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# Wind Power Development in Egypt: Historical Overview, Current Status, and Prospects

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*Many nations are keen to increase their use of renewable energy, given its significance for long-term energy independence, development, and climate change mitigation. The Egyptian government is taking significant steps to promote renewable energy, especially wind energy, which will hopefully contribute 14% of total electricity generation by 2035. This paper discusses the growth of wind power in Egypt, providing valuable information for those interested in developing wind projects. It reviews the national renewable energy plan, policies, and other renewable resources. Additionally, it emphasizes the technical, economic, and environmental aspects of wind power. The paper aims to determine whether wind power is an effective and promising option for electricity generation in Egypt and offers recommendations to policymakers to enhance its growth.*

**Keywords:** *Renewable Energy, Wind Power Development, Wind History, Wind Vision, Egypt*

## Introduction

Many countries are keen on utilizing clean energy potential and incorporating it into their national energy strategies. Fossil fuels are on the verge of depletion sooner or later and will not be able to supply demand in the future in addition to being a source of emissions contributing to climate change. Wind power is one of the most flourishing, cost-effective, and technically mature renewables, accounting for 8% of total electricity generation. It has experienced a growth of 12% over the last decade, achieving 1021 GW of installed capacity worldwide (IRENA, 2023b; REN21, 2024). Naturally, COVID-19 pandemic-related limitations disrupted supply chains, caused unemployment, delayed or postponed bids and investments, and resulted in canceled projects, particularly in onshore wind farms. Despite these challenges, wind energy has adapted and grown in some parts of the world (REN21, 2021). Wind energy is expected to have a critical role in global electricity transformation, giving significant environmental and socioeconomic benefits. By 2050, it would supply more than one-third of the total electricity demand and contribute more than 25% of the total $CO_2$ emissions reductions, which mitigate climate change impacts. Furthermore, it is anticipated that over 6 million employment possibilities will be created, necessitating attention to capacity building in the world in order to handle the growth of the wind industry (IRENA, 2019).

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Numerous factors influence wind power deployment, including government policies, finance, oil prices, geopolitical risk, political stability, trade openness, $CO_2$ emissions, climatic conditions, industrial infrastructure investment, power demand, public acceptance, environmental effects, and people engagement (Fatima et al., 2021; Wang et al., 2023). Over the last years, cost reductions owing to ongoing technological improvements and subsidy policies contributed to wind farm deployment in most parts of the world. On the other hand, wind energy continues to face some challenges such as grid and transmission infrastructure, prolonged permit duration, policy uncertainty, and social acceptance (IEA, 2020; REN21, 2022). The purpose of this global overview is to highlight the factors that make wind energy a promising and viable resource worldwide, thereby providing a foundation for discussing its potential for expansion in Egypt.

Regarding the growth of renewable sources among Arab nations, Egypt comes in first, followed by Jordan and Morocco (Habib et al., 2023). In addition, Egypt ranked 22nd on the Climate Change Performance Index (CCPI), which evaluates countries' climate protection efforts based on four categories: greenhouse gas emissions, renewable energy, energy use, and climate policy (Burck et al., 2024). Egypt has a variety of renewable energy sources, including hydropower, onshore wind, solar PV, solar CSP, and biomass, and it is also striving to utilize new ones. However, it is heavily reliant on fossil fuels, accounting for more than 85% of total power generation. Despite substantial societal and political changes over the previous decade, progress in renewables has been accomplished. Egypt has succeeded in adding greater than 3 GW to its installed capacity for renewable energy. Egypt has made an effort to enhance the country's investment environment and boost policies for energy transitions (EEHC, 2024; NREA, 2024). In order to meet the growing demand for power for purposes of socioeconomic development, as well as environmental concerns, the Integrated Sustainable Energy Strategy (ISES) was developed, which took into account energy source diversification, expansion of renewable energy sources, and energy use rationalization. The strategy aims to produce 42% by 2035 of total electricity from renewable sources (IRENA, 2018).

Egypt has favorable conditions for wind energy development, including an abundant wind resource that is one of the best in the world, especially in the Gulf of Suez area, where the mean wind power density reaches 600 $W/m^2$ at a height of 50 m, the availability of large uninhabited desert areas, and donor support, which includes studies, capacity building, and grants (ElSobki et al., 2009). Furthermore, Egypt has manufacturing wind turbine components due to its low labor costs, inexpensive industrial energy, and easy access to steel and glass. As a result, some parts of wind turbines, like towers, are more affordable due to local manufacturing (Salah et al., 2022). However, wind power provides for just 3% of Egypt's total electric energy supply (Ritchie et al., 2024b), and future projects are unlikely to meet the target of 14% by 2035.

Hence, this research article aims to describe wind power development over the years in Egypt. It also examines the factors that have supported and hindered growth, as well as how these factors may change in the future, and it talks about the prerequisites that need to be met before wind power can be implemented on a large scale. Such an article can assist decision-makers and stakeholders in making enlightened decisions on wind energy development.

## Renewable Energy Sources

### *Strategy*

Energy is crucial for economic development. Egypt relies on fossil fuels for power generation, but their stocks are diminishing. Also, electricity generation from fossil fuels is the main source of greenhouse gas emissions, accounting for 88.51 million tons (Mt) (Ritchie et al., 2024a). It is therefore necessary to implement policies for an energy transition to phase out fossil fuels and reduce emissions, and the high potential of wind and solar radiation helps well towards this. On the other side, as the population grows, there will be an increased need for power production to meet the higher demand, as energy consumption per capita increased by 8% between 2020 and 2022 (Ritchie et al., 2024b). The strategic approach of a nation has other goals besides energy security, including environmental sustainability and economic competitiveness (Papanikos, 2017). As a result, an energy development strategy was developed in 2015 with four goals: ensuring energy security of supply, ensuring sustainability, improving institutional and corporate governance, and strengthening competitive markets and regulation. The Energy Strategy (2015 – 2035) aims to expand the deployment of renewable energy sources, as illustrated in Table 1, and to implement suitable infrastructure for projects. Projects involving this strategy will be carried out through public-private partnerships. In addition, the strategy includes policies regarding energy efficiency, nuclear power addition, improved natural gas utilization, reforming energy subsidies, and the inclusion of coal-fired generation with its attendant environmental consequences (SES, 2015).

**Table 1.** *Renewable Energy Targets by 2035*

| Renewable Energy Source | Expected Electric Energy (%) |
|---|---|
| Hydropower | 2 |
| Onshore Wind | 14 |
| Solar PV | 22 |
| Solar CSP | 4 |

Source: (NREA, 2024)

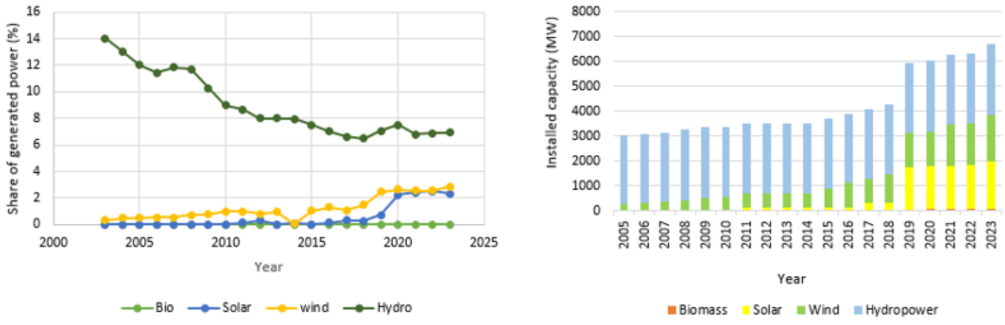
Decree-Law No. 203 was issued in 2014 to grow renewable energy generation. Some policy instruments were adopted to support renewables deployment and investment push: (1) competitive bidding, which is a call for tenders issued by the New and Renewable Energy Authority (NREA) to install a specific number of MW of renewable sources. (2) Feed-in Tariff (FIT) aims to set the energy price and duration of purchase for each type of energy and support producers at a price above the market. It guarantees a fixed price for energy producers, usually involving a long-term period from 20 to 25 years. Thus, FIT has the potential to minimize economic concerns while increasing investment incentives. (3) Independent Power Producers

(IPP), whose developers can either use the generated electricity to power their own loads or to supply distribution utilities depending on consumption. (4) The feed-in tariff system allows investors usufruct rights to the lands required for renewable energy in exchange for 2% of the total energy sold by the project. (5) Electricity subscribers will be obliged to use a certain percentage of renewable energy at reasonable prices. This proportion must be determined at least three months before the beginning of the fiscal year to absorb the electricity generated by the plants that are expected to be operational during the year (ElKhayat, 2016; NREA, 2014).

