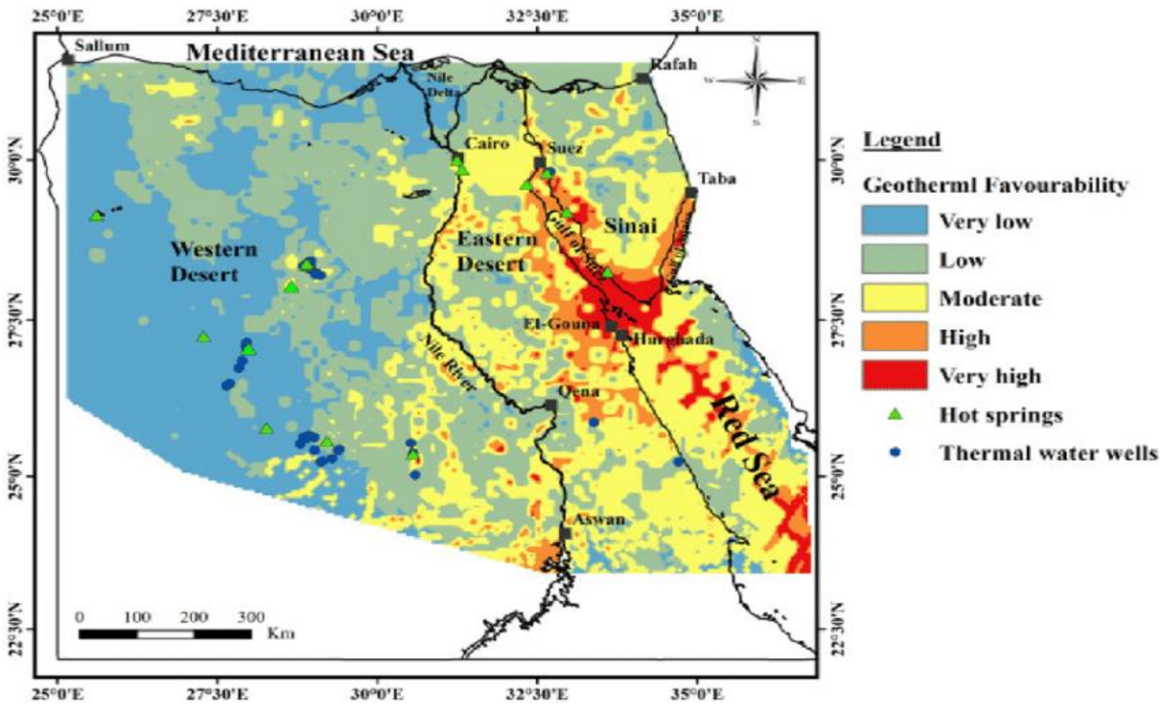

Figure 11. Optimal sites for the extraction of geothermal energy in Egypt (Moustafa et al., 2022).

Geothermal power is not being established properly within Egypt right now, although authorities are becoming increasingly curious about its potential as a green power source. Egypt recently employed low-quality geothermal substances for district heating, aquaculture, agricultural uses, and greenhouses, even though they are not appropriate for electricity generation (Shawky et al., 2024). Tourists often use thermal water for therapeutic purposes and as swimming areas. The Hammam Faraun region has enough geothermal stocks, making it a promising location for future geothermal applications and usage (Fahil et al., 2020). Further exploration efforts in the geochemical and geophysical domains are essential to precisely determining Egypt's geothermal resource prospects.

Energy Storage Systems

The advancement of sustainable energy is beginning to gain traction as a workable response to electricity-associated issues (Raihan & Voumik, 2022a; 2022b). However, as sustainable energy advancement moves forward, particular concerns still need to be resolved (Raihan, 2023e; 2023f; 2023g; 2023h; 2023i; 2023j; 2024b). One is the irregular and inconsistent nature of the procedure utilized to generate green power; for instance, during cloudy and windless days, solar and wind power cannot continuously offer electricity. Therefore, the solution to the aforementioned problems lies in figuring out how to preserve sustainable electricity during its production phase (i.e., when it is abundant but not being used) and deliver it when and when it is required. This problem can be solved by installing energy storage technologies in photovoltaic and wind generators (Raihan & Tuspekova, 2022b; 2022c; 2022d; 2022e; 2023a; 2023b). Energy storage solutions can preserve extra energy produced during peak generating times that could be squandered if not utilized, as well as provide reliable energy for power plants during unfavorable weather. Therefore, power storage has become one of the biggest problems facing the sustainable energy industry (as well as other power industries) (Liu and Du, 2020). Energy storage solutions are initially concerned with the storage of electricity. Electricity grid fluctuations can be minimized by preserving or releasing electrical power based on grid workload. There are different energy storage systems, such as electrochemical, chemical, mechanical, and thermal (Hayat et al., 2020).

