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# Towards a sustainable energy future for Egypt: A systematic review of renewable energy sources, technologies, challenges, and recommendations

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ABSTRACT

Egypt has a significant role in international energy transit, being one of the major economies in the African continent. However, its energy sector is still overwhelmed with the local energy demands. It has been predicted that Egypt's $CO_2$ emissions could increase by around 125% from 2012 to 2035 if the nation's energy demand is met using conventional power generation technologies. Given that Egypt has signed the Kyoto protocol and recognised the role of international cooperation in facing climate change, the country should focus on meeting the growing energy demand using clean energy technologies. In the meantime, Egypt has been facing many challenges due to the water scarcity issues and environmental risks arising from the lack of efficient solid waste management strategies over the last few decades. It has been predicted that the country's crude oil reserves might be depleted within the next 15 years or so. To face these challenges effectively and enforce the Egyptian role in international energy transit, renewable energy (RE) technologies and their applications should be the main focus of the current/future Egyptian energy frameworks. This review summarises the current energy outlook of Egypt while analysing the country's potential to harness energy from sustainable sources. In general, it has been found that Egypt's renewable energy sector is yet to be exploited for sustainable energy production through its diverse and plentiful resources. Eventually, two scenarios have been proposed to consider in achieving the nation's 2035 energy target, which is to generate 42% of the country's energy need through renewable sources. This study should help Egypt and other countries to set the way forward in achieving the NET ZERO target that the whole world aims to fulfil over the next few decades.

## 1. Introduction

Cleaner production is an important concept that is concerned with introducing methods and practices to avoid potential environmental damages. A wide range of cleaner production initiatives contributes to sustainable development through efficient management of energy resources and the development of new technologies and new ways of assisting policies-development (Giannetti et al., 2020). The UN declared the 2030 agenda to transform the world towards sustainable development by setting 17 sustainable development goals (Kjaerheim, 2005). Among these 17 goals, the seventh goal is dedicated to increasing the share of renewable energy substantially in the global energy mix to move towards a green energy future (UN, 2015).

Achieving an entirely green energy future is one of the main targets that all nations across the globe aims for. However, most of them may not still have a clear vision or a way forward for reaching this target. According to the Paris historic climate agreement, the global temperature rise should be maintained below 2 °C within this century to tackle the global energy crisis and climate change effectively (IRENA, 2018a). As per the guidelines, the current annual energy-related $CO_2$ emissions must be reduced by over 70% by 2050. Over the last few decades, people have been abusing natural resources across the globe, and this has been causing many adverse effects on the environment/nature. These effects could not be reversed if the abusive activities continue to happen in the same way/capacity for a few more decades (Bhuiyan et al., 2021). To date, there have been several alarming signs/catastrophes caused by the destruction done to the planet Earth by human beings. One of the most recent incidents is the disappearance of the A68 iceberg, which was

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covering an area of nearly 6000 km$^2$ (2300 mi$^2$) when it broke away from Antarctica in 2017. One of the key destruction that human beings are causing to this planet is the burning of fossil fuels to power the world, where fossil fuels accounted for around 80% of the globe's total energy consumption in 2019 (REN, 2021). In this regard, renewable energies and energy efficiency improvements should pave a path towards controlling the emissions and reversing the adverse effects caused within a planned time frame (IRENA, 2018a).

Renewable energy sources can be used to produce electricity/energy without combustion. Hence, they can significantly contribute to reducing harmful emissions/particles and support the health and welfare of all human beings, animals, and plants. This should result in improved living standards and motivate decision-makers to invest more in the renewable energy sector (Dettner and Blohm, 2021). The carbon-neutral goal, set by the European Union and agreed upon by Egypt to follow, can be achieved through the subsequent developments of existing sustainable technologies. Wind farms have proven to provide the most promising solution, alongside solar photovoltaics reaching 43% of the electricity generation share across the EU by 2050. The transition from conventional energy sources to renewable energy sources will positively impact the environment and the economy. It has been predicted that this transition would create 1.5 M new job opportunities within the next 30 years in Europe alone (Potrč et al., 2021).

Egypt has a significant role in the international energy market due to many reasons, particularly due to its location (Hegazy, 2015). Egypt is located in North Africa and the Arab region with approximately 3000 km of coastlines on the Mediterranean, Red Sea, and the Gulf of Suez and Aqaba, and also at the crossroads between Europe, Middle East, Asia, and Africa (IRENA, 2018b). Additionally, Egypt is home to one of the key transportation routes of the world 'the Suez Canal' and the Suez-Mediterranean Pipeline (SUMED). These help Egypt to be in a strategic position in the international energy market. Provided that the Egyptian government still meets its growing energy demand using the conventional power generation techniques, $CO_2$ emissions are expected to increase from around 800 Mmt in 2012 to above 1800 Mmt in 2035, marking a massive 125% increment (Bottoms, 2016). According to the rate of increase in the consumption of conventional energy sources in Egypt alongside the $CO_2$ emissions over the period from 1971 to 2016 (for 47 years as shown in Fig. 1) (The world bank, 2022), it is evident that Egypt is still relying primarily on the conventional energy resources.

In Egypt, electricity demand has been growing rapidly over the last few decades due to population growth, urbanisation, economic growth, industrial output, and energy subsidies. The electricity consumption reached 156300 GWh in 2015/16 (IRENA, 2018b); where 66% of the total consumption was supplied by natural gases, 7% by hydro energy and only 8% by renewable energy sources (IRENA, 2018b). Egypt is responsible for 8% of the RE production in the African region, with 93 Mtoe (million tonnes of oil equivalent) of electricity production from renewable sources. In 2020, solar energy in Egypt accounted for 1.9% of its total electricity production, making it the second-highest renewable energy source. Egypt is the second country in Africa after South Africa in solar energy utilisation, ranked thirty-first worldwide (IRENA, 2021). As for wind energy, Egypt generated wind power with a capacity of 5.4 MW and 545 MW from Hurghada and Zafarana wind farms, respectively, in 2001. At a reported cost of $6.8B, the Zafarana wind farm was completed in 2015 and has grown its capacity to 340 and 600 MW by 2017 and 2018, respectively. As a part of the strategy to increase wind power to 7.2 GW by 2020, the government intends to develop wind energy generation capacity during the next few years. In 2020, wind energy was responsible for 1.44% of the total produced electricity, making it the third-highest renewable energy source in Egypt (Shouman and Khattab, 2015). About 90% of the nation's hydroelectricity is produced by the Aswan High Dam located across the Nile River with a generation capacity of 2300 MW.

Despite the relatively small contribution of Egypt to the African and the global RE market, Egypt has a power generation potential of 73,656 TWh/y through concentrated solar power (CSP) technology along with a potential of 7650 TWh/y via wind energy. This is followed by 36.0, 15.3, 25.7 and 80 TWh/y through photovoltaic panels (PV), bioenergy, geothermal and hydro power, respectively (DLR, 2005). Despite this, according to the most recent annual report issued in 2018 by the Egyptian Electricity Holding Company (EEHC), Egypt's total current installed power generation capacity is around 54.5 GW. Of this total generation capacity, renewable energy accounts only for 10% (IRENA, 2018b). It is clear that the utilised RE sources in Egypt are not yet comparable to the existing potential, where Egypt's geography, temperature, and wind speeds have placed the country in an ideal position for producing energy via renewable sources (Group E.I, 2014). At present, Egypt has set an ambitious objective of achieving 42% of its energy generation capacity from renewable sources by 2035 (known as the 2035 energy target) (IRENA, 2018b).

To better exploit the RE potential in Egypt, a few review studies have covered different aspects of RE technologies. Khalil et al. (2010) proposed an action plan to allow for the development of novel materials and local components' design to enhance the competitiveness and efficiency of renewable energy systems in Egypt. This study has focused on solar, wind, and biomass energies. El-Kholy and Faried (2011) presented a

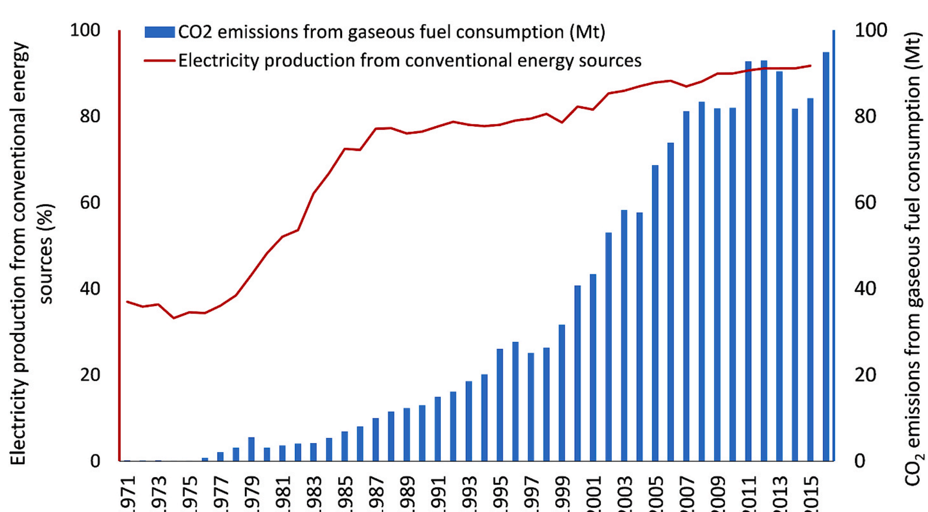



**Fig. 1.** Electricity production from conventional energy sources and $CO_2$ emissions from gaseous fuel consumption (Mt) over the years from 1971 to 2016 (The world bank, 2022).

study for managing the energy demand in Egypt using renewable energy resources, including hydro, biomass, solar and wind energy resources. Similarly, solar and wind energy potentials were investigated in Egypt in 2012 (Ibrahim, 2012). Jamel et al. (2013) discussed the advances in integrating solar thermal technologies with non-conventional power generation systems in several countries including Egypt. Later, a review study was presented on the renewable energy development in Africa with a focus on Egypt and Nigeria, including hyrdropower, solar, wind and biomass energies (Aliyu et al., 2018). Obukhov and Ibrahim (2017) analysed the RE potential in Egypt, where the key focus was on wind and solar energies. It is worth noting that not all aspects of renewable energy generation have been covered thoroughly by these previous studies, as no much attention has been paid to some renewable energy sources such as wave and tidal, nuclear, bio, geothermal and renewable desalination systems and so forth. Obviously, some of these neglected energy sources should be within Egypt's potential future energy frameworks.

This work aims to carry out a comprehensive review of the energy outlook of Egypt in a more broad way. First, the current renewable energy generation profile of Egypt will be analysed. Then, the country's potential to harness sustainable energies from all the key sources will be investigated together with the possible limitations and challenges (Dasanayaka et al., 2022). Hence, an evaluation can be made on the possibility of realising Egypt's 2035 energy plan. Eventually, several recommendations will be made on the country's potential to harness energy from different renewable sources while analysing the current energy-related policies and possible challenges in installing renewable energy systems. The current status and future prospects of renewable and sustainable energy resources in Egypt are discussed, including private and governmental plans to meet the country's electricity demand. This would set a good guideline for the Egyptian authorities to realise the nation's renewable energy goals, such as the 2035 energy plan and eventually become a NET-ZERO nation.

## 2. Egypt compared to world averages

In the process of planning to increase the renewable energy establishments of a country, it is important to identify its position compared with other countries that are on the same journey. Therefore, this section provides a comparison of Egypt's RE potential/market with other countries.

### 2.1. Hydroelectricity

Hydropower is an integral part of the electricity generation of many countries. Some countries such as India, Russia, Canada, the United States, Brazil, China and Norway generate at least 50% of their electricity from hydro; where the estimated global hydropower capacity has increased from 35 GW in 2014 to about 1055 GW as of July 2018. It has been predicted that hydropower will account for around 15% of the world's electrical energy needs by 2040. Hydropower is the highest utilised renewable energy source worldwide, and its growth is expected to continue due to its effectiveness and given the future availability of water sources. With respect to Egypt, the share of renewable sources in the total electricity demand achieved 30%, as shown in Fig. 2, when Aswan High Dam started working in 1985. Nonetheless, the share of electricity production from RE sources gradually declined with the rapid increase of non-renewable energy sources to cater to the growing energy demand with no considerable expansion in renewable energy production. As shown in Fig. 2, Egypt has re-captured its renewable energy-momentum and the electricity generation from low-carbon sources and started to bounce back from its lowest level, which was around 9% in 2017.

Around 94% of the nation's hydroelectricity is still produced by the Aswan High Dam (2650 MW), while Esna, Naga Hammadi and New Asyut Barrage also generate 84 MW, 64 MW, and 40 MW, respectively. Egypt now is the fourth highest country in Africa with a total capacity of 2800 MW, but compared to the rest of the world, the hydropower in Egypt is unrecognised (Shouman, 2017). Unfortunately, the hydropower capacities of Egypt and Sudan will be significantly affected as the Grand Ethiopian Renaissance Dam (GERD) starts to fill the second dam (which will happen in 3 years). This would reduce the water quantities received by Sudan and Egypt.

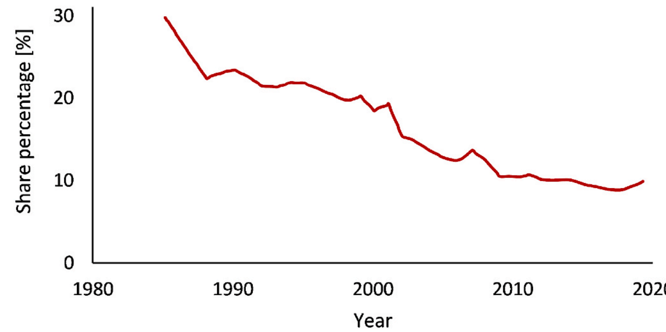



**Fig. 2.** Share of electricity production from low-carbon sources in Egypt (Ritchie and Roser, 2020).

### 2.2. Solar energy

The overall global capacity of solar energy utilisation has reached 177 GW, marking another record year of expansion with 40 GW of new capacity in 2021. Even though there was a considerable decrease in new installations across the EU, China reached the goals for distributed solar systems with a total installed capacity of 43 GW as of 2015. Around 60% of the worldwide solar PV capacity was installed within 3 years, from 2014 to 2017. Egypt has the highest daily typical irradiance values in Northern Africa, averaging from 2000 to 3200 $kWh/m^2/y$ with average sunshine of 9–11 h/d. According to the Egyptian government, the solar energy generation capacities could be extended further by 3500 MW by 2027 (Shouman, 2017). In 2020, solar energy in Egypt accounted only for 1.9% of the produced electricity, making it the country's second-highest renewable energy source. Egypt is the second-highest solar energy generator in Africa after South Africa, whilst it is the thirty-first worldwide (IRENA, 2021).

### 2.3. Wind energy

Many countries, including Denmark, Nicaragua, Portugal, and Spain, have the potential to achieve their electricity needs using wind energy (Europe Statistics, 2021). The USA leads the world wind energy generation while Asia is in second place, passing Europe's share for the seventh consecutive year. In Asia, China dominates the wind energy market holding a share of more than 70%. In 2001, Egypt generated 5.4 MW and 545 MW of wind power from Hurghada and Zafarana wind farms, respectively. At a reported cost of $6.8B, the Zafarana wind farm was completed in 2015, and then it had grown its capacity to 545 MW by 2018. As a part of the strategy to increase wind power to 7.2 GW by 2022, the Egyptian government intends to develop wind energy generation capacity during the next few years. In 2020, wind energy was responsible for 1.44% of the total produced electricity, making it the third-highest renewable energy source in Egypt (Shouman and Khattab, 2015).

### 2.4. Other renewable energy sources

Egypt would have an excellent potential for both biomass and geothermal usage in the future if the government encouraged investments in Feed-in-Tariff (FIT) as they did with solar energy. In 2020, all renewable energy resources other than hydro, solar, and wind technologies were responsible for only 0.16% of the country's total electricity generation (Shouman, 2017).

In summary, based on the IRENA report in 2018, only 15% of Egypt's electricity consumption has been supplied by renewable energy resources, including hydro energy. Nonetheless, the nation aims to satisfy 42% of its energy demand from renewable energy resources by 2035 which seems to be challenging. Therefore, the following sections discuss Egypt's potential in different renewable energy technologies and propose possible scenarios for utilising this potential to achieve this 2035 energy target.

## 3. Solar energy technologies (SET)

### *3.1. Solar thermal technologies*

The potential CSP locations across globe are identified using the global distribution of direct normal irradiance (DNI) (Trieb, 2009); where commercially feasible CSP plants should maintain a DNI of at least 2000–2800 kWh/m$^2$/y, which is equivalent to 5.5–7.7 kWh/m$^2$/d. Accordingly, the "Sun Belt" region is North Africa, the Middle East, the Mediterranean, and vast areas in the United States (Islam et al., 2018). Egypt is one of the Middle East and North African (MENA) region countries with an average direct solar radiation ranging from 5.5 to more than 9.0 kWh/m$^2$/d and a sunshine duration of duration of 9–11 h/d. In 1991, Egypt's solar Atlas was released, and this showed annual direct normal intensities ranging between 1970 and 3200 kWh/m$^2$. The Global Atlas platform of the International Renewable Energy Agency (IRENA) combines the recent irradiation potential with a new solar Atlas released in 2016; this also has recognised Egypt's high solar potential. Accordingly, Egypt is one of the most suitable regions globally to exploit solar energy for power generation and thermal heating applications (IRENA, 2018b). Solar energy farms should preferably be located near areas with a high DNI, which are indicated by the orange and red zones in Fig. 3; where the highest potential areas are the cities located along the Red Sea coast.