*Renewable Sources*

Egypt has an abundance of potential for green energy. Egypt is one of the Arab world's pioneers in renewable energy sources, ranking with the largest installed capacity (Habib et al., 2023). Its current renewable energy sources include hydropower, onshore wind power, solar power [PV & CSP], and biomass. Their installed capacity was 6691 MW, which comprised 25875 GWh, or 12% of the total electricity generated, as illustrated in Figure 1 (NREA, 2024; Ritchie et al., 2024b).

**Figure 1.** *Growth of Renewable Energy Sources*




(a) Renewable energy's share of total generated electricity from 2005 to 2023

(b) Installed Capacity of renewable energy sources from 2005 to 2023

Source: (EEHC, 2022; NREA, 2024; Ritchie et al., 2024b)

Furthermore, Egypt seeks to expand its sustainable energy portfolio and incorporate new energy sources like geothermal and nuclear energy to boost the stability of its electrical grids. Geothermal energy is obtained from heat and pressure differentials in the Earth's crust that can provide direct thermal energy or electricity using steam turbines. This makes geothermal a weather-independent renewable energy source. Geothermal energy is theoretically available everywhere, but it may be difficult to obtain in many areas. Besides power generation, it can also meet heating and cooling requirements, as well as value-added mineral extraction. Geothermal power capacity was around 15 GW in the world, which produced 101 TWh of electricity generated and 560 PJ of directly usable heat energy. Geothermal development has numerous advantages, but it also has drawbacks. These include exploration risks, a lengthy implementation period, and high capital costs (IRENA, 2023a; REN21, 2023). For thousands of years, Egyptians have utilized geothermal energy by using the warm water from hot springs for limited health purposes. Egypt still uses geothermal energy for direct heating, not power generation. Most geothermal resources are found in the Western and Eastern Deserts, along the Gulf of Suez. There are further low-thermal springs close to Helwan City that are sulfur-enriched. The most important location is in the Gulf of Suez since constructing geothermal power plants along the Gulf's shore is an important step to start generating electricity. Policymakers have become more interested in geothermal potential as a new type of renewable energy source. Thus, Egyptian and international entities collaborated on a research project to build capacity for both technicians and academics and exploit available geothermal potential (Lashin, 2020; NREA, 2024; Salah et al., 2022).

One sustainable energy source is nuclear energy, which contributes to 9% of the power generated globally (REN21, 2023). Egypt intended to include nuclear energy as part of its energy strategy. By 2035, it is anticipated that nuclear energy will provide 3% of the power generated, helping to fulfill the growing energy demand sustainably and so lowering climate change impacts. Nuclear plants do not produce both $CO_2$ emissions and other air pollutants. Furthermore, the amount of radioactive emission they create may be lower than that of radioactive isotopes present in coal soot and ash. In 2015, the Egyptian and Russian governments signed an agreement to construct the first nuclear power plant, which will be constructed with a 4800 MW capacity and be situated at the El-Dabaa site. But as of right now, not much has been done to finish this project (Salah et al., 2022).

Hydropower

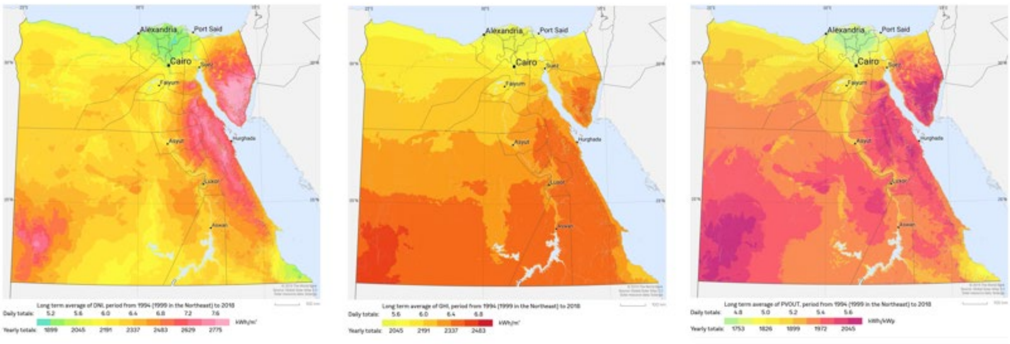
Hydropower is one of the oldest renewable sources in the world, accounting for 14% of total energy production. Despite a 2% decrease in power generated over the last ten years, it remains a significant resource (REN21, 2024). Its ability to store energy and provide a sustainable baseload, unlike other intermittent renewable energy sources, combined with its high efficiency, low maintenance costs, and long life, makes it a clean resource worth deploying (Eshra et al., 2021; Wasti et al., 2021). In Egypt, Hydropower is a significant renewable source. It dammed its only major river, the Nile, where six power plants are suited totaling 2832 MW. Hydropower generated 14967 Gwh, which contributed to 7% of total power generation (NREA, 2024; Ritchie et al., 2024b). The hydropower projects known as Aswan Dam and High Dam were constructed in the 1960s and were able to supply most of Egypt's electrical needs up until the 1980s. In partnership with the Ministry of Water Resources and Public Works, the Aswan 2 power plant was established in 1985. Other projects that followed included the Isna hydropower plant in 1993, the Naga-Hamadi power plant in 2008, and the Assuit project in 2018. The future plan is for a 2,400 MW water pumping and storage project in the Ataqa area to increase hydropower capacity (IRENA, 2018).

Since solar and wind energy dominate the renewable strategy, hydropower share is unlikely to change much shortly and has limited chances to increase its hydro capacity in the future. Hydropower potential will also be negatively impacted by the Grand Ethiopian Renaissance Dam as Egypt would receive less water as a result. Also, hydropower projects are situated along rivers, which are vulnerable to the effects of climate change. Most Egyptian hydropower plants are projected to face a wetter climate with increased precipitation and water flow, which would lead to positive and negative impacts. Egypt is expected to have a greater hydropower generation capacity factor under climate change scenarios. On the other side, the expected rise in severe rainfall and pluvial floods may cause sediment and floating debris that pose a risk to hydropower plants (IEA, 2023).