In general, energy storage can motivate the modernization and transformation of traditional energy connections while simultaneously enhancing the predictability and manageability of intermittent sustainable energy sources. For this reason, different solutions can be utilized, and they have both merits and demerits. So, it is a hard task to select a good system for several uses. Currently, choosing an appropriate energy storage system can minimize the total cost of a sustainable energy system and enhance its efficiency (Pfleger et al., 2015; Hayat et al., 2022).

Renewable Energy Policies in Egypt

In 1986, the Egyptian government established the New and Renewable Energies Authority (NREA) to promote the growth of green power sources. The government created the "ISES-2035" unified green power mechanism to advance green energy solutions and confirm a steady and safe supply of sustainable power to fulfill the country's demands. As part of this new approach, the energy sector will widen green power and power efficiency, with green power sources expected to provide 42% of the nation's electricity demand by 2035 (IRENA, 2018). Moreover, the government implemented an integrated water management program (IWMP) in 2017 to eradicate the water crisis and fulfill water needs and was motivated to initiate another project in 2037. The goal of this project was to preserve the water resources and meet their demands, which included desalinating sea water for the country. Additionally, Egypt partnered with Russia to establish the first nuclear energy plant in EL-Dabaa. Furthermore, the country is expanding its linkage to the Mediterranean energy pool. The objective of this project is to link the electrical systems throughout northern Africa. The funding for solar panels in Egypt will be able to increase to meet the country's electricity export market due to programs like the Solar Plan of the Union for the Mediterranean, Deseret, and Trangreen (Patlitzianas, 2011). In this case, cross-border linkages are considered essential to improving the integration of green energy sources. It can increase connections, which would make it possible for more variable green power sources to proliferate (Pupo-Roncallo et al., 2021).

Egypt's Feed-in Tariff (FiT) program was launched in 2014 to help the country's renewable energy sector, especially solar, overcome challenges. The program's goals included:

- Increasing renewable energy production: The program aimed to install 2,500 MW of renewable energy capacity, including 2,300 MW of solar and 2,000 MW of wind (Salah & Elkady, 2016).
- Reducing emissions: The program was intended to reduce emissions of local pollutants and CO2, as well as water consumption (Elsayed, 2017).
- Diversifying the energy sector: The program was intended to help Egypt move towards a more diverse and environmentally sustainable electricity sector (Elsayed, 2017).

- Reducing reliance on hydrocarbon imports: The program was intended to help Egypt reduce its reliance on costly hydrocarbon imports (Elsayed, 2017).
- Attracting private investment: The program was intended to stimulate private investment in the renewable energy sector (Elsayed, 2017).

Challenges in Egypt's Renewable Energy Sector

The advancement of the green energy industry is confronting several challenges, such as manufacturing, technological, economic, and political (Raihan et al., 2022b; 2022c; 2022d; 2022e; 2023b). Encouraging the adoption of green power solutions in the Egyptian market is closely related to the energy price and the advancement of new technology. Therefore, it is essential to decrease the costs associated with those technologies to make them more viable with traditional electricity sources. A drastic solution to this issue is to enhance the proportion of several green energy technologies manufactured locally (Raihan & Tuspekova, 2022f; 2022g; 2022h; 2022i; 2022j). Egypt has various prospects for producing solar and wind electricity components. For instance, turbine towers are affordable in Egypt since they are produced there. The other parts, such as the blades and associated electronics, are not yet being manufactured locally. The main reason behind this problem is inadequate training (Loudiyi et al., 2018). Innovative technological development is still in its early stages in Egypt. Moreover, they are still at the experimental stage, which is why they are not being produced on a large scale. Low technological command involves ignorance of the intricacies involved in the design, development, and production of solar and wind electricity components. The available equipment is functioning with less endurance and efficiency, and there is significant storage of appropriate equipment for direct geothermal usage. This indicates that Egypt is not ready to step into the international arena in the case of technological advancements. Since there is no training center to educate people regarding renewable energy technologies, the lack of skill hinders the production of sustainable energy (Njoh, 2021).

Moreover, there are legislative obstacles that reduce the movement of sustainable energy within the Egyptian context. A cohesive regional regulatory framework, including trade and regulations, has not yet been established. There are unbalanced regulations in the government sector. Third parties cannot access them due to limited grids. The use of geothermal electricity is not governed by any laws, rules, or policies. The government has no interest in investment projects or encouragement for the industrialization of geothermal electricity. Governmental supervision over the amount of funding in the sustainable power sector and the direction of corporate investment is lacking. This can be upgraded by revising policies such as tax and interest rates, which would lead the price mechanism forward and motivate the industry to consider its R&D (Zhen et al., 2021). To create a sustainable electricity system, laws and regulations about public health, environmental preservation, and natural habitats have been created (Raihan et al., 2022f; 2022g; 2022h; 2023c; 2023d; 2024a). However, during the investigation phase of a geothermal project, there might be adverse effects on the environment. NGOs are reluctant to participate in the publication of green power. People are now centralized on nonrenewable energy due to its lower price and instead decentralized on renewable energy, which has a comparatively higher price (Raihan et al., 2023e; 2023f; 2024b; 2024c; 2024d). Egypt provides subsidies on energy prices, which make them more affordable than the electricity tariffs associated with various green energy sources. However, it is interesting that during 2019–2020 and 2020–2021, the subsidies for petroleum goods were minimized by over 1.9 times. Even with the 2021 yearly interest rate remaining above 10%, SME still finds it difficult to finance because of its high payback rates. Management of price distortions in the sector by the implementation of side payments and uniform pricing with a price cap to limit strategic behavior in flexible markets. Using side payments and consistent pricing with a maximum price to restrain strategic behavior in dynamic markets can help control price anomalies in the industry.