Various CSP technologies have been examined in Egypt to assess the feasibility of those technologies under the Egyptian climate conditions. Horn et al. (2004) investigated the technical and economic feasibility of

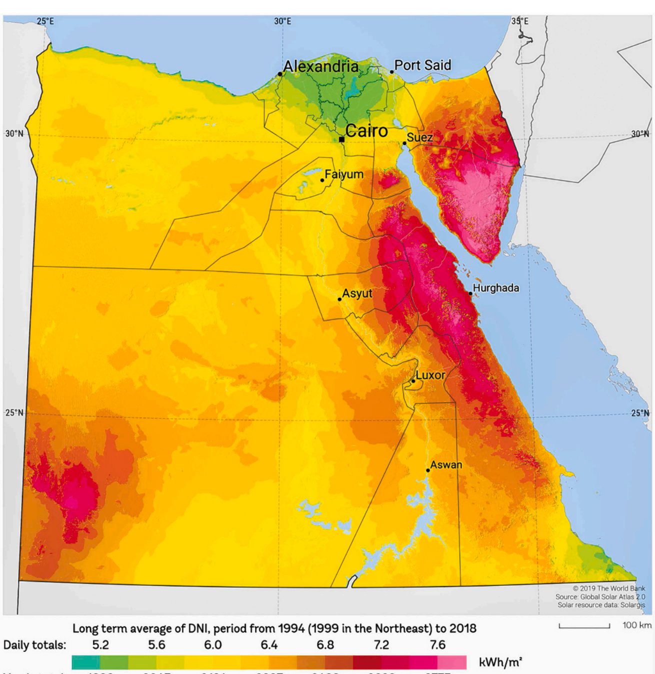



**Fig. 3.** Egypt's Solar Atlas with the details of direct normal radiation (Energy-Data).

using both parabolic trough collector (PTC) and the volumetric air receiver technologies with combined cycle power plants. Their analysis showed that integrating solar combined cycle power plant (ISCCS) systems with PTC systems is as attractive as integrating them with air tower systems; where similar electricity and incremental costs have been achieved for both technologies. The levelised electricity cost (LEC) of both technologies was 0.031 $/kWh; where the LEC for equivalent conventional combined cycles ranges between 0.03 and 0.04 $/kWh. Additionally, the levelised electricity cost of the solar portion of the ISCCS plant was around 0.10 $/kWh; which is below the actual typical solar LEC of 0.15 $/kWh. The possible reduction in $CO_2$ emissions with ISCC plants would allow us to meet the financial support provided by the World Bank with the support of global environmental facilities. Thus, ISCC plants were found to be beneficial in terms of both environmental and economic aspects for future renewable energy generation in Egypt (Horn et al., 2004). Likewise, a methodology has been introduced for integrating solar technologies in combined cycle plants in Egypt (El-Sayed, 2005). This analysis has presented the economic impact of solar energy as a function of cost/benefit ratio. As a result, it has been revealed that solar-power plants are technically feasible and contain a lot of positive features that are important for future power generation systems.

El-Haroun (2012) assessed the performance of solar chimney power plants located in several locations in Egypt, including Ras Banas, Hurghada, Suez, Kharga, Aswan and New Valley. This study showed that a solar chimney plant with a chimney height and diameter of 500 m and 50 m respectively and a collector diameter of 3000 m is capable of producing 18 −19.6 MW of power. This would result in yearly energy production of 1.6–1.7 × 10$^8$ kWh and maximum power output between 20 and 23 MW in June. Additionally, Bady et al. (2015) developed a model to evaluate the performance of a solar chimney located in Egypt. The DNI level in this location resulted in the generation of 4.8 MW and 2.6 MW during summer and winter, respectively, for a chimney with a height and diameter of 445 and 54 m respectively and a collector diameter of 1110 m. Mustafa et al. (2012) assessed the advantages of installing a solar power tower (SPT) system PS10 (which is similar to the one located in Sanlúcar la Mayor Spain) in Aswan, Egypt. The DNI in Aswan exceeded the DNI in Sanlúcar la Mayor, Spain, by 16% and installing a similar size/type of SPT plant in Aswan could provide 35.95% more power output. Additionally, it has been found that increasing the receiver height in Aswan by 45 m should increase the cost efficiency by 2.32%. To accommodate the operating conditions in Aswan, an innovative model has been applied to the plant, and it resulted in an increase in the optical efficiency and output power by 2.93% and 4.2%, respectively, compared to the basic PS10 model of Aswan. The final modified system achieved a power output greater than the plant located in Sanlúcar la Mayor Spain by 41.6%. Eventually, the feasibility analysis showed that the specific cost of energy produced by the SPT plant in Aswan would be less by 36.66% than that of the plant in Spain.

Further to the solar power tower, Abdelhady (2014) assessed the performance and economics of a stand-alone power plant equipped with 200,000 m$^2$ of parabolic trough field in El-kharga Oasis in Egypt. The plant has been designed to provide 6 MW and 21 MW of electric and thermal power, respectively, at an estimated LEC of 1.25 $/kWh (Abdelhady, 2014). The implementation of the proposed plant could reduce the requirement for fossil fuels by 7,291 t/y while reducing the $CO_2$ emissions by 71,712.22 t/y.

In the same context, Rady et al. (2015) proposed a conceptual design for a small scale solar power plant to power a medical centre in Egypt. The solar field has been developed to generate 120 kW for a summer day at a DNI of 900 W/m$^2$ and at a temperature of 30 °C; where a combined system of a parabolic trough collector (PTC) and linear Fresnel collectors (LFR) has been modelled at different conditions for both winter and summer days. They found that the power output of the PTC solar field allows a stable operation of both the Organic Rankine Cycle (ORC) and a thermally driven chiller (TDC) (Rady et al., 2015). Nonetheless, using a linear Fresnel reflector instead of a PTC reduced the operational hours by 50% and 30% for the ORC and TDC, respectively. It has been proven that the CSP multi-generation plants are potential candidates for power generation in the Mediterranean region (Rady et al., 2015). Similarly, Elmohlawy et al. (2018) evaluated the performance of PTCs as a part of a 108 MW solar thermal plant to be located in Aswan, Egypt. This analysis indicated a solar field efficiency of 73% and 67% in summer and winter, respectively. The performance of a 500 MW parabolic trough solar power plant has been investigated in three different locations in Egypt, comprising Aswan, Al-Arish and Hurghada with a 16-hour storage system; where this included the development of a complete solar thermal plant with a storage system. The results indicated that Aswan city is the best location for constructing a 500 MW solar power plant under the Egyptian climate (Mohamed et al., 2019).

Temraz et al. (2020) examined the performance of an existing ISCC power plant in Egypt under Kuraymat climate conditions at northern and eastern latitudes of 29°16′ and 31°15′ respectively, with DNI levels between 700 and 800 W/m$^2$. The solar field in these locations was found to have a low exergetic efficiency (17.8%). Integrating the solar field with a combined cycle resulted in a reduction in the thermal efficiency of the plant. Therefore, ISCC power plants could not enhance the overall thermal efficiency of Brayton cycle for developing economically feasible solar power plants. Later, Abdelhady (2021) investigated the performance of a solar dish (SD) power plant from both technical and economic aspects under the Egyptian weather conditions near Aswan city in the south of Egypt. The analysis results estimated 105 GWh/y of energy production from a 50 MW plant with a levelised cost of energy of 0.14/kWh. The installation of this plant could reduce the $CO_2$ emissions by 45 Mt together with a reduction in fossil fuel consumption of 21.64 thousand t/y.

Despite the huge potential of CSP technologies in Egypt and the positive impact of ISCC plants on the environment, only a single ISCC plant has been constructed in Egypt and put into commercial operation in 2011. A 140 MW solar thermal power plant integrated with a combined-cycle was constructed in the Kuraymat area, at northern and eastern latitudes of 29°16′ and 31°15′ respectively. This plant has been constructed with a 20 MW solar energy capacity, across a 644,000 m$^2$ solar field, with a 120 MW gas-fired combined cycle (IRENA, 2018b). In 2015/2016, 164 GWh/y was produced from the plant, and this plant could reduce $CO_2$ emissions by about 20,000 t/y by reducing conventional fuel consumption by about 10,000 t/y. Meanwhile, in 2015, Egyptian electricity transmission cooperation (EETC) and the new and renewable energy authority (NREA) initiated a tender for developing a new concentrated solar power system in Kom Ombo- Aswan, Egypt, with a power rating of 100 MW (IRENA, 2018b). In 2019, the Egyptian government announced a plan for building five CSP plants with a total capacity of 250 MW. This plan involves an investment of $1.25B, where 70% of the investment is expected to be supplied by international funding bodies (Newsroom, 2019).

In summary, the implementation of hybrid CSP technologies could reduce $CO_2$ emissions in Egypt by a significant level. Nonetheless, the current low natural gas prices discourage the public from using renewable energy technologies that could be slightly higher in price. Reducing the cost of CSP technologies by providing local components manufacturing should be one of the potential ways to enhance regional renewable energy development. More details on the potential of manufacturing CSP components in Egypt will be discussed in Section 3.1.1.

#### 3.1.1. CSP components manufacturing potential in Egypt

Egypt has key strengths for manufacturing CSP components, including low labour cost, low energy cost for the industrial sector, availability of raw materials such as glass and steel, and strong manufacturing capability (The world bank, 2022). Khalil et al. (2010) proposed an action plan to allow for the development of novel materials and local components design. This plan included assessing the available resources, system performance and grid integration to enhance the competitiveness and efficiency of renewable energy systems. The action plan has been set to supply 16% of the energy demand from RE technologies by 2022 and then to cover 50% of the nation's electricity consumption from RE technologies by 2050. Achieving this target would result in $CO_2$ emissions reduction by 209 Mt by 2022 (fossil fuel consumption by 78 Mt of oil equivalent (MTOE)).

Later, Fatouh et al. (2003) examined the design and performance characteristics of a PTC with the view of the local manufacturing of PTC systems. Then, they concluded that the local Egyptian market and manufacturing have the potential to implement these technologies successfully in Egypt. Similarly, Servert and Cerrajero (2015a) assessed the potential of CSP components manufacturing in Egypt (details are summarised in Fig. 4) while exploring the strategic challenges for developing the local solar energy industry (Servert and Cerrajero, 2015a). For the Egyptian labour, challenges have been summarised into four key aspects: the lack of technical knowledge related to the design and manufacturing of solar energy components, shortness of qualification for operation and maintenance, absence of specialised training centres for skills development, and the low productivity. Though facilities are available to manufacture steel and float glass, extra investments are needed to meet CSP glass needs. The Egyptian glass is normally produced with a relatively high level of iron content which does not fulfil the CSP glass requirements. Additionally, the Egyptian interest rate has been maintained above 10% from 2010 to 2015, reaching 16% in 2012. This makes the investment difficult for small and medium companies due to the high payback. It is worth emphasising that, based on the central bank of Egypt, the annual interest rate is kept below 10% in 2021 (Moneim, 2021) and hence, investments face fewer risks and difficulties for the time being. Extending the solar market should result in creating 3000 new jobs and increase the gross domestic product (GDP) by more than 300 M $/y (Servert and Cerrajero, 2015a).

### 3.2. Photovoltaic technologies (PV)

Solar photovoltaic (PV) systems have been used for various applications such as lighting, pumping, commercial advertising, desalination and cold storage in Egypt since the early 1980s. This technology has been used in remote locations for emergency roads and navigation lighting as well (IRENA, 2018b). Egypt has a great potential for using PV panels in most parts of the country due to the fact that Egypt is one of the sunbelt countries. The highest potential locations are around the Red Sea coast and Upper Egypt cities such as Luxor, Aswan, and Asyut, as indicated in Fig. 5.

EL-Shimy (2009) studied the best possible location to place a 10 MW PV plant connected to the grid in Egypt. NASA renewable energy resource website suggested that 29 sites in Egypt are the best PV plant locations due to the available high solar radiation throughout the whole year. According to the analytical results, PV plants could potentially achieve maximum and minimum capacity factors of 33.7% and 27.6% at Wahat Kharga and Safaga, respectively. At the same time, the energy production could be 29.493 GWh/y and 24.202 GWh/y, respectively. The average capacity factor and energy production for the 29 sites were 30.9% and 26.35 GWh/y respectively. Also, the financial analysis showed that constructing a PV plant would be profitable in any of the 29 locations, while Kharga has the highest GHG emission reduction, energy production and profitability. NASA renewable energy resource website confirms that the climate in Egypt is compatible with the PV modules' safety operating conditions, considering various parameters such as the long-term monthly average relative humidity, sun hours, solar radiation and air temperature (EL-Shimy, 2009).

Similarly, Sultan et al. (2018) examined the technical feasibility of 27 locations in Egypt for the installation of 100 MW PV power plants. Based on the analysis, Southeast Egypt, on the shore of the Red Sea, and the East of the Nile River were found to be the best locations for

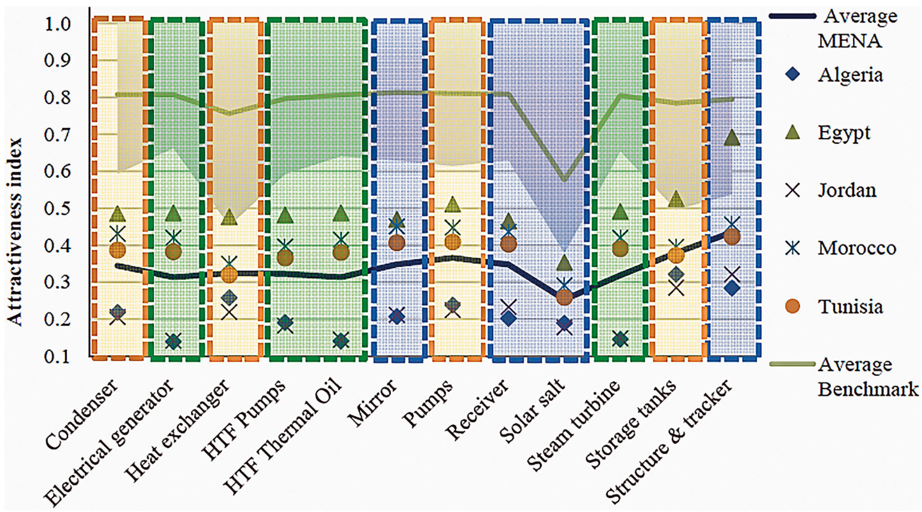



**Fig. 4.** Normalised attractiveness index for CSP component industries (Servert and Cerrajero, 2015a).

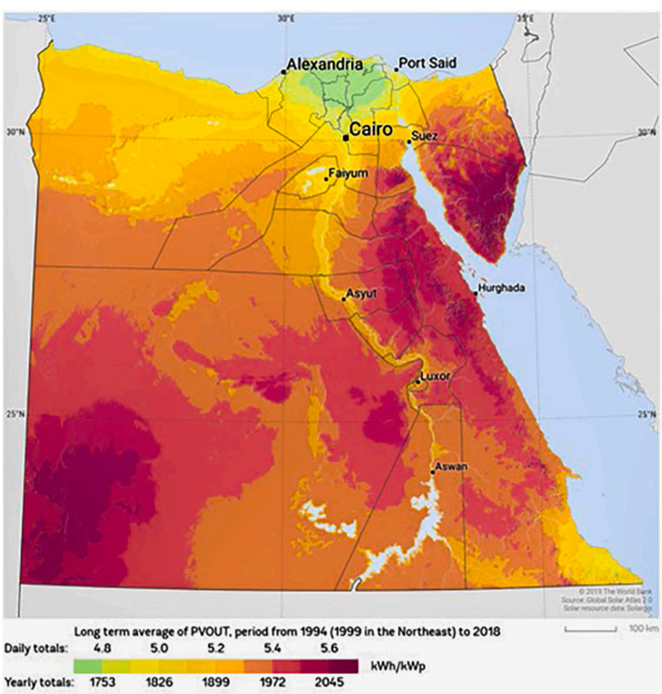



**Fig. 5.** Solar photovoltaic potential in Egypt (Energy-Data).

installing large-scale PV plants. The installation of a 100 MW solar plant could result in $CO_2$ reduction by 75,451.74 t/y. Shouman et al. (2016) studied the use of a standalone PV system in El Kharga Oasis for a typical family house with no access to the grid. They carried out an economic study for the system where the total cost of the system and electricity were found to be $3606.68 and $0.17/kWh, respectively. It has been concluded that the price of energy of a PV system in rural areas is competitive with the energy cost of conventional energy sources.

Rezk et al. (2019) presented a techno-economic assessment of using stand-alone PV-battery systems for agriculture applications in isolated regions, such as Alminya, Egypt, where diesel generators are expensive and grid connections are not available. They compared the energy cost of a stand-alone PVbattery to the use of diesel generators and grid extension alternatives. The analysis results have shown that using a diesel generator system resulted in higher energy cost, by 69.74%, compared to a PV-battery system and the best solution was found to be a combination of grid extension and PV-battery systems for rural areas in Upper Egypt. Similarly, Shouman (2017) represented a study for rural areas with no access to centralised electricity; where the research has focused on solar electricity and its economic use for electrification in villages. It has been found that the cost of installing a 1 kWh PV system is less than using diesel generators for rural residential electricity. Sadeq et al. (2020) compared the PV technology potential for four different locations in Egypt, including Hurghada, Aswan, Alexandria and Cairo. The comparison showed that Aswan has the highest specific yield and the capacity factor of 2062 kWh/kWp/y and 24%, respectively, and the lowest simple payback period and levelised cost of energy of 4.3 years and 0.56 EGP/kWh, respectively.

Gabr et al. (2020) evaluated the economics of a rooftop grid-connected PV system for residential buildings in Egypt. They found that the best system size (with the minimum Cost of Energy (COE) and Net Present Cost (NPC) for low, medium and high energy consumption) is a 20 kWp PV system with a maximum renewable fraction of 91.1%, 86.7% and 81.1% respectively. It has been found that the PV size should be increased, with the increase in load patterns, to minimise the payback period and then maximise bill savings. Later, Sadeq and Abdellatif (2021) developed an online pre-sizing tool for grid-connected PV systems. This tool allows people to study the feasibility of PV systems at any location of their choice, and this should help to increase the public interest in using PV systems without the need for consultation.

On a different matter, a comparative analysis has been conducted between concentrated solar thermal and photovoltaic technologies for power generation purposes in Luxor, Egypt, and Gela, Italy, from energy production and land use perspectives. CSP plants showed better feasibility in regards to both aspects in Egypt compared to Italy. The CSP plant located in Luxor, with a power rating of 3 MW, showed an energy cost of 0.162 €/kWh compared to 0.319 and 0.190 €/kWh for a CSP plant and a PV plant located in Italy, respectively (Desideri and Campana, 2014). CSP plants in El-Fayoum city showed different results in comparison to Luxor city. The average CSP technical potential was found to be 131 kW with a standard deviation of 10.4 compared to an average potential of 312 kW for PV systems with a standard deviation of 23 (Effat and El-Zeiny, 2017). As for the state of PV installation in Egypt, the total capacity of the installed PV system was 6 MW in 2013. In 2014, the feed-in-tariff (FIT) scheme was introduced by the ministry of electricity and renewable energy (MOERE) at a cost of $0.04/KWh, which encouraged the installation of PV systems. Then by the end of 2016, the total installed PV system capacity was increased by five times compared to the capacity of 2013. The Egyptian government started to effectively use PV panels to solve the electricity shortage by using them for straightforward applications such as streetlights.

#### 3.2.1. Grid-connected solar PV

New and Renewable Energy Authority (NREA) has completed the feasibility studies of two major photovoltaic plants in the Hurghada and Kom Ombo regions, with a capacity of 20 MW and 26 MW respectively. These plants are expected to produce approximately 32 GWh and 42 GWh respectively each year and should reduce approximately 40,000 t of $CO_2$ emissions together. Table 1 lists additional details of planned grid-connected projects in Egypt.

The solar park in Benban is a power plant complex composed of 41 solar power plants in Aswan, Egypt. The project consists of small PV plants developed by several independent companies with a total energy generation capacity of 1.8 GW and will be developed under NREA supervision. This project is a part of the Nubian Suns Renewable Energy FIT Programme announced in the last quarter of 2014 to support the Egyptian government to realise its plans for generating 20% of the nation's electricity demand from responsible renewable sources by 2022 (EgyptNews, 2019). The early phase of this project started with developing a 50 MW solar power plant by Infinity Solar, which began operations in March 2018 and was completed in 2019. This produces more than 4 TWh of power and contributes to reducing 2 Mt of $CO_2$ emissions annually (Ritchie and Roser, 2020).