Solar Power

Solar power PV experienced a noticeable increase from 2013 to 2023, reaching 1185 GW of installed capacity worldwide (REN21, 2024). Based on the Global Solar Atlas in Figure 2, solar energy is dispersed across the country. Egypt is thus among the best areas in the world that can exploit solar radiation for thermal heating and power generation. Sunshine may generate energy with a density of 1970 to 3200 kWh/m$^2$ and occurs between 2900 and 3200 hours on average. Solar can be applied for solar water heaters and photovoltaic or concentrated solar power plant installations. Solar water heaters have been employed in many places since the 1980s, such as new cities and tourist destinations. In addition, solar PV is being installed for lighting on roadways, in remote locations, and in villages. In 2010, a 140 MW CSP project was installed. Due to the high expense of CSP deployment, more attention has been given to expanding PV projects (SES, 2015). In the last few years, solar power installed capacity has increased significantly, reaching 1910 MW for combined CSP at Al Karimat and PV at Kom Ombo, Banana, and Zafarana. (NREA, 2024; Othman & Khallaf, 2023; Salah et al., 2022). It is worth noting that the strategy aspires to achieve 6% of CSP by 2035, the future projects, whether held by the private sector or the New and Renewable Energy Authority (NREA), are entirely solar PV plants, and there are no plans for CSP.

**Figure 2.** *Solar Atlas Maps of Egypt*




(a) Direct normal irradiation (b) Global horizontal irradiation (c) Photovoltaic power potential

Source: (Global Solar Atlas, 2019)

Biomass

Egypt has a lot of biomass resources, including agricultural waste, municipal solid waste, sewage waste, and animal waste. All of these sources have the potential to generate a significant amount of clean electricity, especially in rural areas, but they are currently being used inefficiently. Based on a study, 3.1 million tons of rice straw can create 2477 GWh of electricity in a year. Three biomass plants with a combined capacity of 60 MW have been established over the past few years. Its current contribution is small, but efforts will be undertaken to expand deployment since Egypt wants biomass to play a larger role in the energy mix (Aliyu et al., 2018; NREA, 2024; SES, 2015).

In summary, the current state of renewable energy in Egypt was reviewed in relation to each renewable energy source, as well as the plans and policies that have been implemented. This review is crucial for understanding the available energy sources in Egypt and identifying which ones are competitive with wind energy. Hydropower, for instance, faces challenges that prevent it from competing with wind energy, while biomass is still in its early stages. Other sources, such as nuclear and geothermal energy, are still in the planning phase. On the other hand, solar energy has proven to be a successful source that can compete with wind energy in recent years. This comparison is crucial for understanding the strengths and limitations of each source, as well as for evaluating their potential to contribute to the energy mix. Hence, it becomes easier to identify why wind energy is the focus of this research article and whether it holds promise as a sustainable option for the future.

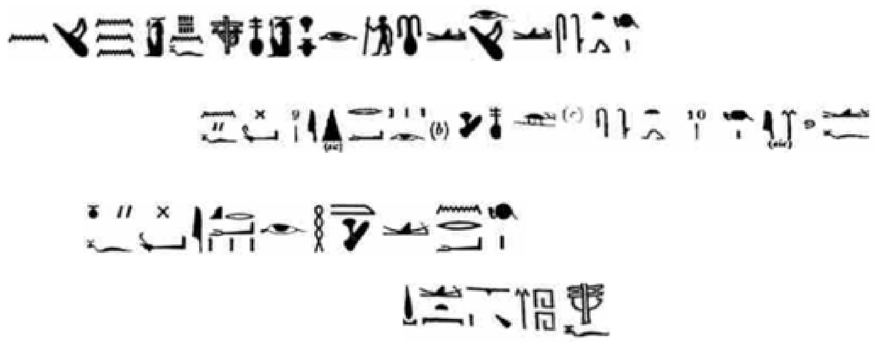
## Wind Power

This section consists of (a) the history of wind harnessing by the Egyptians, and (b) the use of wind to generate electricity. It highlights the long-standing relationship Egyptians have had with wind, emphasizing both its historical utilization and the growing interest in wind as a resource for electricity generation in the 20th century. While existing literature has touched on various aspects of wind energy, this paper uniquely addresses the historical context in a structured and comprehensive manner, providing valuable insights and contributing to the broader understanding of wind's role in Egypt.

### *History of Harnessing Wind by Egyptians*

The ancient Egyptians expressed the value and functions of the wind in various contexts, as highlighted through the texts of the Temple of Esna in hieroglyphic language, as seen in Figure 3. Based on ancient Egyptian beliefs, wind was considered a force that sustains life and the Egyptian cosmos (ELSAYED & A., 2018). Since ancient eras, wind resource has been harnessed for various purposes (Rishmany et al., 2017). Egyptians have relied on windmills featuring long vertical shafts and rectangular blades for a variety of uses, such as grain grinding, irrigation, and sugarcane industries (K. R. Rao, 2019).

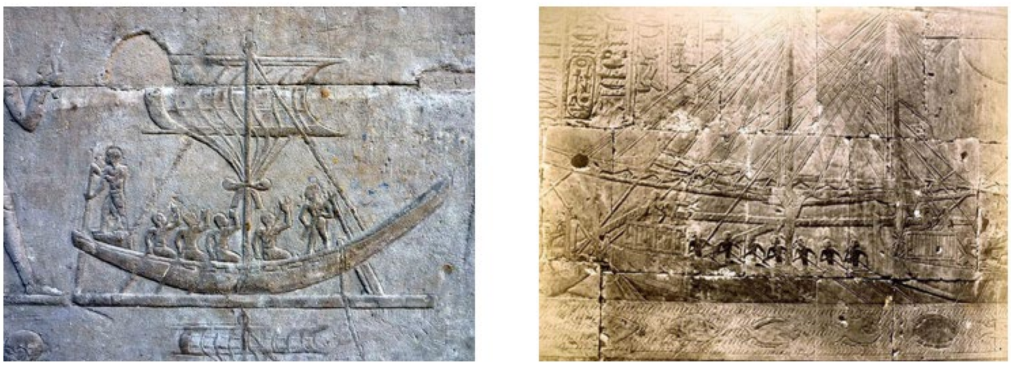
**Figure 3**. *Boat Navigation in the Ancient Egyptian Representation on Temple of Esna Texts – Luxor*



Source: (Elsayed, 2018)

Over 4000 BC, ancient Egyptians were able to sail wind-powered sailing ships across the Nile River, as shown in Figure 4, allowing them to trade, explore, and communicate. Furthermore, during the Fifth Dynasty of ancient Egypt, around 2500 BC, commercial and exploratory expeditions along the East Coast of Africa to the Land of Punt were made (Ragheb, 2017), which aided in the development and prosperity of Egyptian civilization. Ancient sailors demonstrated their advancement in the art of seamanship and wind knowledge by being able to complete an outward and return voyage using sail power to determine the monsoon's directions (Solari, 2019).

**Figure 4.** *Wind-powered Sailing Ships on the Walls of Egyptian Temples*



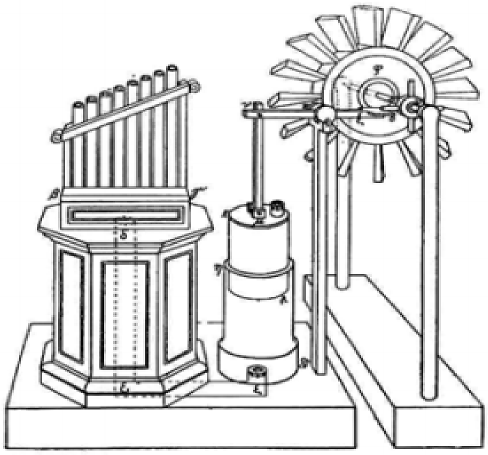
(a) Relief for an ancient Egyptian sailing ship on the walls of Edfu Temple, Aswan-Egypt

(b) Relief for an ancient Egyptian sailing ship on the walls of Deir Al Bahari Queen Hatshepsut's Temple in Luxor- Egypt

Source:(Alberta, 2023; Ragheb, 2017)

Ancient Greek scientists made significant contributions to and had an impact on world civilizations. In ancient Greek Egypt, Hero of Alexandria "Heron" was a mathematician, physicist, and engineer who invented the first wind-powered machine. Figure 5 depicts Heron's organ, which was also known as a "wind organ" or "hydraulis". It featured a small windwheel that powered a piston and forced air through the organ pipes, creating music. It was used as an entertainment instrument (Ragheb, 2017; J. S. Rao, 2011).