Certain local communities are impoverished, do not accept government support, and are unable to pay to use costly green energy. In this case, the local government ought to oversee funding services via locally based microfinance organizations. Poor-income families that are unable to interact with banks can benefit from this subsidy and assistance with managing their debt (Suman, 2021). The growth and establishment of green electricity solutions may face political hindrances in the near future, despite Egypt's efforts to motivate the consumption of green energy through the addition of flexible policies and decrees. These challenges may include inadequate capacity for interrelationships with prospective nations and the coordination and control of interrelationships. Ultimately, one of the biggest obstacles to the adoption and financing of green power solutions in Egypt is the infrastructure, specifically when it comes to the distribution of electricity from the wind industry, which calls for the distribution of energy to specialized power stations and high-voltage cables.

Conclusions and Recommendations

A healthier production is essential to safeguarding environmental harm, especially in light of the recurrent and devastating natural calamities caused by the impacts of global warming and large-scale resource depletion. A key component of healthier production, environmentally friendly development paves the path for zero carbon emissions within the following decades through the effective consumption of fossil fuels. However, there are very few review papers published based on sustainable energy technologies that Egypt should employ to produce electricity in the future. This study provides an analysis of Egypt's electricity scenario, looking into the state's capacity to utilize all competitive green energy sources, comparing the country's conditions to the global norms, and discussing the challenges confronting the growth of the green energy industry. Egypt is using solar power, holding 31st place all over the world, which is far behind many other nations in the adoption of green power technologies. Even though these electricity sources have the potential to significantly enhance Egypt's electricity demands, their current share of the country's electricity output is 0.16% due to the consumption of biogas, geothermal, wave, and nuclear electricity. Some necessary recommendations for these power sources that can offer power security for Egypt's growth and well-being in the near future are as follows:

- It is important to support and promote private-sector financing for green energy initiatives.
- There are various places where solar power can be harnessed, but the locations between the Red Sea coast and the Nile River have the most potential.
- For small-scale energy production, local regions close to the coast can take advantage of wave electricity potential.
- The governing body should partner with Ethiopia to find a better way that would be favorable for both nations. This partnership is important for the Egyptians so that they can ensure constant production of hydropower and pave the way for the future to enhance hydropower generation.
- The ideal place in Egypt to get all of its electricity from sustainable sources is the Gulf of Suez due to its abundant sun, geothermal, and wind resources.
- The primary locations along the Mediterranean coast where wind power could be utilized are Sallum, Matruh, and Port Saied.
- Southern Egypt has excellent potential for solar, wind, and bioenergy, though it is less concentrated than the Gulf of Suez.
- Biomass derived from crop residue has excellent potential for energy generation and may help Egypt meet its increasing energy needs.

- The Middle Delta has the greatest possibility for biomass electricity plants since it has the biggest amount of residues from sewage, agriculture, manure, and municipal solid waste, and these potentialities make the location preferable for biomass electricity production.
- The construction of geothermal energy plants along the Gulf of Suez's coast is an important initiative for boosting the promotion of geothermal power. In this case, caution must be used to avoid endangering the environment.
- To attract tourists, there should be greater attention and in-depth scientific research done to create new geothermal-fed villages around Hammam Faraun Spring.
- Biomass and geothermal power are the indicators of green power sources that should be included in the FIT project.
- Necessary initiatives should be adopted to eliminate the existing obstacles, including infrastructure obstacles, fossil fuel subsidies, and higher interest rates.
- The Egyptian government should offer subsidies to SMEs to ensure local technology advancement and increase green power competitiveness in the electricity market.
- It is better to enact new laws or amend existing ones to ensure the adoption of green power technologies and develop connections with neighboring nations.
- To improve the expertise of field staff, training programs for local laborers should be designed and launched. In order to safeguard natural resources, it should also be the duty of all stakeholders to take effective initiatives.
- Programs at the national level should be launched to inform the general public regarding the value of shifting to green power sources and to make clear how they fit into the net zero path.
- Finally, the ongoing progress of Egypt in the green energy industry should make it possible to meet the terms of the Paris Agreement by decreasing its CO_2 footprint and actively addressing global warming.

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