#### 3.2.2. Distributed solar PV

Several initiatives have been initiated since 2013 for the installation of small-scale PV systems in Egypt. Initially, the Cabinet of Minister's initiative forced the use of PV systems on all government buildings' rooftops for over 1000 buildings, and this provided a total installed PV capacity of 20–30 MW (IRENA, 2018b). Later, in the middle of 2014, the first phase of the FIT has been adopted and the installation of distributed PV systems on the grid began, with a total installed capacity of 300 MW. In 2015/16, NREA implemented several off-grid PV projects, in cooperation with the United Arab Emirates, for electricity production for remote communities with a total capacity of 32 MW; including 6942 stand-alone systems with a total capacity of 2 MW (IRENA, 2018b).

Solar PV distribution technology is developing quickly in Egypt due to the development of several pipeline projects; where industries and businesses can link PV systems on a small scale to meet their increased energy demand and hence reduce their energy costs. It is estimated that Egypt has more than 125 installed solar PV power plants with a capacity of 9000 MW accompanied by $CO_2$ emission reductions by approximately 9 t/y (Egypt-PV, 2021).

In summary, several locations can be identified for PV plants in Egypt with a great generation capacity potential for areas between the Red Sea coast and cities like Asyut, Luxor and Aswan. The construction of Benban Solar park helped Egypt to become one of the leading countries in using clean electricity from PV panels. A major portion of potential areas identified for the PV technologies is within the deserts. Hence, those lands can potentially be used for electricity production purposes if the government plans to start new initiatives such as the Benban solar park.

**Table 1**
Grid-connected PV plants in Egypt (IRENA, 2018b).

| Project | Size (MW) | Statues |
|---|---|---|
| Benban Solar Park | 1465 | Operational |
| PV Net Metering | 100 | Operational |
| West Nile | 200 | Operational |
| Decentralized PV systems | 32 | Operational |
| Private Sector | 200 | Under construction |
| Kom Ombo | 26 | Under construction |
| West Nile | 600 | Under Development |
| Kom Ombo | 50 | Under Development |
| Zaafarana | 50 | Under Development |
| Private Sector | 200 | Under Development |

#### 3.2.3. Solar water heating

The annual energy report declared that the residential sector accounts for 47% of the total energy consumption in Egypt, as shown in Fig. 6. Solar water heating (SWH) constitutes an excellent potential for reducing energy consumption from conventional energy sources such as the consumption of electricity, diesel or natural gases (Abdrabo and Soliman, 2008). Egypt has a solar water heating potential of around 16 PJ/annum for chemical, food, textile and agriculture industries operating at temperatures below 100 °C with a collector area of 4.6 M $m^2$ (Sharma et al., 2017). Several researches focused on investigating the feasibility and the performance of different solar water heating systems in Egypt while investigating the potential locations for implementing this technology. A summary of the findings reported by the existing studies on developing SWH systems under the Egyptian climate is presented in Table 2.

The feasibility of solar water heating and cooling systems has been investigated in different locations in Egypt, including Aswan, Kharga, Asyout, Cairo and Matruh in 1994. This study showed that the solar water heaters are feasible for all locations based on the calculated life cycle savings. It has been found that the optimum solar collector area varies significantly with the location in Egypt (Sorour and Ghoneim, 1994). Unfortunately, Abdrabo and Soliman (2008) found that SWH is hard to compete with conventional heaters owing to the low demand level for the technology and the lack of market incentives in the Egyptian market. This is due to the previous installation of low-quality SWH, and the low quality, lack of reliability and durability of such heaters had a negative effect on the SWH sales recorded over the period from 1994 to 1997 (Abdrabo and Soliman, 2008).

Calise et al. (2021) provided a techno-economic assessment for energy efficiency options in Naples, Italy and Fayoum, Egypt. The proposed systems are based on driving domestic water heating using evacuated tube collectors (ETC) and PV panels. The proposed energy measures resulted in 67% and 58% primary energy savings in Fayoum and Naples districts respectively. The higher savings achieved in Egypt are due to the higher solar radiation in Fayoum compared to Naples. The payback period in Naples was 5 years compared to 23 years in Fayoum due to the subsidised cost of natural gas in Egypt. The performance of solar water heaters has improved significantly for both passive and active systems with the introduction of nanofluids to be used as a working fluid, which could encourage their use in the next few years (Eltaweel and Abdel-Rehim, 2021).

As for the environmental impact of the SWH technologies, Reda et al. (2016) examined the optimisation of a solar-driven adsorption cooling system for a residential application located in Assiut, Egypt. The proposed system resulted in lower carbon dioxide emissions; the $CO_2$ level has been reduced from 1062 $kgCO_{2eq}/kWc$ (for a system entirely driven by natural gas) to 193 kg $CO_{2eq}/kWc$ for a system driven by solar energy.

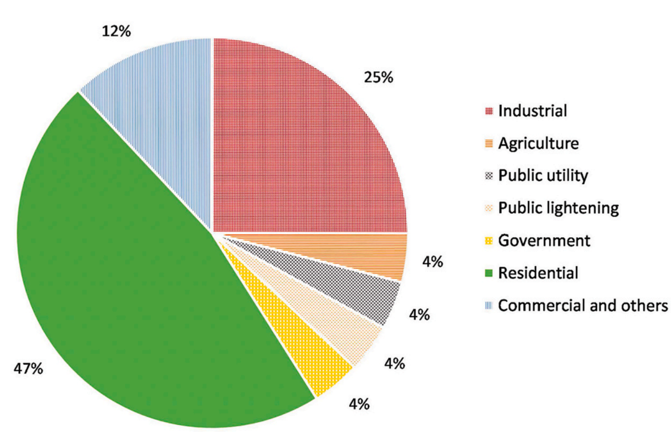



**Fig. 6.** Annual report 2015/16 by the Egyptian electricity holding company (IRENA, 2018b).

**Table 2**
A summary of the findings reported by previous studies on solar water heating technologies in Egypt.

| Description of the study/Remarks | Location | References |
|---|---|---|
| Examined the optimum parameters for solar water heating system | Alexandria | Ammar et al. (1989) |
| Proposed a design for solar water heating system that fulfils the energy needs of water and space heating for a house | Alexandria | Ghoneim et al. (1993) |
| Investigated the feasibility of solar water heating and cooling systems | Aswan, Kharga, Asyout, Cairo and Matruh | Sorour and Ghoneim (1994) |
| Investigated the aspects of choosing the tilt angle for solar flat plate collectors | Helwan | Elminir et al. (2006) |
| Assessed the economic aspects of solar water heaters | – | Abdrabo and Soliman (2008) |
| Proposed a typical water and space heating solar system for a hospital building | Sante Catherine | Fahmy et al. (2010) |
| Examined the optimisation of a residential scale solar driven adsorption cooling system | Assiut | Reda et al. (2016) |
| Assessed the solar industrial heating in many countries including Egypt | – | Sharma et al. (2017) |
| Integrated a tubular daylight device with SWH | Cairo | Marmoush et al. (2018) |
| Investigated the performance of using nanofluid as the working fluid in a thermosyphon solar collector under the Egyptian weather | Cairo | Eltaweel and Abdel-Rehim (2019) |
| Introduced an enhancement for a hybrid solar desalination system | Alexandria | Abd Elbar and Hassan (2020) |
| Investigated the potential of domestic solar hot water usage in Egypt | – | Shiqwarah et al. (2020) |
| Presented an assessment study for the productivity, exergy, exergoeconomics, and enviroeconomics of hybrid solar distiller using direct salty water | Upper Egypt | Hassan et al. (2021) |
| Examined a hemi-spherical solar collector under the Egyptian climate | Cairo | Ebaid et al. (2021) |

Based on the aforementioned studies, solar heating systems constitute promising alternatives for the residential sector in Egypt by reducing the consumption of conventional energy resources and $CO_2$ emissions.

### 3.3. Solar desalination systems

Desalination plants in the MENA region constitute around 75% of the world's desalination plant capacity (Al-Otaibi, 2015). Around 35 $Bm^3$/y of water consumption is supplied by non-sustainable water sources, including groundwater and fossil fuel desalination. Meanwhile, the global water deficit is expected to reach 155 $Bm^3$/y by 2050 (DLR, 2005), and Egypt will be affected by it. Egypt is under water scarcity limit owing to insufficient resource management. Additionally, the Nile River share of 5 $Bm^3$/d is threatened by GERD (Walsh and Sengupta, 2020). Around 5.8 and 1.5 M people are still living in rural and urban slums, respectively, where the accessibility of spring water is limited (UNICEF, 2017). The Egyptian government has already initiated some programs for water desalination to overcome this problem (Amin et al., 2020a). Solar desalination systems are promising candidates for providing sustainable water sources in Egypt, considering its CSP potential (32 GW) and available coastal areas on the Mediterranean and the Red Sea (El-Sadek, 2010). In this context, several researches focused on investigating the feasibility and the performance of different solar water desalination systems in Egypt, as well as identifying the potential locations suitable for this technology. As a result, some promising locations for solar water desalination have been identified as follows:

- Along the Red Sea coast, brackish water with total dissolved solids (TDS) of 1000 ppm
- Along the northwest coast, brackish to saline water with TDS of 1000–10,000 ppm
- Sinai coastal zone and wadis, brackish water with TDS of 1000 ppm
- The northern desert (El-Sadek, 2010).

A multi-criteria analysis has been conducted to choose the optimum locations for solar water desalination. This assessment was based on some of the key factors such as solar radiation, transportation networks, topography, land cover/land use, saline water surfaces parameters and population (Mohamed, 2020). As a result, vast areas in the western desert and around the coastal areas were found to be suitable for solar desalination stations. Around 24.6% of the land in Egypt was considered appropriate for solar desalination stations accounting for 24,0842 $km^2$ near the saline water surfaces. Additionally, up to 17% of the land (166, 146.36 $km^2$) was classified as a moderate suitability. The remaining 58.4% of the land was classified with low suitability for solar desalination plants.

Upper Egypt's big cities, including Asuit, Sohag, Aswan, Qena, ElKharga oasis and Toshka are gifted with the highest potential for groundwater solar desalination, as indicated in Fig. 7. The West Delta area is selected for surface water and the Mediterranean Sea for desalination (Salim, 2012). These locations were specified based on a multi-criteria analysis, including the effects of aquifer depth, solar radiation, aquifer salinity, distance from the Delta and the Nile Valley, dunes, the incidence of flash floods, rock faults, and seawater intrusion in the North Delta.

In the meantime, various solar desalination technologies have been investigated for research purposes in Egypt. Reverse Osmosis (RO) systems were suitable for development in Sinai and the Gulf of Aqaba region, where PV panels can replace the diesel generators for providing the power needed. Abou Rayan et al. (2001) developed a RO system to supply the anticipated water consumption to satisfy the demand of over 40 hotels, and touristic resorts under construction, which accounts for 2000 $m^3$/d . Additionally, RO water desalination systems, driven by a

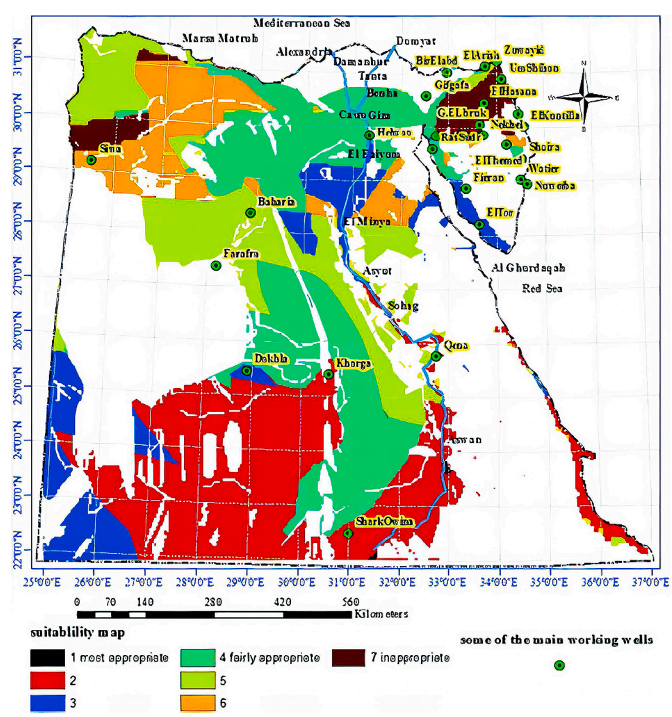



**Fig. 7.** Suitable locations for groundwater solar desalination in Egypt (Salim, 2012).

small PV system, were found to produce water at a cost of 3.73 $\$/m^3$(Ahmad and Schmid, 2002).

A stand-alone reverse osmosis desalination unit powered by a PV system has been installed in remote areas in Egypt. This unit can desalinate brackish water and saline water with a salinity level of up to 25,000 ppm and produces 3–5 $m^3$/d of freshwater. Two main challenges were identified with this system: (i) the first challenge is the intermittent and variable solar power demands the installation of batteries in some remote areas, and (ii) the second challenge is the battery cost that adds to the PV/RO system results in a water cost of 5.6–9.3 LE/$m^3$ (Abo Zaid, 2015). Likewise, the price of solar PV technologies was found to be higher than solar thermal technologies for desalination plants. Hence, its usage is limited to small scale applications in remote areas in Egypt (Lamei et al., 2008).

Further to the above studies, other desalination candidates have been integrated with renewable energy technologies. For example, modified solar still has been integrated with a parabolic trough collector and found to offer higher water productivity for the system, where the freshwater productivity could be increased by 18% (Abdel-Rehim and Lasheen, 2007). Similarly, a multi-effect distillation system has been coupled with the Clausius-Rankine cycle powered by a solar central receiver system in Al-Kosseir, Egypt (Servert and Cerrajero, 2015b). The effect of the increase of heating steam temperature and heat transfer surface area on the annual electricity and water production has been studied using weather and seawater data for the selected location. It has been found that the annual water production can be more than doubled for a heating steam temperature increase of 25 °C from 65 °C to 90 °C. Nonetheless, this resulted in a reduction in the electricity generation potential by 11%. Additionally, the water production rate increased by 30% due to increasing the plant's heat transfer surface area, which sacrificed the electricity production by only 1% (Servert and Cerrajero, 2015b). Likewise, a Multi-Effect Distillation (MED) and RO systems have been integrated with a PTC solar system in Ras Gharib. It has been found that integrated systems are technically and economically feasible. A solar field of 250,000 $m^2$ can produce a total of 22,775 $m^3$/d of freshwater and 15.5 MWe of power based on the climate conditions in July. The water has been produced at 0.442 $\$/m^3$ and 0.416 $\$/m^3$ for the MED and RO plants respectively (Moharram et al., 2021).

Offshore desalination plants have also been examined for the technology implementation in Egypt. Amin et al. (2020b) investigated the suitability of floating desalination plants (FDP) versus the commonly used floating production storage and offloading systems (FPSO) in Ras Ghareb city in Egypt. It has been concluded that a FDP results in better motion responses compared to a FPSO in the same wavebands. Amin et al. (2021) extended the previous study with a proposed hydrodynamics-based design to support the offshore desalination plant and a wind turbine. Similarly, the feasibility of offshore FDP integrated with marine renewable energy has been assessed in Ras Ghaleb, Egypt (Amin et al., 2020a). It has been concluded that a mobile FDP is suitable for coastal areas in Egypt with no need for infrastructure development to the national grid for water and power production. The proposed FDP concept has proven to be feasible for meeting the required stability and performing efficiently under Egyptian environmental conditions. A summary of the previously reported works focusing on solar desalination systems in Egypt is presented in Table 3.

Some other countries, like Pakistan, also face the water scarcity problem similar to Egypt; where using improved irrigation systems and low cost RE electricity (i.e. the desalination sector powered by RE) have been found to help in facing this problem (Caldera et al., 2021). Given that Egypt has a great potential for solar water desalination, a similar analysis should be carried out to investigate the potential of powering the desalination sector in Egypt with RE resources. This should simultaneously solve water and energy shortage problems in Egypt while reducing $CO_2$ emissions.

**Table 3**
A summary of the previous works focusing on solar desalination systems in Egypt.

| Description of the study/ remarks | Location | References |
|---|---|---|
| Integrated solar still with a reverse osmosis (RO) system for future applications in supplementary irrigation | along the Red Sea coast, along the northwest coast, Sinai coastal zone and wadis | El-Kady and El-Shibini (2001) |
| Investigated the feasibility of installing solar desalination units | Sinai and Gulf of Aqaba | Abou Rayan et al. (2001) |
| Investigated the feasibility of desalinating brackish water using PV technologies | rural areas | Ahmad and Schmid (2002) |
| Introduced two modifications for solar desalination systems | Cairo | Abdel-Rehim and Lasheen (2005) |
| Introduced a modification for an existing solar still desalination system | Cairo | Abdel-Rehim and Lasheen (2007) |
| Conducted a cost analysis for desalination plants based on both PV and solar thermal technologies | remote areas | Lamei et al. (2008) |
| Demonstrated the importance of seawater desalination for water security in Egypt | Egypt | El-Sadek (2010) |
| Conducted a feasibility analysis for an integrated hybrid concentrating solar power (CSP) and seawater desalination (DES) system | Mediterranean countries including Egypt | Moser et al. (2011) |
| Investigated the promising locations in Egypt for solar water desalination based on the solar radiation | –. | Salim (2012) |
| Evaluated the thermodynamic characteristics of coupling solar power plants and desalination units | Port Safaga, Egypt | Blanco et al. (2013) |
| Examined the feasibility of a stand-alone reverse osmosis desalination unit powered by photovoltaic systems | Northwest coast of Egypt | Abo Zaid (2015) |
| Introduced a multi-effect distillation system coupled powered by a solar central receiver system | Al-Kosseir, Egypt | Servert and Cerrajero (2015b) |
| Installed a water desalination system driving water for a small green house hydroponic cultivation | –. | Khattab et al. (2016) |
| Conducted an energy and exergy analysis for a solar still | New Borg El-Arab City, Alexandria, Egypt | Yousef et al. (2017) |
| Evaluated the performance of a combined solar tower power plant with low temperature desalination systems | ELGouna, Egypt | Wellmann et al. (2018) |
| Conducted a multi-criteria analysis model for groundwater management | Moghra Oasis, Egypt | Sayed et al. (2019) |
| Highlighted the suitable areas for the installation of future solar desalination stations | Western desert and around the coastal areas | Mohamed (2020) |
| Introduced a novel mobile floating desalination plant | Ras Ghareb city in Egypt | Amin et al. (2020b) |
| Investigated the performance of a hybrid renewable energy system used to drive a small RO desalination | Ras El Bar city, Egypt | Ibrahim et al. (2020) |
| Developed a model to investigate the feasibility of integrating a CSP plant with water desalination systems | Ras Gharib, Egypt. | Moharram et al. (2021) |
| Reviewed desalination processes integrated with renewable technologies | remote areas | Kashyout et al. (2021) |

## 4. Wind energy technologies (WET)

Wind energy resources have been evaluated in various locations in Egypt. The new wind atlas of Egypt, which was published in 2016 on IRENA's Global Atlas platform, is presented in Fig. 8a and 8b. Along with the developed wind maps, numerous studies have previously examined potential wind energy plant locations in Egypt. Hamid (2011) investigated cost-effective wind farm locations in Egypt by developing a new geographic information system (GIS) linked to a multi-criteria decision support system. The results of this study suggested that 30% of the Egyptian land is suitable for harnessing power from the wind.