**Figure 5.** *Heron's Wind-powered Wheel*

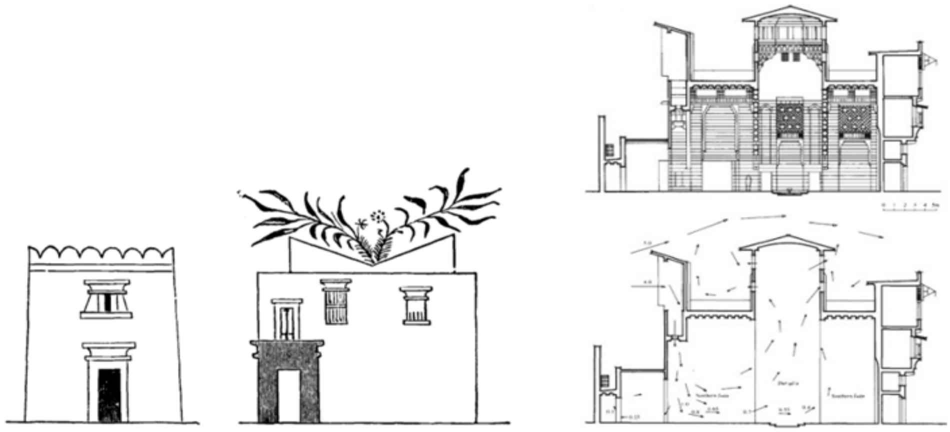


Source: (Papadopoulos, 2007)

In areas vulnerable to extreme weather conditions, humans attempted to induce pleasant winds in their houses or block harmful winds to improve living conditions. Taking wind into consideration during urban planning emerged in ancient Egyptian civilization, as illustrated in Egyptian papyrus 3500 years ago BC. It was simulated in Tell El Amarna, which King Akhenaton established on the banks of the Nile in 1376 BC. The city was ventilated by aligning all of its main roads with the coolest winds. Muslim-Arab architecture also responded to social, urban, and climate conditions. Buildings formerly had natural ventilation systems that provided natural cooling and sufficient lighting without the need to purchase equipment or incur energy expenditures (El-Borombaly & Molina-Prieto, 2015; Solari, 2019).

In order to provide thermal comfort within buildings, wind catchers, also known as wind towers, were first used in Pharaoh houses during the 19th Dynasty in Neb-Amun around 1300 B.C. It is a small roof-mounted tower with an opening facing the predominant wind, which blows colder air than the house's interior. Air in the tower shaft is forced down the shaft to cool the house due to wind velocity at this opening is higher than it is at the lower windows. They additionally perform a natural selection purpose, which means that if the inside air temperature drops below that of the outside, a pressure buildup stops the catcher from bringing in the cool air; if the outside air temperature drops below that of the inside, the wind that enters through the catcher expels the cooler air and radiates throughout the house. Several residences had "Malqaf" on their roofs. Its use during Egyptian civilization can be observed in paintings discovered in Thebes tombs and during the 14th century Bahri Mamluk period, as shown in Figure 6, for a classical house with a central tower for hot air escape and a Malqaf on the left (El-Borombaly & Molina-Prieto, 2015; Solari, 2019).

**Figure 6.** *Use of Wind for Ventilation in Egypt over Times*



(a) Windcatcher in the home of Neb-Amun, in Gourna - Luxor back to the 9th dynasty (1305–1196 BC)

(b) "Malqaf" – Section of Qā'a of Muhib Ad-Din Ash-Shāfi Al-Muwaqqi house in Cairo - Egypt back to 1350

Source: (El-Borombaly & Molina-Prieto, 2015; Solari, 2019)

It is concluded that natural ventilation improves indoor air quality, lowers costs, and rationalizes energy use, which all have positive socio-economic and environmental effects. Because Egypt has a hot, dry climate and is among the nations likely to experience negative effects from climate change as it gets hotter and drier, it is crucial to raise awareness of climatic architecture in order to prepare for these unfavorable effects of climate change.

**Figure 7.** *Windmills with Multiple Sails in Egypt during the Nineteenth Century*

(a) Windmills with multiple sails in Al Qabbari region - Alexandria in the 19th century

(b) Windmills with multiple sails in Cairo in the 19th century

Source: (Ragheb, 2017; Touregypt, 2024)

Throughout history, windmills have been utilized for a wide range of purposes in numerous countries, including milling grains, grinding spices, sawing lumber, ventilation in mines, producing gunpowder, oil extraction from oil seeds, nuts, and grains, and converting old rags into paper. The Middle Eastern civilizations utilized windmills with woven reed sails over 200–100 BC to grind grain. During the reign of Omar Ibn Al Khattab, the second Islamic Khalifa, a Persian created the first windmill for grains in AD 644. After that, windmills in Egypt were adapted and utilized to smash sugarcane to extract sugar and make molasses (Ragheb, 2017).

Multiple sails emerged during the reign of Muhammad Ali Pasha in the nineteenth century, as depicted in Figure 7 in Alexandria and Cairo. Windmills usually were built on coasts and in the highlands to take advantage of strong winds and thus crush a large amount of grain, as well as far away from residential areas due to the noise they make when rotating. It took hundreds of years for windmills to develop into the various designs, components, and features they have nowadays. This has allowed humanity to harness wind more widely, whether for electricity generation or other purposes.

*Harnessing Wind to Generate Electricity*

The development of wind to generate electricity has emerged considering the 1990s, and currently, wind power is one of Egypt's most significant sustainable energy sources. Egypt began investing in wind power in the Hurghada region in 1993, where an average wind speed of 6 m/s. A 5 MW demonstration wind farm was constructed, and 40% of its components were manufactured locally. It consisted of 42 two-blade and three-blade wind turbines with capacities ranging from 100 to 300 Kw. Capacity factors exceeded 18%, and this project achieved economic and environmental benefits during its operating period, including 5 million kWh, 1000 tons of fuel saved, and 2800 tons of $CO_2$ emissions reduced by the end of 2013 (NREA, 2024).