The characteristics of available wind energy have been presented for three locations in Egypt, namely, Marsa Matruh, El-Suez and EI-Kharjah (Rizk, 1987). The three locations proved to have an average annual wind speed ranging from 4.6 to 5.5 m/s at 20 m above the ground level and average energy between 638 and 1127 kWh/m$^2$ (Rizk, 1987). Similarly, the wind energy potential for other fifteen locations was investigated over both coastal and interior areas, including Hurghada, Zafarana, Abu Darag, Aswan, Al-arish, Assuit, Matruh, Rafah, Alexandria, Cairo, El Quiser and Elbaharia. The average power density was found to be ranging from 30 to 467 W/m$^2$. It has been concluded that the Mediterranean Sea and the Red Sea are promising locations for wind farms and some interior regions such as Aswan, El Dabaa, Cairo and Elkharga. The mean shape (k) and scale factors (c) were found to be 2.45, and 9.16 m/s, respectively, for the Red Sea coast stations, and 1.31 & 3.74 m/s and 1.28 & 4.7 m/s are for the interior and Mediterranean coast stations, respectively (Mayhoub and Azzam, 1997).

Work by Ahmed (2012) spotted El-Dakhla and Kharga as potential locations for wind power generation projects, having a power density of 377 and 333 W/m$^2$, respectively, at an elevation of 70 m. The annual mean speeds were found to be 5.2 and 6.5 m/s for both locations (at heights of 10 and 24.5 m) respectively. On the contrary, the feasibility of installing a stand-alone wind energy technology have proven that Cairo has low wind resources capacity. Despite the low wind resources, a wind project in Cairo could be financially feasible if the annual electricity price experienced an increase of 5% coupled with a discount rate of 8% (Hamouda, 2012). (Shata and Hanitsch, 2006) found that the Mediterranean Sea in north Egypt is a suitable location for wind energy extraction as the average wind ranges between 5 and 6 m/s.

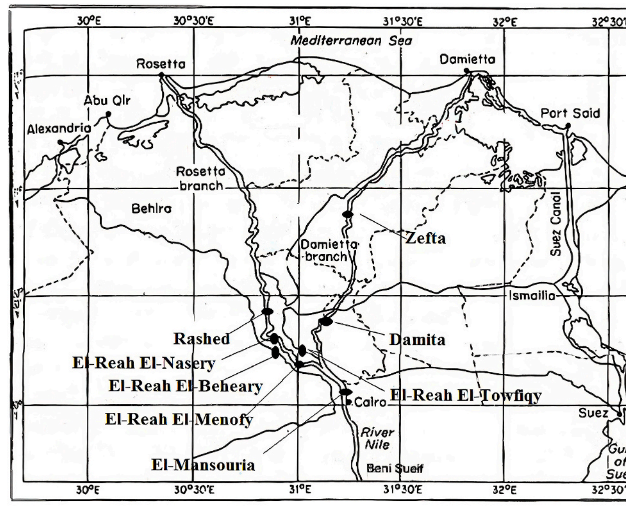
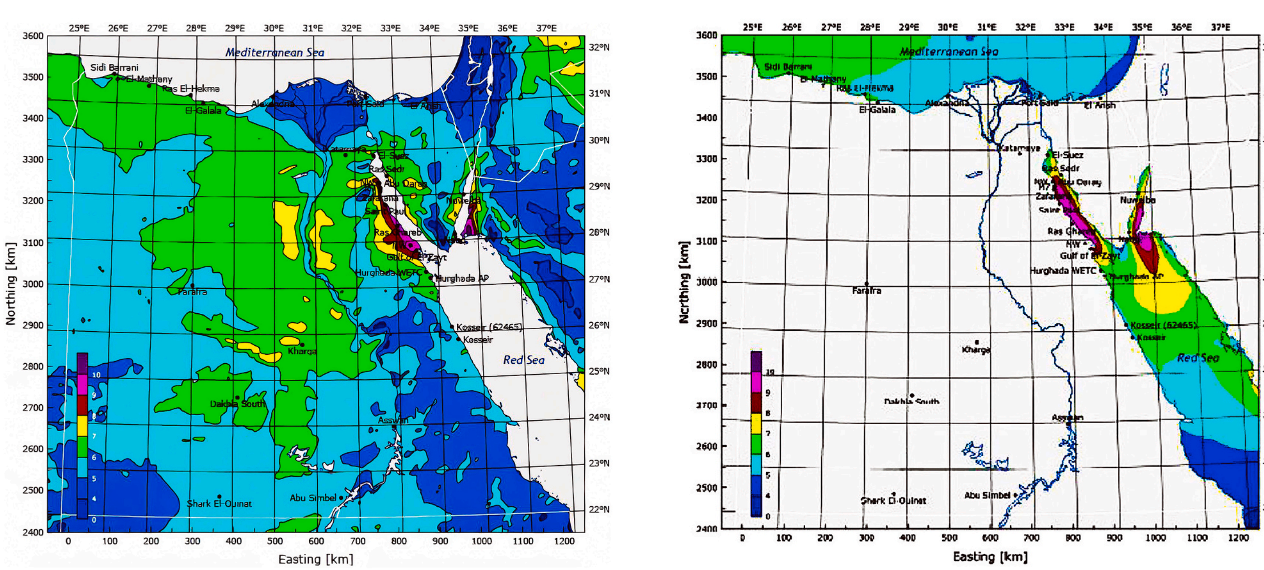



Fig. 9. Potential locations of small hydropower plants in Northern Egypt (Hatata et al., 2019).

Additionally, Sidi Barrani, Marsa Matruh and El Dabaa located in this region are suitable for wind-based electricity generation. The shift in power density along the coast of the Mediterranean Sea was insignificant. Power densities ranging from 180 to 230 and 260–330 W/m$^2$ were obtained at 30–50 m above the ground level at Sidi Barrani, Mersa Matruh and El Dabaa. Hence, the installation of wind farms with capacities of up to 1 MW would be feasible at these locations.

The wind energy potential has been evaluated at other locations along the Mediterranean Sea coast, including Port Said and Sallum, Dekheila and El-Dabaa. Power densities were 180–210 and 120–140 W/m$^2$ at elevations ranging between 30 and 50 m, above the ground level, for Port Said, Sallum, and Dekheila respectively. This energy level allows for applications such as water pumping and electricity generation by installing wind turbines of up to a 100 kW power rating. A cost analysis has been carried out for a 1 MW wind turbine to be installed in El-Dabaa, and competitive pricing with the other stations along the coast has been obtained; with a specific cost of 0.02 € per kWh (Shata and




(a) (b)

Fig. 8. (a) Egypt's wind atlas; colour bar from dark blue to dark purple stands for the different wind speeds where the highest and lowest speeds are donated by the purple and blue colours, respectively at a 50 m altitude, (b) Offshore wind resource map of Egypt: mean wind speeds at 50 m altitude (Global Energy Network Institute). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Hanitsch, 2006). A similar type of analysis conducted for Port-Said city in Egypt reported an average wind speed ranging between 4.6 and 5.8 m/s at 19–50 m height. Given that the minimum required wind speed for operating wind farms in Egypt is about 3 m/s at a height of 20 m and 2.54 m/s at 10 m, Port-Said city's wind speeds easily meet these requirements. The available power densities were found to be suitable for electricity generation for medium-sized wind turbines (150–600 kW) throughout the year (Lashin and Shata, 2012).

Likewise, the possibility of constructing a 45 MW wind farm has been investigated in Aswan with 30 wind turbines with each rating of 1.5 MW (Ahmed, 2011a). In Aswan, the wind blowing speed ranges from 5.3 to 6.1 m/s for 79% of the time over the year at a 10 m elevation and the annual wind energy power density was found to be 363 kWh/m$^2$ at a 100 m height. Therefore, it has been concluded that a power rating greater than 1 MW at 100 m height is suitable for this location and the wind turbine "Fuhrländer FLMD 77" with a power rating of 1.5 MW has been chosen for this location. A power output of 152 GWh/y should be generated from the 45 MW farm with a capacity factor of 39% and at a cost of 2 €cent/kWh; it is considered to be economically feasible considering the national tariffs.

Ahmed and Abouzeid (2001) presented a study to utilise wind energy in coastal and remote areas in Egypt. The study revealed that economical and feasible implementations for wind energy could be done by two means. The first method is to implement small to medium wind turbines with capacities ranging between 100 and 200 kW and integrated with other sources for North Coast and Sharq El-Ouinat. The second option is through the implementation of large scale wind-driven generators on the Red Sea coast from Zaafarana to Hurghada. In the west southern Egyptian desert, at Sharq El-Ouinat City, the wind speed was found to blow at an average speed of 6.5 m/s at 10 m altitude with a minimum and maximum speeds of 5.4 and 7.4 m/s during September and December respectively. Additionally, the wind speeds at Shark El-Ouinat City were above the cut-in speeds for 84% of the whole year and Sharq El-Ouinat city could offer great potential in harnessing wind energy. A power density of 582 kW/m$^2$, at 100 m hub height, was achieved at Sharq El-Ouinat, which provides a greater power level than several stations located in the United States, Great Britain, Brazil, Russia and Holland. Eventually, a 150 MW wind park is proposed to be installed in Sharq El-Ouinat city. This farm should result in a capacity factor of 56% with an annual power gain of 730,791 MWh/y. This farm could also produce economically feasible electricity at the cost of 1.3 € cent/kWh; which could be competitive with the wind energy prices internationally (Ahmed, 2018a).

The average annual wind speeds have been found to be 8.3 m/s in Ras Ghareb at a 10 m height with maximum and minimum speeds of 10.2 and 6.4 m/s in June and January respectively. A wind speed of 5 m/s is available for 54% of the whole year, at a 10 m height, and a speed of 12.5 m/s is available for 51% of the year at an altitude of 24.5 m. Also, the wind at Ras Ghareb blows approximately 77% of the time over the year from the NNW to WNW directions. This wind behaviour is associated with a high scale parameter (k) based on the Weibull parameters for all seasons over the year except for the winter. Overall, an average power density of more than 360 W/m$^2$ could be obtained annually at a 10 m height. Therefore, Ras Ghareb also possesses a high potential for wind-based electricity generation (Ahmed, 2011b).

The wind energy potential across the gulf of the Suez region of Egypt has also been investigated (EL-Shimy, 2010). It has been found that the 600 kW "NORDEX" is the optimal commercial wind turbine generator (WTG) for El-Zafarana and Ras Ghareb sites. The estimated turbine-performance-index (TPI), normalised average power output and capacity factor were equivalent to 0.5862, 0.7881 and 0.5125, respectively, for El-Zafarana site compared to 0.5951, 0.6998 and 0.5859 for Ras Ghareb site. Similarly, a wind turbine with a 600 kW capacity was identified as the optimal WTG for the Gulf of EL-Zayt site with an estimated TPI, normalised average power output and capacity factor of 0.5953, 0.7425 and 0.5525, respectively.

In 2012, Saleh et al. (2012) assessed different methods, including mean wind speed, modified maximum likelihood, maximum likelihood and graphical and power density methods, to select the optimum method for estimating Weibull distribution parameters for the wind speed in the Zafarana wind farm, and Suez Gulf, in Egypt. Both the maximum likelihood and the mean wind speed methods were suitable for wind speed distribution analysis in El Zafarana site. El-Sayed (2002) developed a probabilistic approach of wind-generated electricity to evaluate the capacity credit of a 600 MW wind farm located in El Zafarana. The study concluded that the 600 MW wind farm is feasible from both economical and environmental perspectives, with a total generation capacity of 2600 GWh/y.

Likewise, Ahmed (2018b) assessed the wind characteristics and energy potential of multiple locations along the Gulf of Suez and Aqaba at the northern Red Sea, including Ras Seder, El Tor, Abu Redis and Nabq. The analysis results confirmed that Ras Seder and Nabq are the optimum locations with a potential wind energy capacity of around 314 and 249 kWh/m$^2$ at a 50 m height, respectively. Hence, both of these locations can be specified as international regions for onshore wind power generation using turbines with a scale of a few hundred MWs. The potential of installing a 580 MW onshore wind farm has been assessed, and this could produce 2335 GWh/yr at an average cost of \$0.0184 to \$0.0422; which is less than the current local electricity tariff. Ramadan (2017) presented a resource assessment for harnessing wind power in Sinai Peninsula, Egypt, designing a 200 MW wind turbine to be operated at an average wind speed of 7.8 m/s and an elevation of 80 m. This 200 MW wind farm has proven to achieve a positive Net Present Value (NPV) with an international return rate (IRR) of 12% at an 8% discount rate. Abd El Sattar et al. (2020) evaluated the levelised cost of wind energy considering multiple locations in Egypt. The LCOE was found to vary between 0.052 − 0.041 \$/kWh, 0.121 − 0.095 \$/kWh and 0.941 − 0.326 \$/kWh for regions I, II and III respectively, Where regions I, II, and III are the locations with wind speed ranges of 8 − 11 m/s, 6 − 8 m/s and ≤ 6 m/s, respectively.

Abdelhady et al. (2017) provided an assessment of the levelised cost of electricity of 7 MW offshore wind energy facilities located along the Mediterranean Sea in Egypt. The analysis revealed that the energy could be harvested with minimum and maximum production at Alexandria and El-Dabaa stations with 55% and 63% capacity factors, respectively. A power density between 577 and 1056 W/m$^2$ has been achieved at a 100 m . The offhore system resulted in a LCOE of about 0.075–0.079 \$/kWh. Likewise, another work on offshore wind energy identified approximately 33 GW of wind power across the Red Sea region (Mahdy and Bahaj, 2018).

Energy storage systems are widely considered for wind energy technologies to stabilise the energy supplies and tackle the intermittent power production. Principally, various storage systems can be integrated with wind technologies including underground pumped-hydroelectric energy storage (UPHES), pumped-hydroelectric energy storage (PHES) systems, compressed air energy storage (CAES), battery energy storage (BES), flywheel energy storage (FES), flow battery energy storage (FBES), supercapacitor energy storage (SCES), superconducting magnetic energy storage (SMES), thermal energy storage systems (TESS) and hydrogen energy storage systems (HESS) (Leahy et al., 2009) (see Section section 12 for more detail son HESS). In this regard, ElBeheiry (2011) developed a bi-directional process to store and expand energy simultaneously or separately using a mechanically-actuated compressor. A similar system has been proposed by Ramadan et al. (2016) to be used in Suez, Egypt. This study has been concerned with using CAES systems to stabilise the energy supply in the Egyptian grid. The addition of a CAES system could provide the energy during the periods at which the wind energy is less than the grid load demand. Such a system could play a significant role in power intermittency situations that the Egyptian grid might face in future with the increase in wind energy share of the national power supply, which is at 12% at present. Ultimately, the potential of integrating wind energy into the Egyptian grid during critical load variations has been investigated (Attya and Hartkopf, 2013). The results confirmed that the system performance is at an acceptable level with a medium wind energy penetration to the grid considering frequency drops during the operation (Attya and Hartkopf, 2013). Although wind energy is considered a clean energy source, there are drawbacks to this technology (more details are discussed in Section 15). Hence, advances in technology should help to narrow/avoid these drawbacks (Chowdhury et al., 2022).

In summary, Egypt is gifted with enormous wind energy potential in multiple locations where the wind blows at speeds above the cut-in speed required for wind farms. These potential locations include Marsa Matruh, Sidi Barrani, El Dabaa, El-Suez and EI-Kharga, Ras Ghareb, Zafarana, Shark El-Ouinat, Port-Said city together with several other cities. A summary of potential locations with high wind energy capacities is presented in Table 4, together with key characteristic parameters.

To exploit the immense potential of wind energy in Egypt, the first wind farm was constructed in Hurghada in 1993 with a total installed capacity of 5.2 MW. Afterwards, the NREA developed a series of large-scale wind farms with a capacity of 545 MW in 2010/2011 in cooperation with multiple countries, including Japan, Germany, Spain and Denmark. Then, this capacity increased to 750 MW by November 2015, under an engineering, procurement and construction (EPC) scheme in Zaafarana and Gulf of El Zayt. This scheme provided an energy production of 260 GWh and 2058 GWh in 2001/02 and 2015/16, respectively. Due to the installation of these farms, fuel savings were increased from 58 Mtoe to 432 Mtoe from 2001/02 to 2015/16. The $CO_2$ emissions have also been reduced by 0.143 and 1.131 Mt in 2001/02 and 2015/16, respectively (IRENA, 2018b). As per a signed memorandum of understanding between Siemens and the NREA in April 2015, several projects accounting for a generation capacity of 2000 MW are being developed by Siemens. The details of these planned wind projects until 2023 are presented in Table 5.

It is worth noting that the housing ministry demonstrated the establishment of a new project called ‘El-Alamein city’ at the heart of the North West Coast. El-Alamein city project is located within the administrative borders of Marsa Matruh governorate and 48 km from the international road connecting Alexandria and Matruh. This project has been designed to accommodate more than 400,000 inhabitants (EgyptToday, 2019). Hence, high-level energy demand should be anticipated at these locations. Off-shore wind farms could be suitable in this regard to avoid the possible noise and operational effects of wind farms nearby residential and tourist areas.

**Table 4**
A summary of potential wind energy locations in Egypt.

| Location | Power density (W/$m^2$)/height (m) | Wind speed (m/s)/height (m) |
|---|---|---|
| Aswan (Ahmed, 2011a) | 363.0/100.0 | 5.3–6.1/10.0 & 6.9–7.5/ 50.0–70.00 |
| Assuit (Mayhoub and Azzam, 1997) | 128.9/25.0 | 3.5–5.7/25.0 |
| El-Kharga (Ahmed, 2012) | 377.0/70.0 | 5.4/10.0 & 6.5/ 24.5 |
| El-Dakhla (Ahmed, 2012) | 333.0/70.0 | 5.2/10.0 & 6.4/ 24.5 |
| Mersa Matruh, El-Suez and El-Kharga (Rizk, 1987) | 73.0–112.0/20.0 | 4.6–5.5/20.0 |
| Sidi Barrani, Mersa Matruh and El Dabaa (Shata and Hanitsch, 2006) | 260.0–330.0/50.0 | 5.0–5.4/10.0 |
| Sallum, Dekheila, and Port Said (Shata and Hanitsch, 2006) | 180.0–210.0/50.0 | 4.4 - > 4.6/10.0 |
| Port-Said city (Lashin and Shata, 2012) | 19.0–72.0/10.0 | 4.6–5.8/19.0–50.0 |
| Ras Ghareb (Ahmed, 2011b) | 338.0–625.0/10.0 | 6.4–10.2/10.0 |
| Ras Seder and Nabq (Ahmed, 2018b) | 59.0–268.0/10.0 & 42.0–192.0/10.0 | 8.6 & 8.0/50.0 |
| Ras Seder (Ramadan, 2017) | 66.8–481.6 | 6.52/10.0 & 7.21/ 25.0 |
| Shark El-Ouinat City (Ahmed, 2018a) | 582.0/100.0 | 6.5/10.0 |

**Table 5**
A list of wind energy projects to be installed in Egypt up until 2023 (IRENA, 2018b).

| Project | Size (MW) | Status | Contract |
|---|---|---|---|
| Gulf of Suez | 250 | Under development | NREA-KfW, EIB, AFD EPC scheme |
| Gulf of Suez | 250 | Under development | GDF Suez, Toyota, Orascom BOO scheme |
| Gulf of Suez | 200 | Under development | NREA-Masdar EPC scheme |
| Gulf of Suez | 200 | Under development | AFD-KfW EPC scheme |
| Gulf of Suez | 2000 | Under development | Siemens EPC scheme |
| Gabal El Zayt | 220 | Under construction | NREA-Japan-JICA EPC scheme |
| Gulf El Zayt | 320 | Under construction | Italgen BOO scheme |
| Gabal El Zayt1 | 120 | Under construction | Spain-NREA |
| West Nile-1 | 250 | Under development | BOO scheme |
| West Nile 1 | 200 | Under development | Japan EPC scheme |
| West Nile 1 | 600 | Tender-bidding Phase | NREA IPP scheme |

## 5. Wave and tidal energy technologies

Superior wave energy conditions are realised in medium to high latitudes and in deep water, at a depth greater than 40 m, where a power density of 60–70 kW/m can be achieved (Ruud Kempener, 2014). In this regard, the UK, the US, Australia, Chile, New Zealand, Ireland, and South Africa have excellent water resources with an average wave energy power density ranging from 40 to 60 kW/m (Ruud Kempener, 2014). On the other hand, Levantine’s coastal areas are characterised by low wave energy, with an average power density of 2 kW/m. The western coastline of Cyprus island has the highest energy potential over Levantine’s coastal area, with an average energy level of 2.5 kW/m. Following Cyprus, Alexandria, the third-largest city in Egypt, is considered among the potential areas with comparable wave energy to Cyprus. The wave energy in Alexandria is concentrated at values below 2 kW/m with a relatively high standard deviation value of 5 kW/m. Nonetheless, a kind of stable and frequent behaviour existed between May and September where moderate deviations were found, and hence the wave energy potential can be exploited (Shehata et al., 2017). The mean wave energy was found to be higher between December and March compared to the summer months. It is associated with a higher variability level; that could be extracted from the power the sea in Egypt was found to be more than five times the average wave energy (10 kW/m) during the winter months (Zodiatis et al., 2014). The Southern Mediterranean basin on the Egyptian coast, located between the Nile Delta and Libyan borders, has a potential power of 3.35 kW/m and 6.8 kW/m of wave energy during the summer and winter periods, respectively, with a wave energy capacity of 36003 kWh/m and wave heights between 1 and 4 m for energy period between 4 and 8 s (Shehata et al., 2017).

In addition to the 1150 km coastal zone located along the Mediterranean Sea, Egypt is gifted with another 1200 km and 650 km long coastlines along the Red Sea’s Gulf of Suez and Red Sea’s Gulf of Aqaba, respectively (Amin et al., 2020a). In 2016, a work focused on the wave energy resources of the Red Sea found that the mean wave power along the Egyptian east coast is around 1.12 kW/m during winter and 1.05, 1.0

and 0.89 kW/m during post-winter, summer and post-summer periods, respectively (Aboobacker et al., 2017). Shehata et al. (2017) conducted a comparative study for different wave turbine designs based on conditions relevant to the northern coast of Egypt (Shehata et al., 2017). They found that a well turbine can generate a maximum power of 2.2 kW under a sinusoidal wave with a periodic time ($t_s$) of 6 s. Additionally, Bayoumi and El-Gamal (2010) presented a research plan to extract the wave energy potential and investigated the feasibility of harnessing wave energy in Egypt. This plan presents a map for potential wave energy locations in Egypt. It then discusses the selection of suitable wave energy converters (WEC) that fulfil the different sea conditions. Similarly, Bayoumi et al. (2010) implemented a numerical analysis to obtain Piersom-Moskowitz spectrum to estimate the wave power density distribution in the Mediterranean Sea at Sidi-Barrani, Egypt, throughout the year. They found that the power per unit width varies between 2 and 5 kW/m in this location.

Dajani et al. (2012) investigated the potential of tidal energy for the three main coastal zones in Egypt; the Red Sea, the Mediterranean sea and the Gulf of Suez. The velocity of the tidal current in the Red Sea was between 0.5 and 0.6 m/s with a maximum value of 1 m/s. The average tidal current speed reached about 1.5 m/s and 2 m/s on the Egyptian Mediterranean coast and the Nile River. Given that vertical and horizontal mounted-axis turbines are the main candidates for extracting the tidal power, the horizontal and vertical mounted-axis turbines have been recommended for use in the Nile River and the Red and Mediterranean sea. Likewise, Fahmy (2010) developed a mathematical model to study the electro-hydro energy capacity of the Red Sea in Egypt, as a large amount of energy is stored in tides. The developed model can be used to analyse the utilisation of small tidal generators for remote areas with a power rating between 1 and 10 MW.

Later, El-Geziry and Radwan (2012) carried out a sea-level analysis, in Alexandria, Egypt, using a one decade (1996–2005) of data to evaluate tidal and surge elevations. Based on the analysis, the astronomical tidal elevation was found to vary from 11.12 to 10.57 cm with an average value of 0.001 cm, while the surge fluctuations were found to vary from 14.64 to 87.15 cm, with an average value of 50.66 cm. Although, it seems that the mean wave power on Egyptian coasts is not that promising compared to the significant potential in the ocean's coastal zones, the wave energy potential in Egypt can be exploited for small scale power generation. This can be beneficial for producing electricity for the private sector and rural areas around the coastal zones.

## 6. Hydropower technologies

The Egyptian civilisation was primarily developed along the Nile River; where the river provided a reliable and rich soil for growing crops and allowed for the development of a wide-reaching trade network with other civilisations. The Nile River is the primary hydro-power source for several African nations, including Egypt. In the late 1960s and early 1970s, the Aswan High Dam was constructed, which was able to reduce the effect of the annual flooding while providing around 30% of the nation's electricity demand with a hydroelectricity generation rate of 13,545 GWh annually. However, given that the electricity demand has been growing rapidly in Egypt and then this demand has been catered through non-renewable energy sources, the share of hydroelectricity production of the total generated electricity declined significantly from 30% to 7.2% by the time of 2015 (EEHC, 2016a,b).

Hydropower is the most mature renewable energy technology in Egypt (as in many other countries), with an average annual growth rate of only 1.2% from 2011 to 2016. Therefore, several projects have been carried out, as listed in Table 6. In 2022, the country's largest hydropower plant called Gabal Alattaqa, with a capacity of 2400 MW construction began to power the nation, which is located at Attaqa, Suez. This will operate at peak times with an overall head of 28 m (Mohamed, 2019).

Further to the ongoing projects, several researchers have studied the future potential of hydropower plants in Egypt. Hatata et al. (2019) assessed the potential locations and a feasibility study for small hydropower plants in Egypt. Eight different locations have been studied in Northern Egypt with 5 years of actual data, and these locations are presented in Fig. 9. The most effective configuration for the selected locations has been analysed using a MATLAB program according to the possible annual energy generation capacity. This study demonstrated that small hydropower projects could be established in many places across Egypt to provide a good energy alternative with a total energy generation capacity of 15.6 GWh.

**Table 6**
Details of Egypt's hydropower stations (EEHC, 2016a,b).

| Station | Annual electricity generation [GWh] | Capacity [MW] |
|---|---|---|
| High dam | 9484 | 2100 |
| Aswan-1 | 1578 | 280 |
| Aswan-2 | 1523 | 270 |
| Isna | 507 | 86 |
| Naga Hamady | 453 | 64 |
| Assiut | 240 | 32 |

At present, the Egyptian Electricity Ministry plans to implement small hydropower stations in the Nile delta in Northern Egypt. Several studies have been conducted, in this region, in coordination with the Hydroelectric Power Plants Executive Authority (HPPEA), and at least seven potential sites have been identified for small-scale hydropower stations. The Egyptian Electricity Ministry plans to set up hydroelectric plants with a capacity of 2–5 MW. The German development agency Kreditanstalt für Wiederaufbau (KfW) supported the construction of small dams in the Upper Nile region, and the project was assigned for a cost of € 30 M (Takouleu, 2020). Nonetheless, Abdellatif et al. (2018) stated that pumped-storage hydroelectric power plants can only be economically competitive, compared to the current simple cycle gas turbine plants, if the local gas prices increase to the international levels. The Egyptian government should consider relaxing the conditions and limitations that could demotivate the installation of hydroelectric plants.

Regarding the environmental impact of constructing a dam oriented power generation plant, Rashad and Ismail (2000) studied and reviewed the environmental impact of the Aswan high dam. It has been concluded that the large formation of upstream water reservoir caused several disadvantageous effects, such as the rise in river water levels, bank erosion and meandering, bad water quality in northern Egypt, evaporation from the reservoir and coastal erosion. On the other hand, Ethiopia has built the GERD on the Nile, which affects the amount of water that will reach Egypt and hence, will have a negative effect on the hydroelectricity production in the coming years (Walsh and Sengupta, 2020). Aswan high dam will lose around 20–30% of its hydropower potential due to the effect of the GERD. The GERD will also affect the rest of Egypt's hydropower plants, except for the Attaqa plant, which will use recyclable sewage water (Ramadan et al., 2020). If the GERD is filled in 2 years, Nasser lake feeding the Aswan high dam will lose around 37.26 billion cubic meters of water (BCM)/y (El-Nashar and Elyamany, 2018). Heggy et al. (2021) studied the consequences that Egypt would face if the GERD is filled in the short-term 3 y scenario. They stated that the current cultivated area would be reduced by up to 72%, leading to $ 51B total loss in agricultural GDP, which could lead to a significant reduction in the overall national GDP leading to severe socioeconomic instabilities.

Consequently, the Egyptian government needs to come to an agreement with the Ethiopian authorities to find a solution that could be beneficial for both sides. This agreement is massively important for the Egyptian side to maintain the country's hydropower production constant.

## 7. Bioenergy

Bioenergy is an alternative energy source that offers reliable and essential energy for many households, yet it does not cause global warming (Wu et al., 2020). Globally, biomass production is around 146 B mt/y approximately. The production level and purpose vary from country to country, where the developed countries use the biomass to produce electricity or liquid energy. In contrast, some developing countries use it for heating and cooking purposes (Lu et al., 2009). Nearly 79% of the world's total bioenergy conversion to thermal energy is located in Asia and Africa. It is worth noting that the biomass conversion process is complex with respect to the selection of the appropriate technology that should result in a socially admissible, environmentally harmless and technologically robust process (Bilgen et al., 2015). There are several potential advantages to driving gas-based electricity using biomass systems. First, the operational efficiency is better than the commercial use of natural combustion systems. Second, the system efficiency is comparable to that obtained by coal-based systems (Cho et al., 2013). Eventually, agricultural and forestry residues and carbon dioxide reduction are attractive to renovate rural economies and reduce energy dependency (Baruah and Baruah, 2014).

Egypt has multiple unused energy sources, whilst the extensively used resources for power generation are limited to petroleum and natural gases. The nation generates vast quantities of solid waste which were recorded to be 89 Mt in 2012. If used optimally, through solid waste recycling processes rather than dumping into landfills or incinerating, these wastes could be a hidden treasure for centuries, generating enough electricity to supply millions of houses. This would significantly reduce the need to obtain energy from other conventional resources (MEE, 2016).

Egypt has excellent potential for bioenergy resources for applications such as heat and combined power plants. Egypt produces a substantial quantity of biomass of approximately 40 Mt/y. The agricultural sector constitutes around 14.5% of the gross domestic products in the national economy as of 2014 (Long et al., 2013). The largest volume of residues is generated from the agricultural sector every year, followed by municipal and animal wastes. Open burning is the most frequently used technique for waste disposal in Egypt. Around 52% of agricultural residues have been directly burned in fields or in effective burners. Egypt is one of the eleven fastest-growing countries emitting greenhouse gases globally and the main contributors to these emissions are wastes from the agriculture, energy, and industry sectors (Nakhla et al., 2013). To overcome this problem, residues from agriculture should be used as feedstock to generate energy. These residues are divided mainly into two types: livestock and crop residues. Agricultural residues and their corresponding sources in Egypt are listed in Table 7 (UN, 2017).

### 7.1. Production of crop residues

The process of harvesting crops produces organic substances, called crop residues, categorised into primary and secondary residues. Primary residues are produced at the harvesting time in the field and can be collected or spread. In contrast, secondary residues are produced during crop processing and are collected from the processing facility (UN, 2017). Crop production is responsible for around 86% of the residues production in Egypt; about 25.5 Mt/y of residues are produced from cereals, tress and sugar crops. In particular, cereals account for around 67.6% of the total production, making it the most important contributor, then comes sugar cane accounting for 11.3% of total production (UN, 2017). Although not all crop residues can be used for bioenergy, some are entirely utilised for other purposes such as bedding and animal feeding. The residues used in bioenergy are maise, rice from cereals, sugar cane and cotton from fibres, orange and citrus from the fruit category. The production of fruits generates pruning, which is then cut off from a fruit plant. Pruning has high calorific values and excellent physical characteristics, making them suitable for bioenergy production. Palm dates, grapes, olives, oranges and citrus produce pruning at an average rate of 777 thousand t/y; where around 58% of the produced pruning comes from the Middle Delta.

**Table 7**
The sources of the agricultural residues in Egypt (UN, 2017).

| Type of Residue | Sources |
|---|---|
| Stalks | Sunflower, Sesame, Sorghum, Cotton, Maise |
| Straw | Lentil, Flax, Barley, Broad bean, Rice, Wheat |
| Haulms | Soybeans, Peanuts, Sugar beet |
| Pruning | Olives, Grapes, Palm dates, Citrus/orange |
| Manure | Chicken and cattle |
| Bagasse | Sugar canes |

The residues used for bio-energy production are focused in the Middle Delta region, including Behera, Sharkia, Dakahlia and Kafr-Elsheikh, making them responsible for around 46% of the nation's residues. Whilst Upper Egypt, including Menia and Qena, come in second place contributing to 12.9% of the nation's residues. The geographical distribution of the residues available for bioenergy production in Egypt is illustrated in Fig. 10. According to Fig. 10, the high and medium residue production rates are spotted in the Middle Delta region and Middle and Upper Egypt and along the Nile basin, respectively. In contrast, the low rates are spread among governorates further off the Nile and near the coasts (UN, 2017).

### 7.2. Livestock residues

Livestock residues consist of two categories as follows:

- Cattle: cows and buffaloes
- Chicken: layers and boilers

Cattle and chicken manure produce a waste of around 54 Mt/y. Around 57% of the produced manure comes from the Middle delta, 24% and 18% are from Upper Egypt and Middle Egypt, respectively. Of both types of wastes, chicken manure production accounts for around 6.3 Mt/y, with 24% contribution from El-Sharkia followed by 11% from Minya city (Maltsoglou et al., 2017). The total amount of manure available for bioenergy production has been estimated to be 14 Mt/y from livestock residues. Particularly, one-half of the overall availability of cattle manure for bioenergy production is found in the Middle Delta region, with a production rate of 7.8 Mt/y.

The collection and mobilisation of residues spreading across the field can be costly and challenging and requires considerable logistics and coordination among diverse actors in the value chain of bioenergy. Further examination of the actual accessible amounts of energy produced from these residues would be necessary in bio-energy production in Egypt, where specific locations for each available residue should be defined. The effective management of these residues could be highly beneficial for rural farmers and the country's economy.

### 7.3. Sewage waste

Owing to the increased population density and the low wastewater processing capabilities in Egypt, there is an expected future growth in the number and the capacity of wastewater processing plants (WWTPs) to overcome the water scarcity problem in Egypt. Consequently , there will be an increased interest in sewage sludge production (Said et al., 2013). Considering the complete coverage of wastewater systems, the overall wastewater generated by all the Egyptian governorateswas estimated to be around 3.5 $Bm^3/y$ (Lasheen and Ammar, 2009).

Egypt developed 146 wastewater treatment plants with a total capacity of 5 $Mm^3/d$ by 2021. Additionally, a new wastewater treatment plant was built in Bahr Al-Bakar Region in Sharkia governate, with a total cost of 1.2 $B, to maximise the benefits from the agricultural

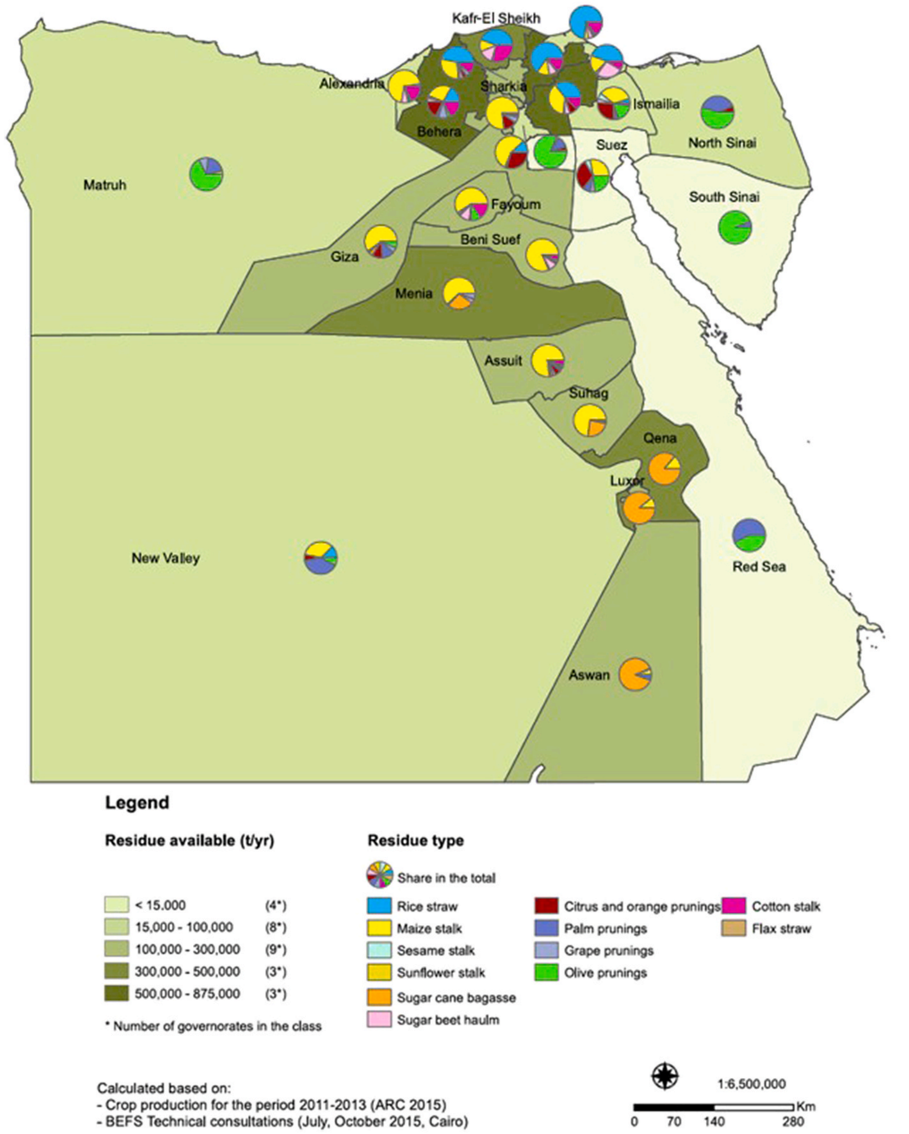



**Fig. 10.** Crop residues distribution map of Egypt (UN, 2017).

wastewater. Bahr Al-Bakar is a 106 km drain that starts from Dakahlia in Middle Delta and passes through Sharkia and Ismalia until it reaches Port Said, Sharkia has the most extended part (EgyptToday, 2021).