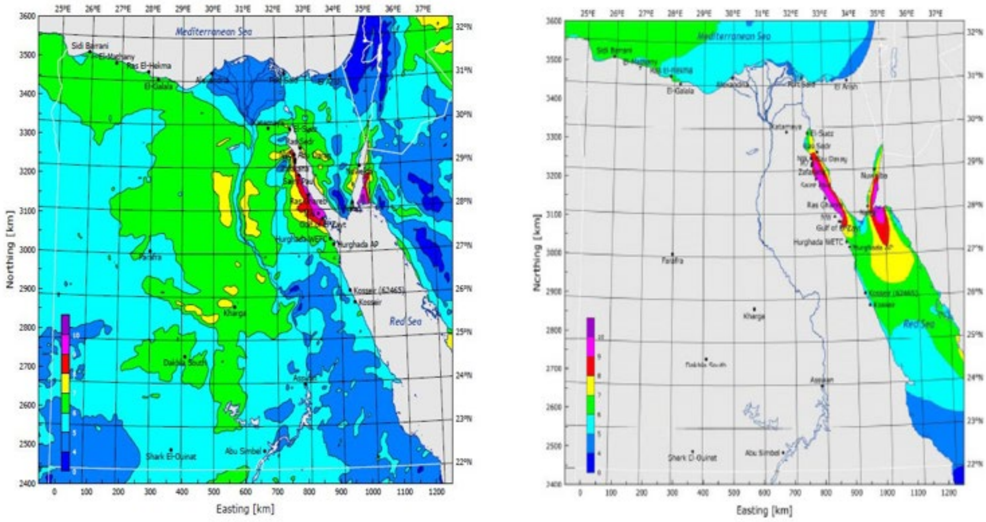
The expansion of wind energy projects necessitates an examination of wind speeds to select suitable sites with high wind power potential for electricity generation, which also supports the design of turbines that suit wind conditions. In collaboration with the New and Renewable Energy Authority (NREA), the Egyptian Meteorological Authority (EMA) and Risø National Laboratory (Risø) have created a comprehensive and diligent Wind Atlas for Egypt using WAsP calculations based on local anemometer measurements for the period 1991 to 2005 at a suitable level for developing bankable projects both onshore and offshore. Figure 8 & Table 2 illustrate that Egypt is distinguished for its strong winds, especially in some areas of the Gulf of Suez and Aqaba, with an average speed exceeding 8 m/s at 50 m. Additionally, promising wind speeds on the Mediterranean and Red Seas are suitable for the installation of offshore wind farms (Mortensen et al., 2005).

**Table 2.** *Wind Power Classes for some Areas at 50 m based on the Wind Atlas for Egypt*

| **Areas** | **Class** | **Resource potential** | **Wind speed (m/s)** | **Wind power density (W/m²)** |
|---|---|---|---|---|
| South Sinai | 1 | Poor | 0 – 4 | 0 – 100 |
| Delta region | 2 | Marginal | 4 – 5 | 100 – 200 |
| Eastern Nile | 3 | Moderate | 5 – 6 | 200 – 300 |
| Kharga Oasis | 4 | Good | 6 – 7 | 300 – 400 |
| Western Nile | 5 | Excellent | 7 – 8 | 400 – 500 |
| Gulf of Aqaba | 6 | Outstanding | 8 – 9 | 500 – 600 |
| Gulf of Suez | 7 | Superb | > 9 | > 600 |

Source: (ElSobki et al., 2009; Mortensen et al., 2006)

**Figure 8.** *Wind Resource based on Wind Atlas of Egypt*




Source: (Mortensen et al., 2006)

Beyond high wind power potential, wind farm planning must take into account several technical, economic, environmental, social, and geographical criteria. Egypt can be divided into five regions based on Wind Atlas; some have significant wind potential, while others have several issues that impede full-scale exploitation and have restrictions that prevent project construction or increase its cost (Feng, 2021; Rediske et al., 2021).

1. The Gulf of Suez has a superb wind power density in addition to the criteria availability that make it suitable for installing wind power projects. Therefore, NREA has allocated aside 1220 km$^2$ of the Suez Gulf region for the installation of 3550 MW (NREA, 2024).
2. The Gulf of Aqaba boasts an outstanding wind power density; however, since the area is considered a nature reserve, onshore wind farms cannot be installed there. In terms of offshore wind development, the water depth is above 200 m, which is deemed uneconomical for offshore wind farms (ElSobki et al., 2009).
3. The West Nile region has an excellent wind power density that can reach 500 W/m$^2$. So, NREA has allocated an area of 3636 km$^2$ for installing wind projects with 23350 MW (NREA, 2024).
4. The Western desert areas near Kharga have a good wind power density that can reach 400 W/m$^2$. While the NREA currently has no wind power projects there, it could provide a significant socio-economic benefit to the local community if a wind farm proposal is put forward.
5. The Eastern Nile area has a moderate wind power density, but it is lower than in the western area. As a result, its development should follow that of the western region. NREA has allocated an area of 841 km$^2$ for installing wind projects with 5800 MW.

6. The Delta region is unsuitable for wind power projects as its marginal wind power density, high population density, and the prevalence of agricultural land.
7. The south of the Sinai Peninsula is not suitable for wind power projects due to its classification as a tourist destination and nature reserve, as well as its low wind power density.

Superb areas with high wind power density are considered commercial for large-scale electricity generation, while moderate areas can be used for producing electricity to develop local communities. On the other hand, poor areas can be exploited for limited-scale agricultural purposes. Besides Wind Atlas, several research was conducted to evaluate wind resource in various locations where wind speed would be sufficient for power generation there (Ahmed, 2010; Ahmed 2011; Ahmed 2012; Ahmed 2018b; Essa & Embaby, 2005; Essa & Mubarak, 2006; Shaltout et al., 2021). Other research was conducted, focusing on technical and economic assessments to identify the best locations for investment (Abd El Sattar et al., 2020; Ahmed, 2018a, 2021; Alham et al., 2023; Hamouda, 2012; Ibrahim, 2022; Shata & Hanitsch, 2006; Shata & Hanitsch 2008).

Offshore wind is a valuable resource that can assist Egypt with its electricity shortage, contribute to its wind power targets, and support the broader regional renewable energy goals, including those of Saudi Arabia. In addition, it has less of a visual impact than onshore wind power sites (Mahdy & Bahaj, 2018). Some research has been conducted concerning the feasibility of constructing offshore wind farms. Certain regions surrounding the Red Sea are suitable for offshore wind farm installation based on a variety of criteria, including high wind power potential and minimal impact on nearby tourist resort lands (Mahdy & Bahaj, 2018). Similarly, based on a techno-economic assessment along the Mediterranean Sea, it would be feasible to install offshore wind farms, especially in the El Dabaa area (Abdelhady et al., 2017). In terms of isolated coastal cities with limited infrastructure, floating hybrid power plants of wind and solar combined with a hydrogen energy storage system is an unconventional solution to raising living standards there. Marsa Alam - Red Sea was determined as an appropriate location (Amin et al., 2022). Also, it was found that the installation of floating hybrid power plants—which combine hydropower and wind—would be viable from an environmental, economic, and technical aspect and would aid in the development of upper Egypt's villages along the River Nile (Arslan & Tezdogan, 2019).

It is worth noting that turbine noise can have an impact on both human health and animal life, frightening birds and small rodents and pushing them from their natural habitats. Thus, the best sites are those with no restrictive causes, such as forests, bird sanctuaries, animal habitats, military zones, ancient sites, and tourism destinations. Additionally, there must be enough space between the wind farm and a residential area to avoid disturbing people at a distance of [1000–3000 m]. Locations that are less than 500 m from agricultural areas should be avoided because agricultural areas can lose their agricultural productivity due to wind farm installation. Naturally, some areas are favorable for both agriculture as well as wind farm construction since turbines occupy only an average of 1% of the area, allowing the land to be used for other purposes (Rediske et al., 2021).

Table 3 & 4 illustrate all wind power projects that are centered in the Suez Gulf region, which has strong winds and capacity factors that can reach 40%, a high value compared to the global average of 37%. Wind power projects are managed by the New and Renewable Energy Authority (NREA), which succeeded in installing a capacity of more than 1370 MW since 2001 thanks to international cooperation, as illustrated in Table 4. Furthermore, the government supported the private sector, resulting in a considerable contribution to investment in wind projects, as seen in Table 5 (IRENA, 2023b; Mortensen, Said, et al., 2006; NREA, 2024).