For years, Egypt's sewage sludge treatment techniques and technologies have been underdeveloped. Al Gabel Asfer's WWTP has applied anaerobic digestion technology for sludge stabilisation and power generation. Additionally, the "windrow composting of dried sewage sludge" treatment technique has been applied in Al Berka WWTP in Alexandria and Cairo. The WWTPs mentioned above are Egypt's largest centralised wastewater treatment plants and produce more than 50% of Egypt's total dry water sewage sludge. The produced dried sludge is used mainly in agriculture, where in 2007 more than 85% of the total sewage sludge produced by all the Egyptian WWTPs (approximately 0.66 Mt) was sold to farmers (Ghazy et al., 2009).

### 7.4. Municipal solid wastes

Municipal solid wastes are originated from several sources such as construction and demolition, commercial, residential and municipal services. The waste generation per capita is found to be higher in more urbanised areas, creating a correlation between waste generation and increased welfare (Badran and El-Haggar, 2006). It was estimated that Egypt generated 15.3 Mt of waste in 2001, where the municipal solid waste in urban centres constituted 75% of the total generated waste. According to the central agency for public mobilisation and statistics, the Egyptian municipal solid wastes were estimated to be approximately 34.6 Mt in 2007 (World Bank, 2005); this indicates a growth in the produced wastes by around 126% in 5 y. Of the total waste amount, around 60% originated from organic wastes, 12% from plastic, 10% from paper, 7% from glass, metals and textiles and 11% from hazardous wastes, demolition, and construction debris (Said et al., 2013). According to Abdrabo (2008), between 30% and 50% of municipal solid wastes were left uncollected on vacant land or by the side of roads in Egypt by 2004. This resulted in 25 M m$^3$ worth of waste that could have been used (EEAA, 2004–2005). Land-filling and incineration are more eco-friendly solid waste treatment techniques that were introduced in Egypt, where sanitary deterrence is typically the cheapest option provided that the necessary deterrence area is available. To date, there are no waste disposal strategies or standards on which compliance and monitoring can be based. However, the Egyptian Environmental Affairs Agency (EEAA) prepared national guidelines for such standards (Bushra, 2000).

### *7.5. Bioenergy technologies*

Bioenergy is generated through the conversion of biomass using different processes. The choice of the process is affected by the economic conditions, environmental standards, desired type of energy, biomass feedstock and project factors. Pyrolysis, gasification, combustion and digestion processes are the most critical technologies for biomass power conversion, as shown in Fig. 11. The anaerobic digestion process is used for some wet raw materials such as slurry, while the rest utilise dry feed (Fazlollahi and Maréchal, 2013).

The new and renewable energy authority presented an annual report in 2019 in which they reported a total installed biomass power of 11.5 MW with 4.7 M kWh of production. They also reported on Egypt's on-going and future biomass projects, which are listed in Table 8 REA (2020)(REA, 2020). The only biomass power plant that produces electricity in Egypt is Algabal Alasfer. This power plant is a sewage treatment plant in which the sewage is used to produce biogas to provide power for 60% of a 23 MW cogeneration cycle and this produces treated water for use in the agricultural sector.

Abdelhady et al. (2021) studied the economic and technical feasibility of developing a biomass power plant in Egypt numerically to select the most suitable supply chain network for national biomass and maximise the total profit. This study recommended the installation of five power stations with a capacity of 460 MW each at Beheira, Gharbia, Beni Suef, and Sohag. Accordingly, an annual net profit of $ 698.56 M could be achieved at the commercial Egyptian price while producing 15, 296.77 GWh and 35,992.40 GWh of electrical and thermal energies, respectively. The results suggested that Egypt possesses promising biomass energy potential as well. Egypt produces 10 Mt of sustainable crop residue yearly on a dry basis and can potentially generate around 11,000 GWh/y of bioenergy, accounting for around 5.5% of the country's electricity generation in 2019. The nation can reduce $CO_2$ emissions by 3.64 Mt/y and environmental emissions by 2.25 Mt/y. Regarding the economic aspects, a biomass power plant could be highly competitive compared to other renewable energy technologies and conventional power plants.

The details relating to the maximum possible theoretical energy generation using biomass wastes in Egypt are shown in Fig. 12 (Said et al., 2013), where around 416.9 PJ can be potentially generated. Due to the large volume and considerably high energy potential, agricultural biomass is a significant part of the total theoretical energy supply (44.6%), followed by municipal solid wastes (41.7%). In particular, rice straw possesses the most significant energy potential of all agricultural biomass residues and accounts for approximately 61.5% of the total energy potential. It can recover its energy in different shapes such as bioethanol, bio-oil, biogas, and syngas. Potential energy production from agricultural crop residues and solid waste could reduce crude oil consumption by 19% (IEA, 2022).

A decree has been issued by the Cabinet of Ministries in 2015 to establish a ministerial committee to study all waste power projects. However, no initiatives have been taken for a FIT for electricity produced from biomass. If a FIT option is available, it will encourage the

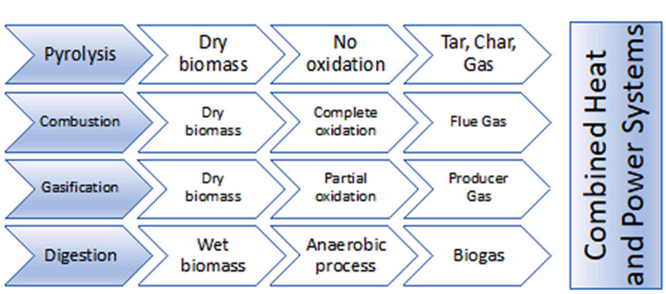



**Fig. 11.** Power conversion technologies from biomass products (Abbasi et al., 2012).

**Table 8**
Recent or on-going biomass projects in Egypt.

| Project name | Capacity (MW) | Status |
|---|---|---|
| Algabal Alasfar | 10 | Installed |
| Private Sector | 1.5 | Installed |
| Private Sector | 3 | Under Construction |
| Private Sector | 51 | Planned Projects |

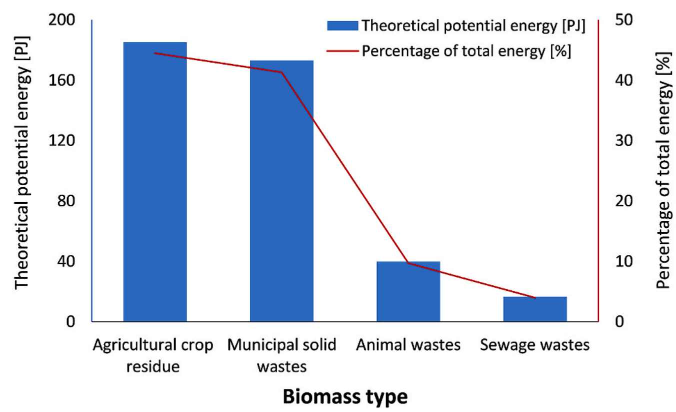



**Fig. 12.** The possible theoretical energy potential from biomass residues in Egypt (Said et al., 2013).

private sector to invest in biomass (MEE, 2015). The Egyptian Environmental Agency (EEAA) developed a bioenergy rural development project (BSRD) in 2009 with the support of the United Nations Development Program funding. This project has made significant progress in developing biogas digesters and establishing bioenergy service providers (BSPs) to support bioenergy penetration in Egypt. The project also seeks to promote entrepreneurship for young graduates, providing exceptional support for women in rural areas, which has led to considerable progress (Kysela, 2013). The BSRD has developed and operated 960 biogas units of various sizes in 18 Egyptian governorates for 3 years of its operation. Twenty registered biogas units were set up and distributed between 1000 families in Egypt's villages, but only a few were constructed (EEHC, 2016a,b). The current market trends are moving towards liberalisation and encouraging private investment. If the private investors can achieve an attractive rate of return on their investment, they tend to see the capital cost as a secondary factor for their investments. The FIT value from biomass electricity production in Egypt using agricultural residues is not as competitive as wind energy, but falls within the world averages. A comparison shows that the proposed FIT is good compared to other FITs in other parts of the world (see Table 9). Concerning the 2022 target of renewable energy in Egypt, a proposed 3% share for biomass generation should be allocated, whilst it should be doubled by 2030 (Abdulrahman and Huisingh, 2018).

Biomass energy generation in Egypt will thrive if the government can change the rules and regulations in political, financial, technical, and institutional bands to promote biomass and attract foreign investments. The Egyptian government needs to encourage biomass energy generation by addressing/releasing some of the barriers associated with the utilisation/generation of biomass in Egypt. The details related to some of these barriers and proposed solutions are summarised in Table 10.

**Table 9**
FIT values for biomass against other renewable sources of energy.

| Reference | Source of electricity generation | FIT ($/kW) |
|---|---|---|
| Adib et al. (2015) | Biomass in the world | 0.06–0.24 |
| Abdulrahman and Huisingh (2018) | Biomass in Egypt | 0.13 |
| NREA (2015) | Wind energy in Egypt | 0.065 |
| NREA (2015) | Solar energy in Egypt | 0.14 |

**Table 10**
Barriers/challenges to the biomass energy generation/utilisation in Egypt (Abdulrahman and Huisingh, 2018).

| Barrier | How to solve |
|---|---|
| Policy | Announcing an objective for biomass production of RE: The goal could be set as the country's absolute capacity to generate and then converted to specific targets based on biomass residues for each governorate. Enforce laws to ban farmers from dumping agricultural residues or burning them to allow a successful way to collect the residues to be used correctly. |
| Institutional | Create a framework with a deadline and a target to promote biomass energy which will require a concerted effort between different ministries. It is essential to promote biomass gasification infrastructure in professional technical authorities of standards and certification procedures to support local investors in determining optimal gasification technologies. Data should be collected and integrated into a central database to give the required information to potential investors. |
| Market | Creating a market for biomass residues by private companies that can buy the residues from the farmers and then sell/process them will create a steady supply to encourage the investors. To stimulate the investment in Egypt's private industry in biomass power generation, the FIT mechanism should be expanded to RE generation from biomass. |
| Financial | Ensure sufficient and easily accessible financial support for private investors via facilitated repayment loans to foster private gasification investment while exempting taxes from biomass plants to encourage foreign investments. |
| Technical | Encourage the Egyptian national research centre and the universities to study and develop a roadmap for the best use of bioenergy resources, and create joint ventures between Egypt, China and Indian governments to allow cooperation on a higher level. |
| Awareness | Broadcasting the success of the gasification plants that both China and India have achieved by arranging conferences for the companies that control the plants to encourage possible cooperation among private investors and increase public awareness of such plants on the national scale. |

In summary, biomass can potentially play a significant role in the energy sector in Egypt and support the nation's aspirations for the utilisaion of sustainable energy sources. Biomass from agricultural waste has a significant energy generation potential and could contribute significantly to fulfilling Egypt's growing energy demand. Although the Egyptian government has announced no objectives for biomass energy production in 2022 renewable energy targets, it is fundamental to account for the biomass energy in the RE plan to accelerate the spread of bioenergy technologies across Egypt. Biomass production should contribute to up to 3% of the electricity production in Egypt by 2035.

Decentralized rice straw gasification is a promising technology. Gasification-based small to medium-sized applications have been successfully carried out in China and Denmark and has proven to have significant potential in supplementing biogas in power production and heat or industrial demands (Korberg et al., 2021). In this regard, the Egyptian government should implement several enablers in policies to encourage and promote energy generation from agricultural residues. Middle Delta has the highest potential for biomass power stations due to the fact that most of the residues from agricultural, manure, sewage, and municipal solid wastes are the highest in this region; mainly in Sharkia and Behera, making them the perfect candidates for immediate implementation of biomass related energy establishments.

## 8. Geothermal

Geothermal energy is an essential renewable energy source that is sustainable, reliable, and green. Geothermal energy is stored as heat under the Earth's crust. However, it generally refers to a portion of the Earth's heat from the shallow soil used to produce electricity, heat-cooling space, aquaculture, and domestic and therapeutic applications (Dickson and Fanelli, 2013). Shallow and deep geothermal techniques are used to exploit low and high enthalpy resources, respectively (Hepburn, 2013). Political and social agendas have shown great interest in recent years in the use of geothermal energy. As of 1994, the global direct installed geothermal power capacity was reported to be 8864 MWt. It has been estimated that the geothermal power capacity might increase from 8864 MWt to 70,885 MWt from 1994 to 2014, which accounts for an 800% increase in 20 years (Lund et al., 2011). The total annual energy consumption worldwide in 2014 was 592,638 TJ where half of this energy has been consumed by heat pumps only. The use of thermal power could save the consumption of around 352 M barrels of equivalent oil annually and prevent the emission of 46.1 and 149.1 Mt of carbon and carbon dioxide, respectively, to the atmosphere (Lund et al., 2011).

In Egypt, thermal water has been directly used for thousands of years when Egyptians used warm water in hot springs for domestic purposes. Warm lakes were used for swimming and medical purposes in wealthy people's houses. Between 2010 and 2014, Egypt experienced a capacity increase in the installed geothermal energy by around 580 MWt (Lund et al., 2011).

In recent years, the interest in low-grade geothermal applications, such as greenhouses, agricultural applications, fish farming and district heating, started to grow. Swimming pools for medical and touristic reasons have been constructed on the eastern coast of the Gulf of Suez by using geothermal water from natural hot springs. Additionally, greenhouses in the Western desert were heated by geothermal water together with the geothermal energy for district heating in winter (Lashin, 2015).

According to the geothermal systems' nature, two primary systems control the geothermal resources in Egypt.The first system is the hot springs controlled by the geology and tectonics of the Gulf of Suez. These springs exist due to structural and tectonics elements; some of them are found on the western and eastern coasts of the Gulf of Suez. The second system is the deposition of the various stratigraphic units in the Western Desert of Egypt, in which there are many flowing hot springs (Lashin, 2015). The majority of Egypt's geothermal resources can be classified as medium to low-temperature potentials, and those around the Gulf of Suez are the most suitable for energy-related applications. Some locations with high enthalpy potential can be found in the offshore deep-sea areas of the Gulf of Suez and the Red Sea. The Egyptian geothermal resources are classified as follows:

- High enthalpy: geothermal abnormalities in the Gulf of Suez and the Red Sea rift of depo-centres.
- Medium enthalpy: hot springs with a surface water temperature of 76 °C can be found in the Gulf of Suez.
- Low enthalpy: the most common type of geothermal source in Egypt that can be found in Sinai, the Western Desert and around the Gulf of Suez.

According to the available geothermal resources in Egypt, geothermal power plants (GPP) are classified into steam cycles for high-temperature sources and binary cycles for low to medium temperature sources (Valdimarsson, 2011). Therefore, the technology used for extracting the geothermal energy is selected based on the category of energy sources; where resources are classified based on their temperatures as shown in Fig. 13a (Gondal et al., 2017).

### 8.1. Geothermal energy utilisation in Egypt

Although the majority of geothermal resources with relatively low enthalpy levels are not suitable for power generation, they are still suitable for direct heating. Egypt is the fourth country with direct energy utilisation in Africa, as indicated in Fig. 13b. 59% of the current geothermal energy in Egypt is used for heating purposes in swimming pool/bathing locations, while 22%, 15% and 4% are used in district heating systems, greenhouse heating, and space heating, respectively (Lund et al., 2011).

To utilise the geothermal energy potential in Egypt effectively,

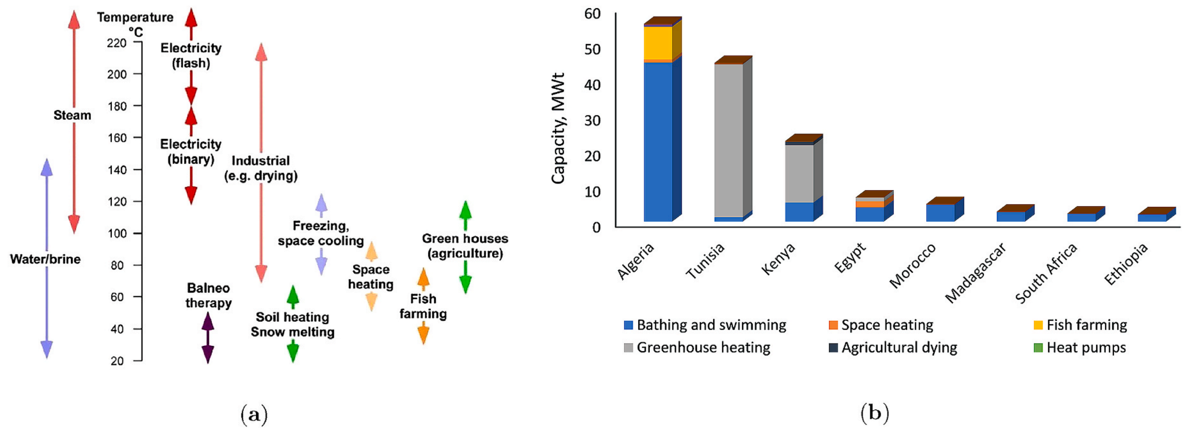



**Fig. 13.** (a) The applications of geothermal energy based on the temperature (Gondal et al., 2017), (b) African direct use of geothermal energy distribution (Lebbihiat et al., 2021).

several studies have been concerned with identifying the potential locations for geothermal energy generation. In this regard, Hammam Faraun area has unique geothermal energy generation characteristics, with 12.4 MWt of thermal energy. This energy can be extracted assuming a geothermal tank temperature of 95 °C, a turbine conversion factor of 0.26, 50 years of work on a proposed geothermal plant, and a recovery factor of 0.20 (Lashin, 2013). Zaher et al. (2011) concluded that Hammam Faraun hot spring area with an initial temperature of 130 °C and 30 y of reservoir operation would result in a geothermal potential of 19.8 MWt, assuming a reservoir depth of 500 m. The estimated geothermal potential ranging from 12.4 to 19.8 MWt is economical and can support building a small-scale binary power station for electricity generation. According to Lashin (2013), geothermal-based energy's FIT cost has been estimated to be 0.12 $/kWh; this is a very competitive cost to encourage investors to start generating clean electricity from geothermal energy. More potential locations have been identified in Egypt for geothermal energy utilisation including some sites in the southwest Gulf of Suez, El-Tur, Abu-Durba, Ras-Badran and Ras-Matarma (Zaher et al., 2011). Abuzied et al. (2020) studied the Gulf of Suez area and then created a potential geothermal map. Most of the promising sites presented by this map for geothermal exploration are the same as those identified by Abdel-Fattah et al. (2021), except that they have added both Abu Rudies and Belayim to the map.

All the above-mentioned sites are featured with the high heat flow capacity and geothermal gradient, making the Gulf of Suez the most promising region for geothermal exploration in Egypt. In the Gulf of Suez, low-scale energy production, using low boiling water geothermal plants with a production of 19.68 MWt from geothermal energy, can be achieved with a 40 y of plant life and a recovery factor of 0.20. The cost of geothermal power generation has been predicted to be around 0.050 to 0.065 *US$/kWh*, making it to be a competitive cost for FIT (Aboulela et al., 2021). At present, geothermal energy has been used for medical and swimming pool purposes and for greenhouses, agriculture, and fish farming applications in the Gulf of Suez region.

Saada (2016) analysed the geothermal sources in Ras Banas in Marsa Alam, Red Sea governorates. A general increase in the geothermal gradient from 24 to 60 °C/km has been found near the rifting zone of the Red Sea. Similarly, Zaher et al. (2018b) investigated the geothermal potential in El-Farafra area in the Western Desert, and they have concluded that the estimated geothermal gradient average temperature is equivalent to 26 °C/km. They classified the Farafra Oasis as a low-temperature resource with six high probability zones for geothermal applications including southern Abu Minqar, southern Farafra, eastern Farafra, and eastern Qasr-Farafra, Bir-Sitta and Ain-Dalla. Another work by Zaher et al. (2018c) investigated Siwa Oasis, a part of the Western Desert near the Libyan border. The analysis results classified Siwa Oasis as a low geothermal resource with a geothermal gradient ranging from 21 to 27 °C/km and the heat flow ranging from 49 to 64 mW/m$^2$. Ultimately, Zaher et al. (2018a) established a geothermal favorability map of Egypt using the Geographic Information System (GIS) model, and this is presented in Fig. 14. In this map, some geothermal hot-spots like Ayun Musa, Hammam Faraun and Hammam Musa located on the eastern and western coasts of the Gulf of Suez and Ain Sukhna respectively, have been classified as high class favourable geothermal regions. Of those locations, the nearby coasts of the Red Sea and Gulf of Suez have been identified as the most promising geothermal areas in Egypt; in particular, El-Gouna, which is located at the south of the Gulf of Suez, has a more significant potential for geothermal energy.

The development of geothermal power plants across the coastal areas of the Gulf of Suez is a promising step forward for initiating the geothermal based electricity generation in Egypt. For Hammam Faraun hot spring, a binary geothermal power plant could be built due to the high energy potential that can be extracted; which could offer a considerable level of electrical power. Other applications such as heat pumps, greenhouses, fish farming, and swimming pools could be used in the Gulf of Suez area. Additionally, there should be more attention and extensive scientific work to develop new geothermal-fed communities around Hammam Faraun spring, particularly for touristic purposes.

In terms of the environmental impact, legislations and decrees on environmental protection, public health, and natural habitats should be developed to support energy systems that respect the environment to guarantee the country's commitment to international agreements.

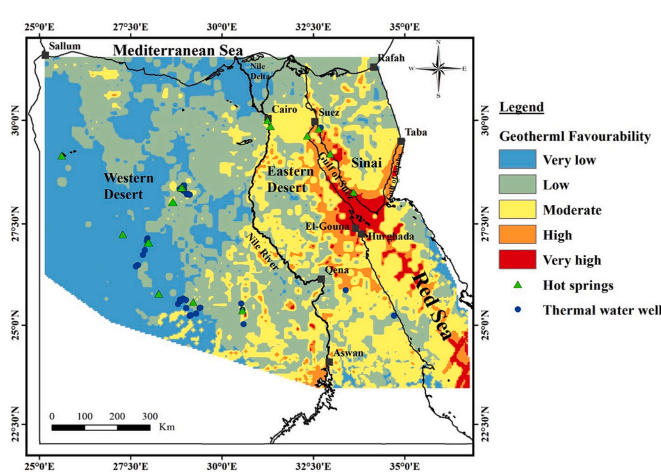



**Fig. 14.** A geothermal map of Egypt showing the geothermal favourability locations (Zaher et al., 2018b).

Nonetheless, all phases of geothermal projects can have environmental consequences such as heat pollution, and soil degradation due to the related exploration activities.

## 9. Nuclear energy technologies

Nuclear energy provides 7% of the world's energy supply, and 14.7% of the global electricity needs (Comsan, 2010). Of the operating nuclear power plants across the globe, only three nuclear plants exist in the MENA region with two of them in the South African Republic with a rating of 1.8 GW and the other in the Islamic Republic of Iran with a power rating of 1 GW (Comsan, 2010). Nuclear power plants provide a sustainable energy source compared to the conventional sources where their lifetime may extend to several thousands of years, given that the appropriate nuclear fuel cycle technology is implemented, contrary to the depletion of oil and gas reserves (Comsan, 2010). With the view that the energy produced by nuclear power plants is renewable, the nuclear energy potential in Egypt is considered in the scope of this paper.

According to the electricity scenario proposed by Comsan (2010), Egypt should be supplying 13.02% of its energy demand using nuclear energy by 2050. In addition to nuclear energy, solar thermal, wind, solar and hydro should provide 72.7%, 9.5%, 2.5% and 2.2% of the energy demand, respectively, (Comsan, 2010) to meet the Egyptian electricity demand using sustainable energy sources. The first agreement to establish the first nuclear power plant in Egypt occurred in 2015 between the Egyptian and the Russian authorities. The plant was designed to operate with a total capacity of 4800 MW with four Water-Water Energy Reactors (VVER) each with 1200 MW. The agreement included building nuclear fuel storage facilities that allow for the plant operation for 60 years where a company called Rosatom is responsible for managing the nuclear waste, training Egyptian experts, maintenance and operation. Regarding the safety aspects, the plant should follow the VVER-1200 safety protocols for protection against internal and external factors and influences (Cauich-López et al., 2019). Ultimately, the northern coast of Egypt, a place called El-Dabaa, was chosen as the suitable location for the plant.

A few studies have investigated the implementation of nuclear energy to extend Egypt's energy generation capacity. Megahed (2009) examined the feasibility of a combined power and desalination plant in El-Dabaa and found that such an installation would be technically and economically feasible and financially viable. Additionally, the Egyptian grid was found to be capable of accommodating a nuclear plant with good stability. For this site, the utilisation of two identical units with a power rating of 600 MW was found to be the most preferable option. To supply potable water, the desalination capacity of the plant should be 150,000 $m^3$/d. Later, ElKhodary et al. (2017) detailed the economic and environmental impact of the establishment of nuclear systems in Egypt and the MENA region. They claimed that the nuclear fission plants do not produce $CO_2$ emissions or any air pollutants, while their radioactive emission level could be less than that of the levels produced by radioactive isotopes found in the coal soot and ash.

Kotb and Abdelaal (2018) examined the impact of installing the first nuclear plant in Egypt by 2030. Three different scenarios have been investigated, including low, basic and high scenarios; where the low scenario does not consider the nuclear plan in the electricity generation. The basic scenario considers the implementation of the first nuclear plant in 2030, while the high scenario studies the effect of the nuclear power plant as a double expectation of the basic scenario. If the implementation of a nuclear power plant was possible, it would help in reducing $CO_2$ emissions by more than 25 Mmt. Additionally, the difference in water withdrawal levels between the high and low scenarios is 7.1 and 14.7 BCM by 2016 and 2030, respectively.

Despite the slowness of the steps taken toward the nuclear energy sector in Egypt, there is a real need to integrate nuclear energy into the Egyptian power sector to meet the increasing energy demand via sustainable sources. In addition to fulfilling the energy demand, integrating nuclear energy systems into the Egyptian energy sector would substantially reduce $CO_2$ emissions and should allow for meeting the Kyoto agreement requirements.

## 10. Hydrogen based energy

Hydrogen is a proven alternative for reducing global warming and meeting the sustainable development goals of the United Nations. A large-scale hybridisation of hydrogen-based sources with RE is a long-term solution for accelerating the essential energy transition (Ogbonnaya et al., 2021). Hydrogen has long been regarded as a valuable commodity gas and a chemical feedstock primarily used in oil refining and fertiliser manufacturing. However, it is a clean and flexible energy carrier made of basic energy sources, hydrogen-containing substances, such as methane and water, or as a by-product of chlor-alkali plants (Maestre et al., 2021). Despite the relevance of this issue, the Egyptian government has not placed a high priority yet on the development of hydrogen-based energy establishments, owing to the lack of developmental plans and lack of access to the technology, capital cost, etc. (Mostafaeipour et al., 2021). However, in August 2021, Siemens Energy and the Egyptian Electricity Holding Company (EEHC) signed a memorandum of understanding to create a hydrogen-based industry in Egypt and this should be the first-ever hydrogen-based energy project in Egypt. Here, Siemens Energy and EEHC will develop a pilot project with 100–200 MW of electrolyzer capacity as part of the first steps, which will aid in the early deployment of the technology and the establishment, and testing of regulatory environments and certification to allow possible plans for expansions (Siemens-energy, 2021b).

## 11. Hybrid renewable energy systems

Integrating renewable energy resources with conventional power systems has shown excellent outcomes, particularly for locations with no access to the grid. Nonetheless, the desired outcomes are obtained only if the right combination of technologies has been set with the proper storage systems. Several researchers have conducted thorough investigations on the use of hybrid renewable energy with conventional energy in different locations in Egypt.

Diab et al. (2015) studied the optimum city for an environmental friendly touristic village in Egypt based on a hybrid RE system. The analysis has been conducted for five different cities, including Aswan, Qena, Alexandria, Giza and Luxor. As they found, Alexandria is the most economical city for hybrid PV/wind/diesel/battery and hybrid wind/diesel/battery systems. Meanwhile, Aswan was found to be the most economical city for hybrid PV/diesel/battery systems. Similarly, a hybrid renewable system including a vertical axis wind turbine and a PV panel has been proposed to drive desalination systems in Egypt. The results showed that the Net Present Cost (NPC) over 15 years lifetime and COE of the PV/wind hybrid system were equivalent to $18,113 and $0.648, respectively, accompanied by a storage capacity of 34%. Whilst, the NPC and COE of a PV/WT/Diesel system was found to be $28,436 and $0.763, respectively, with a zero capacity shortage (Khattab et al., 2016).

In the meantime, Elsayed et al. (2017) provided an economic assessment for a solar/wind hybrid system for application in remote areas in Egypt. It has been concluded that the hybrid system is more economically feasible than a stand-alone PV system. The hybrid system resulted in a present cost of 0.315, 0.352, 0.327, 0.364, 0.32, 0.313 $/kWh for Alexandria, Alsalloum, Shalateen, Suez, Alkharga, Aswan respectively, compared to a cost of 0.58, 0.642, 0.394, 0.6, 0.495, 0.482 $/kWh for the stand-alone PV system, respectively. This cost reduction was due to less batteries and converters in the installed system. Abou El Ela et al. (2017) proposed a hybrid RE system composed of a wind turbine and a Fuel Cell (FC) in Marsa Matrouh. They found that a 3000 kW wind turbine is the optimum candidate for the proposed system. This 3000 kW turbine was capable of producing a surplus power of 249.54

MWh while producing 4,990,898 g of $H_2$, allowing FC to generate 164.4 MWh of power.

Later, Ibrahim et al. (2020) investigated the performance of two-hybrid systems to obtain the optimum design combinations for these systems. As a result, the optimum performance for the first system has been obtained for a 10 kW wind turbine integrated with a 4.90 kW diesel generator and a 20 kW photovoltaic solar panel. This design offered a cost of $0.2252/kWh accompanied by a water cost of $1.10/m$^3$. Similarly, the second combination of 5 kW hydrokinetic turbine, 4.90 kW diesel generator, and 2.82 kW photovoltaic solar panel resulted in power and water costs of $0.1216/kWh and $0.56/m$^3$,respectively. Additionally, this system is capable of reducing $CO_2$ emission by 97.8% (i.e., equivalent to 643.48 kg/y) (Ibrahim et al., 2020).

Atallah et al. (2020) presented a study to satisfy the power demand of reverse osmosis (RO) plants with a freshwater capacity of 100 m$^3$/d for Nakhl, North Sinai by implementing a hybrid power system. The hybrid system consists of wind turbines, photovoltaic panels, converters, storage batteries, and a diesel generator. The most optimum configuration was found to be a hybrid PV/diesel/battery system. It consists of 160 kW PV panels, a 50 kW fixed capacity diesel generator, 19 strings with 190 lead-acid batteries (with a 3.11 kWh rated capacity) and a 39.3 kW converter. The proposed hybrid power system could reduce the $CO_2$ emissions by approximately 94% with an energy cost of $0.1074/kW.

Samy et al. (2020) investigated the techno-economical effect of a combined RE system of PV/wind/Fuel Cell (FC) in the countryside. They studied different scenarios for different setups for a location with latitude and longitude of 29.0 N and 30.9 E, respectively. The simulation results showed that solar PV/Wind/FC combined with an electrolyser for hydrogen production delivers excellent efficiency. The proposed system has proven to be economically viable with a low energy cost of 0.47 $/kWh.

Likewise, Kotb et al. (2020) investigated the economic, technical and environmental feasibility of an off-grid hybrid energy system in Marsa-Matruh. The most cost-effective design has been achieved with a 2625 kW wind turbine integrated with a 41.2 kW PV panel, a 15 kW diesel generator and a 27.4 kW power converter with 92 units of 23.92 kWh lead-acid batteries. The model developed in this study helped in identifying the optimal design and the energy quality of local hybrid renewable energy production systems in remote and isolated villages where access to electricity is not available.

Eventually, Elkadeem et al. (2020) investigated the economical and technical feasibility of a hybrid renewable energy-based microgrid system to supply the required electrical and heat energy for a small city in Safaga, Egypt. They have studied different system configurations, and the highest performance was obtained for a hybrid PV/wind/fuel cell/battery/converter system. The proposed configuration had the lowest values for capital and running costs with an 80% reduction in greenhouse gas emissions.

## 12. Energy storage systems

Renewable energy development is becoming widely recognised as a viable solution to tackle energy concerns. However, there are still some issues that must be addressed as renewable energy development progresses. One is that the renewable energy generation process is discontinuous and intermittent; for example, wind and solar energy cannot continually provide electricity on windless and foggy days. As a result, the key to solve the above challenges is to figure out how to store renewable energy once it is being generated (when they are available but not in use), and then release it whenever/whereever it is needed. This difficulty can be readily addressed if photovoltaic and wind power plants are fitted with energy storage technologies. An energy storage technology can provide a stable power supply for power plants during adverse weather conditions, as well as store excess electricity generated during peak generation times that would be wasted if not used. As a result, one of the most significant challenges that the renewable energy sector (as well as other energy sectors as well) has been experiencing is energy storage (Liu and Du, 2020). The storage of electrical energy is the major focus of energy storage technologies. Electrical energy can be stored or released depending on the grid load, which would reduce the power grid variations. Electrochemical, chemical, mechanical, and thermal are the main examples of types of energy storage systems (Hayat et al., 2020).

Energy storage, in general, can improve the predictability and controllability of intermittent renewable energy generation while also promoting the upgrade and transformation of traditional power systems. Several systems can be used for this purpose; each has advantages and disadvantages, so selecting the appropriate system is a critical task for various applications. Meanwhile, the selection of a suitable storage system can improve the efficiency of the RE system and reduce its overall cost as well (Pfleger et al., 2015; Hayat et al., 2022).

## 13. Renewable energy policies in Egypt

The Egyptian government has supported the development of renewable energies since 1986 by establishing the New and Renewable Energies Authority (NREA). A year later, Decree No. 401 was issued to support the installation and the implementation of solar water heaters in Egypt (Abdrabo and Soliman, 2008). In April 2007, the supreme council of energy declared a plan to produce 20% of the country's energy and electricity from renewable energy resources by 2020. This date has been postponed to 2022 due to the COVID-19 situation. Meanwhile, the plan got updated in 2012–2017 to account for installing 20 MW PV grid commented plants, 4 MW/y, and a 100 MW CSP plant in South Egypt. The next generation target has been set to achieve 23% by 2022, including installing 2.550 MW of CSP, 500 MW PV arrays and 1.2 Mm$^2$ of SWH (Patlitzianas, 2011).

In 2014, the renewable energy law (Decree No. 203/2014) was issued to boost and support new investments in RE technologies in Egypt (IRENA, 2018b). Additionally, cabinet decree No. 1947 was published to set the basis of FIT for renewable energy projects. A year later, decree No. (37/4/15/14) has been issued by the prime minister to provide lands for renewable energy projects. Additionally, electricity law No. 87 has been issued to provide a legislative framework to realise the electricity market reform targets and to incentivise the renewable energy sector. Investment law No. 72 of 2017 has been issued to support foreign investments in Egypt (IRENA, 2018b). In 2019, the prime ministerial decree was issued to determine the FIT from electricity generated by biomass technologies.

In attempts to boost renewable energy technologies in Egypt, the government has developed an integrated sustainable energy strategy, "ISES-2035″, to provide a continuous and secure sustainable energy supply to the nation's needs. This new strategy involves the development of renewable energy and energy efficiency in the power sector (IRENA, 2018b), where renewable energy resources should supply 42% of the country's electricity needs by 2035. In addition, to overcome the Egypt's water crisis and satisfy the nation's water needs, the Egyptian government implemented an integrated water management program (IWMP) till 2017, followed by launching another plan till 2037. This plan was set to safeguard Egypt's water resources and satisfy water needs, which also included seawater desalination for the northern coast and the Red Sea regions.

Regarding nuclear energy, the Egyptian nuclear program was hit by many setbacks that slowed down its progress (Cauich-López et al., 2019). The development of the nuclear energy program has been initiated with an agreement between Egypt and France in 1976 to establish a nuclear reactor. Unfortunately, the cooperation between the two countries has stopped due to some changes experienced in this agreement. In 1976, the government constituted nuclear power plants authority to support the planning and management of the nuclear energy programs in Egypt. The nuclear program in Egypt started with several collaboration agreements with France, the USA, Germany, and Switzerland signed with the Egyptian side for civil usage of nuclear energy and nuclear power plants. Nevertheless, the nuclear plans were suspended in 1986 due to the Chernobyl Nuclear power plant disaster (Cauich-López et al., 2019).