**Table 3.** *Public Wind Power Projects*

| Project | Capacity (MW) | Status | Development parties |
|---|---|---|---|
| Zafarana | 545 | Operational | Germany –Spain – Denmark – Japan |
| Gabal El Zeit | 580 | Operational | Germany – European Union – Spain – Japan |
| Suez Gulf | 252 | Operational | Germany – European Union – France |

Source: (NREA, 2024)

**Table 4.** *Onshore Wind Farms [Public & Private] in Egypt*

| Wind farm | Latitude | Longitude | Nominal power (KW) | N. Turbines | Manufacturer |
|---|---|---|---|---|---|
| Zafarana 1 | 29° 11' 40.5" | 32° 35' 8.7" | 30,000 | 50 | Nordex N43/600 |
| Zafarana 2 | | | 33,000 | 55 | Nordex N43/600 |
| Zafarana 3 | | | 30,360 | 46 | Vestas V47/660 |
| Zafarana 4 | | | 46,860 | 71 | Vestas V47/660 |
| Zafarana 5 | | | 85,000 | 100 | Gamesa G52/850 |
| Zafarana 6 | | | 79,900 | 96 | Gamesa G52/850 |
| Zafarana 7 | | | 119,850 | 141 | Gamesa G52/850 |
| Zafarana 8 | | | 119,850 | 141 | Gamesa G52/850 |
| Gabal El Zeit 1 | 25° 51' 27.7" | 34° 24' 57.6" | 220,000 | 100 | Gamesa G80/2000 |
| Gabal El Zeit 2 | | | 120,000 | 100 | Gamesa G80/2000 |
| Gabal El Zeit 3 | | | 200,000 | 100 | Gamesa G80/2000 |
| Gabal El Zeit 4 | | | 40,000 | 100 | Gamesa G80/2000 |
| West Bakr | 28° 45' 4" | 32° 46' 16.8" | 252,000 | 96 | Siemens-Gamesa SG 2.6-114 |
| Ras Gharib 1 | 28° 24' 1.8" | 32° 57' 16.6" | 262,500 | 125 | Gamesa G97/2000 |
| Ras Gharib 2 | 28° 8' 1.6" | 33° 15' 36.7" | 5,000,000 | 125 | Gamesa G97/2000 |
| Gulf Of Suez | 28° 21' 19" | 33° 3' 43.9" | 250,000 | 70 | Vestas V105-3.6 MW |

Source: (WPN, 2023)

**Table 5.** *Private Wind Power Projects*

| Project | Size (MW) | Status | Contract |
|---|---|---|---|
| West Bakr | 250 | Operational | BOO scheme |
| Ras Gharib | 262 | Operational | BOO scheme |
| Al Bahr al Ahmar 1 | 500 | Under implementation | BOO scheme |
| Amunet 1 | 500 | Under implementation | BOO scheme |
| Infinity | 200 | Under development | BOO scheme |
| Al Bahr al Ahmar 2 | 150 | Under development | BOO scheme |
| Amunet 2 | 500 | Under development | BOO scheme |
| Gulf Of Suez | 1100 | Under development | BOO scheme |
| Siemens Gamesa | 500 | Under development | BOO scheme |
| ACWA Power | 10000 | Planned Project | BOO scheme |
| Scatec | 500 | Planned Project | BOO scheme |
| Infinity - Hassan Allam | 10000 | Planned Project | BOO scheme |
| Toyota Tsusho - Orascom | 300 | Planned Project | BOO scheme |

Source: (NREA, 2024)

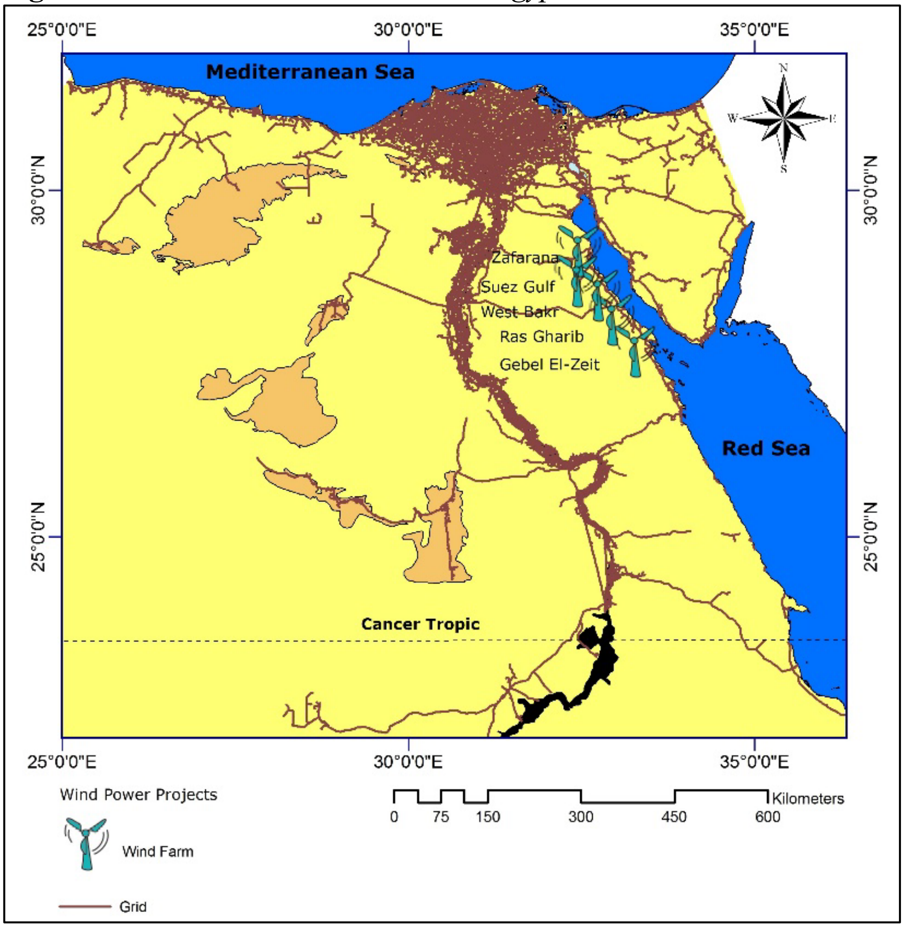
## Technical Aspects of Wind Power

### *Incorporating Wind Power into the Grid*

Power transmission lines are depicted in Figure 9. The plans for significant wind development in the Suez Gulf area certainly necessitate a significant increase in transmission capacity to the area. There is no technical limit to how much wind power can be integrated into the electrical grid. Cost is the main concern: longer transmission lines are more expensive than shorter ones, and as the proportion of wind in the grid increases, more infrastructure will need to be installed to control the quality of the power in the grid.

It has been demonstrated that high-voltage direct current (HVDC) technology is the most cost-effective and efficient when considering economic, environmental, and technical perspectives. This demonstrated how well it worked to integrate renewable energy sources with the national grid and support the increased capacity of the targeted wind farms. Furthermore, because underground heating, ventilation, and air conditioning (HVAC) cables require lower spaces and avoid adverse effects on touristic areas, for instance, they may be more applicable in the Suez Gulf region. This option, however, may necessitate the use of power compensation capacitors. Furthermore, the economic factor must be considered (Elgeziry et al., 2019). Furthermore, hybrid systems are considered to be among the best options for energy sources in isolated areas that have no connection to the national grid (Elsaei et al., 2023; Rashwan et al., 2024). Some studies recommended that hybrid systems, which include wind and other renewable sources, be implemented in remote urban areas and villages in Egypt to supply stable electricity and support communities' development (Effat & El-Zeiny, 2022; Ragab et al., 2021).

**Figure 9**. *Power Transmission Lines in Egypt*




Source: The map was created using ArcGIS, based on data from www.openstreetmap.org

*Manufacturing Wind Turbines*

One approach that could help to lower wind power costs is to manufacture wind power systems locally. Since 2008, the Egyptian investor El-Sewedy Electric Towers (EET) has made plans and investments in the arena for the manufacture of wind energy generation components. Manufacturing enterprises are located in El Ain EL Sokhna - Suez Governorate, near Egypt's largest harbors and the Zafarana and Gabal El Zeit wind projects. The company has been an achievement in becoming a regional leader in the MENA region for energy solutions and its related services, as well as a global leader in cable manufacturing. Annually, it can produce 200 wind turbine towers, which it supplies for projects in Egypt, the USA, Germany, Italy, Poland, and Cyprus (EET, 2024). El-Sewedy officials estimated in a personal interview with the paper's authors that installing locally manufactured wind towers contributes to a 3% reduction in wind farm costs, which is 25% less than the wind tower cost. In addition to the social impacts of recruiting lots of employees about 300 - 400 per project and building capacity via sending technicians to Germany for training to become qualified welders and technicians. All of this supports the economic growth of Egypt. El-Sewedy has the potential to expand into additional wind turbine component production, but this needs strong governmental incentives and support, which are not in place yet. For example, in reality, the customs duties for wind power equipment, components, and spare parts are subject to 2% customs with no value-added tax, while the locally manufactured components are subject to 14% value-added tax. This negatively impacts the competitiveness of the locally manufactured components, which in turn discourages the investors. The Egyptian government's plan must be detailed, with a specified time frame and outlining a minimum local contents percentage for each project (Shankir, 2024).

Climate change-related extreme weather events impose unique design considerations on wind turbines for adaptation. Rising temperatures along with moisture lead to several difficulties, such as metal corroding, lubricant thinning, impaired electronic performance, and altered motion in mechanical systems. Additionally, low temperatures can lead to sensor and turbine icing (Manwell et al., 2010). El-Sewedy officials stated that the wind turbine components are designed to endure and work effectively at temperatures as high as 50 °C. However, the impact of climate change on each renewable source available in Egypt has to be evaluated and a plan must be prepared to adapt to these potential impacts accordingly, manufacturers take this into account (Shankir, 2024).

## Environmental Aspects of Wind Power

Wind power projects require vast land, as installing a capacity of 5 to 9 MW necessitates one km$^2$ of land. Egypt not only has vast uninhabited desert areas, but it also has high-speed winds in many areas, allowing it to enhance its wind energy utilization (Mahmoud, 2012). Therefore, about 7650 Km$^2$ has been allocated for wind and solar power development, as indicated in Table 6.

**Table 6.** *Area Land for Renewable Energy Projects*

| Location | Technology | Land area (Km$^2$) | Planned Capacity (MW) |
|---|---|---|---|
| Suez Gulf | Wind Power | 1220 | 3550 |
| East Nile | Wind Power | 841 | 5800 |
| | Solar Power | 1290 | 34900 |
| West Nile | Wind Power | 3636 | 23350 |
| | Solar Power | 606 | 17400 |
| Benban | Solar Power | 37 | 1800 |
| Kom Ombo | Solar Power | 7 | 260 |

Source: (NREA, 2024)

Installing wind power projects that consist of lots of turbines has some potential adverse environmental effects. The Egyptian promising areas with high wind speeds on the Red Sea coast and Suze Gulf intersect with one of the key crossing points for migrating birds from Asia to Africa. Strategic environmental studies were undertaken to identify areas that were highly sensitive to migratory birds and therefore excluded during project planning. This was necessary to reduce the risk of collisions with wind turbines to conserve soaring birds while utilizing wind power potential. Simultaneously, preventive measures are implemented in the remaining appropriate locations, including monitoring migration routes in spring and fall and determining the appropriate procedure of action for turbines situated along those routes, such as stopping temporarily and determining the duration of the suspension. In addition to photographing and recording data such as bird species and their heights, as well as deaths and injuries (ElKhayat, 2024; RCREEE, 2024). Social and environmental assessments of wind projects were conducted, and the overall conclusion was that these impacts do not pose any significant problems. These effects are minimal when applying sufficient mitigation and monitoring requirements. These studies incorporate the involvement of stakeholders, including the public, to guarantee their support and achieve security and protection for the project via engaging them in employment and purchase opportunities during construction and operation. Public involvement aims to reduce potential negative environmental and social effects, enhance project acceptability, and achieve a balance between development and environmental protection (RCREEE, 2024).

On the other hand, climate change, as an environmental issue, is expected to have an impact on energy infrastructure, supply and demand, and other energy-related sectors. Egypt is considered one of the most vulnerable countries to the potential impacts and threats of climate change (SES, 2015). Therefore, over the past years, the government has given climate change more consideration in its national policies and strategy, which covers the energy sector regarding mitigation and adaptation actions. These actions include assessing the effects of climate change to determine safe locations for the construction of future power plants, as well as building institutional and technical capacity and supporting research and technological development to help the power sector become more climate resilient (IEA, 2023). Some researchers have assessed the impact of climate change on wind power potential under various climate change scenarios. It is expected to vary, with potential increases or decreases in wind power density (Gebaly et al., 2023; Hassaan et al., 2024). The regions with high wind power density will be negatively affected, with a projected decline of up to 1% of land areas. However, the Gulf of Suez area is expected to remain one of the most favorable regions for investment despite the anticipated climate changes (Ghanem et al., 2024).

## Economics of Wind Power

The economic analysis aims to evaluate the cost-effectiveness of wind power compared with available alternatives in Egypt. Natural gas is regarded as a crucial fuel for electricity generation, and it is expected to remain so for the next two decades. The 2022 fossil fuel price increase demonstrated how vulnerable countries that rely on fossil fuels for energy generation are (IRENA, 2023). Egypt has implemented a load-shedding program since the summer of 2023 in response to rising pressure on power stations caused by high local demand (Ahram Online, 2024). When there is not enough gas to adequately serve the power sector due to export commitments or non-power uses, oil plays its role as a short-term balancing option. Concerning chances for other resources, Egypt does not have significant coal reserves, cannot expand its hydropower capacity, and the development of a nuclear power plant at El Dabaa entails several challenges, such as high initial costs and long construction delays. Increasing the number of wind power plants will be beneficial in the short and medium term. Also, solar PV is a strong alternative to wind power since it generates electricity that is comparable to that of wind. Since 2018, Egypt has taken a step toward moving away from foreign donor funding to private sector investment for wind and solar PV project development. In the private sector, investors require an appealing financial environment in which they can generate profits. Renewable prices are 2.5 US cents/kWh for solar power and 3 US cents/kWh for wind power, which is a favorable indicator of investors' interest in the Egyptian market (NREA, 2024). In order to compare wind and solar projects, capital, operating, and avoided costs should be considered.

*Capital Costs*

Wind energy is considered a capital-intensive investment and the factor that determines the generation costs is the initial capital costs. The wind farm project involves four stages, as indicated in Table 7.

**Table 7.** *Wind Farm Project Timeline*

| | Development | Implementation | Operation | Decommissioning |
|---|---|---|---|---|
| Description | Finding a site | Procurement | Operation | Remove |
| | Site Characteristics | Construction | Maintenance | Re-power |
| | Wind farm design | | Administration | |
| | Permissions & licenses | | | |
| | Financing | | | |
| | Public engagement | | | |
| Duration | Up to 5 years | 1 - 2 years | 20 - 25 years | < 1 year |

Source: (Cronin, 2023)

A significant motivation for investing is the capital expenses of wind power in comparison to other electricity generation technologies such as solar PV. The average installed cost of onshore wind power decreased by 42% globally between 2010 and 2022, from USD 2179/kW to USD 1274/kW, with an annual decrease of 10%. Reductions in wind turbine prices were the main cause of this fall. In contrast, solar PV experienced an 83% decrease in total mean installed cost from USD 2.5124/kW in 2010 to USD 876/kW in 2022. Egypt's onshore wind projects [Zafarana and Gulf of El Zayt] cost more than $370 million per MW, while the solar PV project [Benban] cost $2.20 billion (IRENA, 2023; NREA, 2024). Table 8 illustrates the predicted values.

Prices for wind turbines peaked between 2007 and 2010, after a dramatic rise from their lowest point between 2000 and 2002. This was related to advances in turbine design as well as price increases for materials, mainly cement, copper, iron, and steel. Increased government policy support for wind deployment, combined with a demand-supply mismatch, allowed manufacturers to increase their margins.

However, this increased competition does not protect the industry from the effects of supply and demand imbalances. Also, it has resulted in acquisitions in the turbine sector, as well as a shift in production to countries with lower manufacturing costs. In 2022, wind turbine prices decreased, ranging from USD 840/kW to USD 1175/kW, although rotor diameters, hub heights, and nameplate capacities have all increased over the last decade in general. Also, price differences between turbines with different rotor diameters have significantly narrowed. Yet, their prices increased in late 2020 and early 2021 due to COVID-19 and the concurrent market. Inverters and solar PV modules were the main contributors to the 37% cost decrease between 2016 and 2022. All module categories experienced declines at the start of 2023, with declines ranging from 7% to 9%, reflecting an ongoing decreasing trend for module prices (IRENA, 2023).

**Table 8.** *Predicted Investment Costs of Renewables in Egypt*

| Technology | Investment cost ($/KW) | | |
|---|---|---|---|
| | 2015 | 2025 | 2040 |
| Wind | 1200 | 1056 | 1056 |
| PV Utility Scale Size | 1000 | 800 | 742 |
| PV Small Rooftop (<10 - 20kW) | 1200 | 960 | 809 |
| Solar Thermal with Storage (10h – 12h) | 5000 | 4211 | 3027 |
| Solar Thermal Without Storage | 4500 | 3776 | 2715 |

Source: (Giannakidis, 2017)

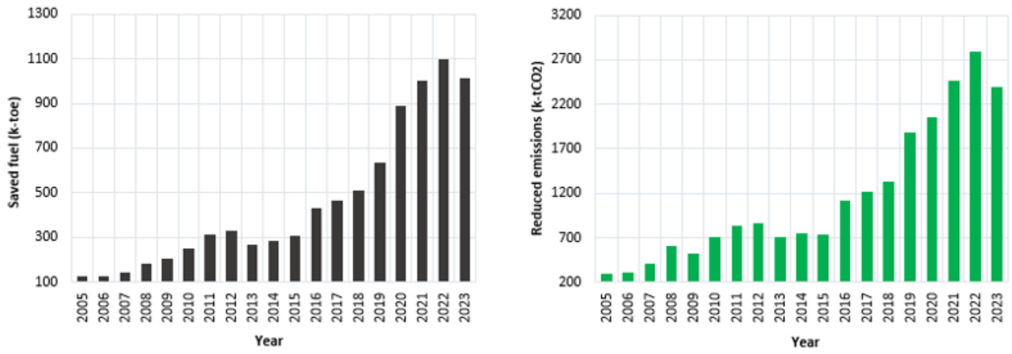
*Operating Costs*

Competitiveness and technological advancements have led to designs that have helped lower operating and maintenance (O&M) costs. Over the last decade, major advancements in onshore wind turbine technology have resulted in higher capacity factors, which have averaged 37% in 2022. The capacity factor is the annual energy output from a wind farm, which is defined by wind resource at the location and turbine of the farm's maximum output. Wind power usually has capacity factors ranging from 25% to 40%. Egypt has excellent wind resources, so its capacity factors may exceed this percentage. For example, Zafarana has a capacity factor of over 35%. High-capacity factors, along with the relatively low cost of local labor and services in Egypt, indicate that O&M costs will be minimal. Also, the global capacity factor of solar PV was 16.9% on average in 2022. This rise can be attributed to two factors: installation in sunnier locations as well as technological advancements. O&M costs for solar PV plants have decreased over the past decade as a result (IRENA, 2023).

*Avoided Costs*

Besides economic and technical maturity, wind-generated electricity ranks second after hydropower in terms of achieving major environmental benefits such as fuel reduction that would be consumed through conventional generating plants. Also, wind power mitigates the emissions that traditional fossil fuel-based power plants would produce. These emissions include particulates, slag, ash, carbon dioxide ($CO_2$), sulfur dioxide ($SO_2$), and oxides of nitrogen ($NO_x$) and thus contribute to climate change mitigation and air quality improvement. In addition to these direct environmental benefits, wind power generation also offers indirect benefits, including improved public health and political advantages resulting from reduced fossil fuel use. As shown in Figure 10, each GWh of wind-generated electricity in Egypt over the past year has saved 1100 k-toe (22%) of fuel and reduced emissions by 2785 k-$tCO_2$. Whereas, each GWh of solar PV-generated electricity has saved 820 k-toe (18%) of fuel and reduced emissions by 1932 k-$tCO_2$ (Manwell et al., 2010; NREA, 2024).

**Figure 10.** *Environmental Benefits of Wind Power from 2005 to 2023*




(a) Saved fuel (b) Reduced emissions

Source: (NREA, 2024)

## Conclusion and Recommendations

This article provides an in-depth overview of wind energy in Egypt, examining its economic, technical, and environmental dimensions. It also includes a comparative discussion with solar energy, highlighting the advantages and challenges of wind power. Wind power is a highly competitive source and a desirable option for investors due to its economic and technical maturity, as well as the avoided costs associated with the environmental benefits achieved. Egypt has favorable conditions for wind power development, especially in the Gulf of Suez region. However, the ambitious wind energy target of 14% by 2035 may not be achievable unless there is a significant acceleration in current and future projects.

- From the time Egypt's strategy was established in 2015 to 2023, wind power has contributed only 3% of the country's total electricity generation. Given this slow progress, it is advisable to update the plan to more accurately reflect the potential contribution of wind energy based on ongoing projects and future investments. The current strategy may need to either revise the 14% target downward or scale up investments substantially to meet this ambitious goal. More accurate forecasting would also help set realistic targets for the coming years.

- The expected duration for each project should be clearly determined during the development phase, considering potential delays or challenges that may hinder progress. These include such as inflation, currency fluctuations, policies, and the costs of adaptation to the impacts of climate change. This will help with the evaluation of progress steps by 2035.
- The development of local manufacturing capabilities for wind energy components is a promising approach to reducing costs and enhancing the domestic industry. For this to succeed, strong government support is critical. This could include offering financial incentives to local investors and defining the minimum of local components for each wind project to protect the Egyptian industry.
- Wind power's intermittency imposes a challenge, as it can increase the cost of generating electricity. This challenge is more pronounced for single wind farms, but it diminishes as the number of wind farms expands and their geographical distribution increases. Therefore, it would be beneficial to invest in a more distributed wind energy network, which could help mitigate the risks associated with variance in wind speeds.
- Despite numerous studies indicating that offshore wind farms could provide significant power generation alongside socio-economic and environmental benefits, Egypt's current strategy does not prioritize offshore wind development. It would be beneficial to revisit this approach and explore the feasibility of developing offshore wind farms in addition to expanding onshore wind projects. Offshore wind power offers higher capacity factors and could help Egypt diversify its renewable energy sources, enhancing grid stability and resilience. Wind power is a promising option that could present opportunities for Egypt to export natural gas, which would generate hard currency and improve the country’s economic situation

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