Later in 1992, a new agreement was signed with the Argentinean Company INVAP to build a light water research reactor with a capacity of 22 MW, where the construction of the process started in the same year and operated in 1997 for the first time. After 10 years, the Russian and Egyptian sides signed an agreement to start cooperating on the nuclear energy program in 2008 and El-Dabaa site has been selected as a promising site to build a power plant. However, the nuclear program stopped following the Egyptian revolution in January 2011 due to political circumstances. In 2013, the Egyptian-Russian agreement was renewed (Cauich-López et al., 2019). In 2015 the Russian and Egyptian presidents declared cooperation in building the first Egyptian nuclear power plant (Cauich-López et al., 2019).

Along with the aforementioned policies, Egypt's interconnections with the Mediterranean power pool are being expanded. The project aims to connect northern Africa's power grids (including Egypt, Algeria, Libya, Tunisia, and Morocco). Programmes such as "Solar Plan of the Union for the Mediterranean", "Deseret", and "Trangreen" will allow for increasing the investment in solar installation in Egypt for the energy export market (Patlitzianas, 2011). Here, cross-border interconnections are seen as a critical component for advancing RE integration. It can raise the connectivity levels, which could allow variable RE systems to penetrate further (Pupo-Roncallo et al., 2021).

Egypt has signed the Kyoto Protocol and recognised the role of international cooperation in facing the issues of climate change, and the guidelines on clean development mechanism (CDM) projects have been adopted (Patlitzianas, 2011). Furthermore, Egypt is the host of the regional centre of the MENA region. Egypt is a member of the Union for the Mediterranean, and it is committed to engaging in the Mediterranean Solar Plan.

## 14. Challenges faced by the renewable energy sector in Egypt

The Egyptian economy faces many competitive pressures that negatively affect the Egyptian market's trade position. This includes competitive pressures from countries in the MENA region such as Tunisia and Morocco, and some neighbouring countries/regions such as East Asia, Europe, China, India and Bangladesh. Consequently, Egypt is still lagging behind other countries in developing industries on a wide scale despite starting the industrialisation process early in the 1920s (Hawash et al., 2007). The development of the renewable energy sector also faces many challenges in Egypt, including technical, manufacturing and political and economic challenges. A summary of the possible challenges that Egypt faces in developing the renewable energy sector is presented in this section.

Promoting the implementation of RE technologies in the Egyptian market is directly linked to the cost of the technology development and the electricity tariffs. So, to increase the competitiveness of the RE technologies against conventional energy sources, it is crucial to reduce the expenses associated with those technologies. Increasing the local manufacturing share of various RE technologies provides a radical solution for this problem.

Egypt has a substantial potential for manufacturing solar and wind energy components. For example, wind turbine towers are manufactured locally and hence they are cost-competitive in Egypt. However, the local manufacturing of the other components, such as the blades and related electronics, is still not happening. Additionally, Egypt has key strengths for manufacturing CSP components, including low labour cost, the low energy cost for the industrial sector, availability of glass and steel and strong manufacturing capability. Nonetheless, the manufacturing of RE technologies is challenged by the following factors:

- Lack of competencies (Loudiyi et al., 2018): this includes a lack of qualifications for operation and maintenance. Egyptian technology is still under development in the solar energy field and investments, are still at the experimental stage and have not reached the level of massive production (Patlitzianas, 2011).
- Low command of technologies: this includes lack of technical knowledge about the design and manufacturing of solar energy components and the design of wind energy components.
- Lack of extensive use of geothermal energy resources: there is a considerable lack of suitable equipment for direct geothermal applications, and the available equipment is operating with low efficiencies and poor durability. This means the country has not reached the international level in terms of technological development.
- Absence of specialised training centres for skills development.
- The shortage of individuals skilled in RE technology is one of the main barriers that can hinder the rise in the RE generation (Njoh, 2021).
- Technical challenges due to the absence of adequate storage technologies (Loudiyi et al., 2018).
- The low production rates are due to the absence of investments and governmental initiatives.

Renewable energy development still faces numerous challenges worldwide, and hence several countries have already taken steps to reform their policies, rules and regulation to promote renewable energy technologies. In this regard, using incentives and subsidies with mandatory regulations would be the best way forward (Kim, 2021). Further to the technical challenges in Egypt, there exist legislation challenges that slow down the development of RE sector in Egypt and some of them are listed below:

- Missing standards and norms: the lack of the establishment of a coherent regional regulatory framework (including conditions for electricity trade, regulation, etc.).
- Non-harmonised regulations between the government sectors.
- Limited grid access for third parties and limited capacity of the electrical grids (Loudiyi et al., 2018).
- Lack of guidelines and regulations or decrees governing geothermal energy. The government is still lagging behind in terms of investment opportunities and support for the industrialisation of geothermal energy.
- The lack of governmental control on the investment scale in the renewable energy sector and the adaptation of industrial investment direction. This can be enhanced through policy adjustments like interest rate and taxation to progress the price mechanism while also guiding the industry to consider their own research and design investments (Zhen et al., 2021).
- Legislations and decrees on environmental protection, public health and natural habitats have been developed to develop an energy system that respects the environment. Nonetheless, all phases of geothermal projects could have environmental consequences such as heat pollution and soil degradation during exploration.
- Non-governmental organisations are not participating in the publication of RE (Elnokaly and Elseragy, 2007).

The development of RE industries encounter some economical challenges that include:

- Fossil fuel subsidies: the current low energy prices (mostly for conventional non-renewable energies) resulted in over-dependency on the conventional energy resources and limited the attraction towards the slightly high priced RE technologies. Electricity tariff is subsidised in Egypt , making it more feasible than the energy tariffs of the various RE techniques. Nonetheless, it is worth mentioning that the subsidies for petroleum products have been cut by almost 1.9 times between 2019-2020 and 2020–2021.
- The annual interest rate is kept below 10% in 2021 (Moneim, 2021), which is still considered to be high, and makes it difficult for small and medium companies to invest due to the high payback levels.
- Management of price distortions in the sector by the implementation of side payments and uniform pricing with a price cap to limit strategic behaviour in flexible markets (Höckner et al., 2020).
- Some rural communities are below the poverty line, not supported by government subsidies, and cannot afford to consume costly RE. In this case, the local governments should manage funding services through micro-finance institutions, such as financial cooperatives, working at a local level. This can help with debt management and provide support for poor households that cannot deal with large banks and financial institutions (Suman, 2021).

The electrical interconnection between Egypt and the neighbouring countries should reduce the capital needed to set up electrical power plants and contribute to solving the energy crisis in Egypt. Regional interconnection between Egypt, Arab and African countries is considered reasonable due to reaching up to 5 hours of time difference alongside the different ambient temperatures between countries (El-Kholy and Faried, 2011). The following is a list of the ongoing and planned interconnection projects between Egypt and neighbouring countries.

- Eastern Interconnection via Jordan to allow for up to 250 MW of power transfer.
- Western interconnection via Libya to allow for 150 MW of power exchange in either direction.
- The Mediterranean Power Pool.
- Interconnection between Egypt and Saudi Arabia to allow for 3000 MW of power exchange.
- The Nile Basin Initiative (NBI) and Eastern Africa Power Pool. This pool is concerned with optimising the use of hydro-power resources in conjunction with the thermal generation, particularly, in the North and South Africa (El-Kholy and Faried, 2011).

Though the Egyptian government moved towards adding some flexible policies and decrees to promote the RE implementation, as discussed in Section 13, there could be some political challenges to the development/expansion of RE technologies, including;

- Weak interconnection capacities with potential countries.
- Organisation and management of interconnections for a foreseeable future (Loudiyi et al., 2018).

Eventually, the infrastructure is also one of the major challenging factors that impede the implementation and the financing of renewable energy technologies in Egypt, particularly transmitting energy from wind farms which requires transmitting electricity to special substations and high voltage cables.

## 15. Environmental benefits and risks analysis

The environmental benefits and some associated risks of potential renewable energy technologies are presented in Table 11.

## 16. The current renewable energy potential in Egypt and energy scenarios for 2035

### 16.1. The current and potential renewable energy locations in Egypt

A map of the current available renewable energy projects in Egypt for electricity generation is presented in Fig. 15, and the project names with their locations are listed in Table 12. The hydropower energy is concentrated in Upper Egypt, while wind energy is concentrated on Red Sea Coast. Additionally, bioenergy-based electricity is generated in one place with a capacity of 10 MW in Algabal Alasfar. Similarly, a single solar thermal power plant is under operation, which is located in Al-Kuraymat with a capacity of 20 MW. Geothermal energy in Egypt is not yet used for electricity production with domestic small scale applications. Solar PV plants are the only renewable energy source found across Egypt rather than concentrated in one or a few locations (Siemens-energy, 2021a).

In a similar manner, another map is developed to highlight the potential locations for renewable energy sources in Egypt and presented in Fig. 16. Although solar energy is potentially high in many locations in Egypt, the mentioned locations in the map have the highest solar irradiance than other parts of Egypt, making them the best possible locations to implement future solar plants (CSP & PV). The Delta region in Northern Egypt has great potential for bioenergy and hydropower, while the Mediterranean coast can be used for wind energy in locations such as Sallum, Matruh and Port Saied. The Gulf of Suez is considered the best location in Egypt that can supply 100% of its consumption from renewable energy because of the high potential of solar, wind and geothermal sources. Southern Egypt also has a high potential in solar, wind and bioenergy , but it is not as concentrated as the Gulf of Suez region. Owing to the diverse renewable energy resources in Egypt, a comparative analysis of potential energy systems can be done using energy system analysis models such as EnergyPLAN which allows for detailed socio-economic feasibility studies (Lund et al., 2021). This should allow for carrying out an energy transition from conventional to RE resources in Egypt; where a similar analysis has been carried out in Iran and allowed for developing five different energy systems focusing on the underlying RE production and efficiency improvements (Noorollahi et al., 2021).

Different studies have been carried out to investigate the feed-in tariff (FIT) values of different renewable energy plants in several locations in Egypt as shown in Table 13. The FIT values vary from one source to another and from one city to another, making the selection of the appropriate energy source in each city easier in terms of KWh cost. More research is needed to investigate the FIT values of wind and solar energies in the Gulf of Suez area due to the high potential in those areas. The FIT values for both the bio and geothermal energies in the Gulf of Suez is also worth further studying.

The present situation as of early 2022 in Egypt is that only 12% of the produced electricity comes from RE sources, and this margin lags behind significantly from the anticipated target by 2022 of having 20% of electricity from RE sources. The government has stated that the 20% is going to be achieved by the new projects that are under negotiation, which were delayed by the global pandemic in 2020.

**Table 11**
The environmental benefits and associated risks of RE.

| Renewable system | Environmental benefits | Risks | Risk Severity |
|---|---|---|---|
| Solar energy (Vyas et al., 2022) | • Reduction of pollutant gases such as $CO_2$, $NO_x$, $SO_2$ and particulate matters.<br>• Improving the quality of water resources.<br>• Improving the reclamation of degraded land.<br>• Reduction of the required transmission lines of the electricity grids systems. | • Large land use.<br>• Impact on ecosystems: due to the use of toxic and flammable materials for the manufacturing of PV modules.<br>• Water pollution due to thermal discharges or accidental discharges of chemicals used in solar thermal.<br>• Light pollution. | • Moderate<br>• Medium-High<br>• Medium<br>• Moderate |
| Wind energy( Chowdhury et al., 2022) | • Reduction in gaseous emissions such as $CO_x$, $SO_x$, $NO_x$ particulate matter (PM) such as soot, or any other air pollutants during the operation phase.<br>• Savings in the public health by $ 9.5B.<br>• Reduce the amount of water needed compared to conventional thermal power plants.<br>• The wind farms in Egypt apply a shut down on demand approach that provides a safe route for migratory birds. | • Noise, visual pollution and electromagnetic interference.<br>• Bird fa.tality, soil erosion and deforestation.<br>• Lightning from towers and electromagnetic radiation.<br>• Hazardous manufacturing processes.<br>• Less energy density, due to the wake effect. | • Moderate<br>• Moderate<br>• Moderate<br>• Moderate<br>• Moderate |
| Hydroenergy (Sayed et al., 2021) | • Less liquid and solid wastes.<br>• Flood control.<br>• Secure water storage and supply for different purposes.<br>• Minimal resources requirements (only for the construction phase).<br>• High working efficiency (approx. 90%). | • Relocation of people and terrestrial wildlife.<br>• Development of aquatic weeds downstream.<br>• Interrupt downstream/upstream passage of aquatic organisms.<br>• Retention of sediment and soil nutrients behind the dams in the reservoir and changes in water quality downstream. | • Moderate-High<br>• Moderate<br>• Moderate-high<br>• Moderate-High |
| Biomass energy (Rather et al., 2022) | • Reduced GHS emissions compared to fossil fuels. | • Exhaustive utilisation of land and water resources.<br>• High soil erosion rate.<br>• Highwater run-off due to soil erosion.<br>• Removal and loss of soil nutrients.<br>• Loss of natural wildlife, habitat, and biota. | • Moderate<br>• Moderate<br>• Moderate<br>• Moderate<br>• Moderate |
| Geothermal energy (De Jesus, 2016) | • Reduced GHS emissions compared to fossil fuels. | • High water demand.<br>• Land subsidence.<br>• Surface disturbance due to the construction and operation of the plant.<br>• Induced landslides and seismic activities.<br>• Thermal pollution associated with waste heat rejection.<br>• *Noise associated with plant construction and operation.*<br>• The offensive odour associated with the abstracted fluid.<br>• Soil contamination associated with soil washout extracted from the geothermal field. | • Moderate<br>• Moderate<br>• Moderate<br>• Moderate<br>• Moderate<br>• Moderate<br>• Moderate<br>• Moderate-High |

The proposed potential scenarios by IRENA for achieving the 2035 goal of having 42% of electricity production from RE sources are discussed below.

Scenario 1: The 42% target will be divided between solar, wind and hydropower, where solar PV is 22%, wind energy is 14%, CSP is 4% and hydropower is 2%. In that scenario, the hydropower will remain the same as of 2022 with no plans to increase the capacity. The solar PV and CSP will increase by nearly 16 and 600 times compared to the current situation, respectively. The wind energy will rise from 1625 MW to 18,000 MW leading to 11 times increase. Even though this scenario seems very ambitious, the minister of NREA said in October 2020 that they are looking for ways to increase the electricity generation based on renewables to 60% by 2035. However, no proposed plans have been disclosed until now (Al-Aees, 2020). IRENA recommended that to achieve the 2035 goal, the Egyptian government must consider key measures, starting with updating the current strategies of the electric power sector to reflect the RE benefits, while clarifying the institutional responsibilities and simplifying the regulations. They also stressed the need for an updated energy strategy to include biomass as a high potential source of energy that is neglected in the current proposed plans. There is a need for reforming the current market framework to develop the projects with economic feasibility while conducting inclusive campaigns to evaluate the wind and solar energy capabilities. They advised expanding the RE complexes to certify financial feasibility, support the risk mitigation, establish a strategic plan to improve local manufacturing and create a prosperous local industry (Farag, 2019).

Scenario 2: The target of 42% by 2035 cannot be achieved from only solar, hydro and wind energy as proposed by the government. However, integration between all available sources of RE is a must to achieve such a high percentage. Although some RE sources hold only a limited potential, harnessing them will be crucial to achieving NET-ZERO targets. The authors propose a scenario based on the conducted literature survey and the potential resource maps of Egypt. There will be no potential to increase the hydropower in this scenario due to the current situation with GERD, meaning it will be responsible for 2% of electricity production by 2035. The proposed scenario will be divided between five RE sources, where solar PV and CSP will produce 15% and 8% of the required electricity in 2035, respectively. The proposed locations for solar energy are the southern Saini Peninsula, the Gulf of Suez, Al Dakhla and Al kharga oasis, together with the coasts of the Red Sea and the eastern side between Asyut and Fayoum. Wind energy could account for 14% with wind farms in Gulf of Suez, Matrouh, Alsalom, Al Kharga, Asyut and alongside the coast of the Red Sea. Biomass with a percentage capacity of 2.97%, will equally be distributed in Beheria, Gharbia, Beni Suef and Sohag. Then, geothermal can provide 0.03% of electricity from

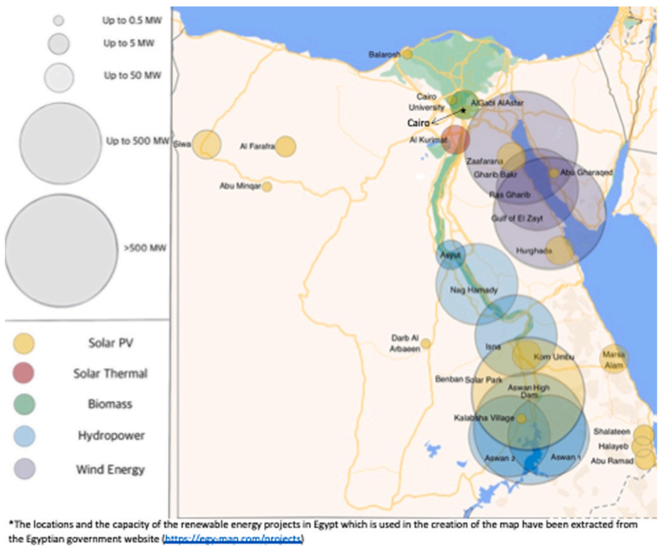



**Fig. 15.** Egypt's map of the current renewable energy projects plants.

sources located in the Gulf of Suez (Hammam Faroun). All the proposed locations have enough vacant lands that can be used in the construction of the power generation establishments for future needs.

## 17. Conclusions

Cleaner production is significantly important to avoid environmental damages, considering the catastrophic natural disasters that are frequently happening worldwide due to global warming effects and the massive scale pollution of natural resources. Sustainable development, through efficient management of energy resources, is an important pillar in cleaner production and set the way forward in achieving the NET ZERO target that the whole world aims to fulfil in the next few decades. Nevertheless, only a few review studies have been reported to investigate the potential RE technologies that should be used in Egypt in the coming decades for power generation purposes. This paper has presented a comprehensive review of the energy outlook in Egypt, including investigating the country's potential in harnessing all the possible sustainable energies while analysing the Egyptian situation compared to the world averages and addressing the challenges facing the development of renewable energy sector. Egypt is lagging behind many other countries in implementing renewable energy technologies; it is globally ranking at the thirty-first position in solar energy utilisation. In the meantime, the utilisation of bio, geothermal, wave and nuclear energy accounts only for 0.16% of the total electricity generation of the country, although these sources can offer a much higher level of contribution to the nation's energy needs. The following are some of the guidelines regarding these energy sources to provide energy security for Egypt's development and welfare for a foreseeable future:

- Investment in renewable energy projects by the private sector should be facilitated and encouraged.
- Several locations can be used for solar energy utilisation with a great potential for areas between the Red Sea coast and the Nile River.
- The wave energy potential can be exploited for small scale power generation in rural areas with coastal access.
- The government needs to come to an agreement with the Ethiopian authorities to find a solution that could be beneficial for both countries. This agreement is important for the Egyptian side to keep the hydropower production constant and allow for future plans to increase the hydropower production.

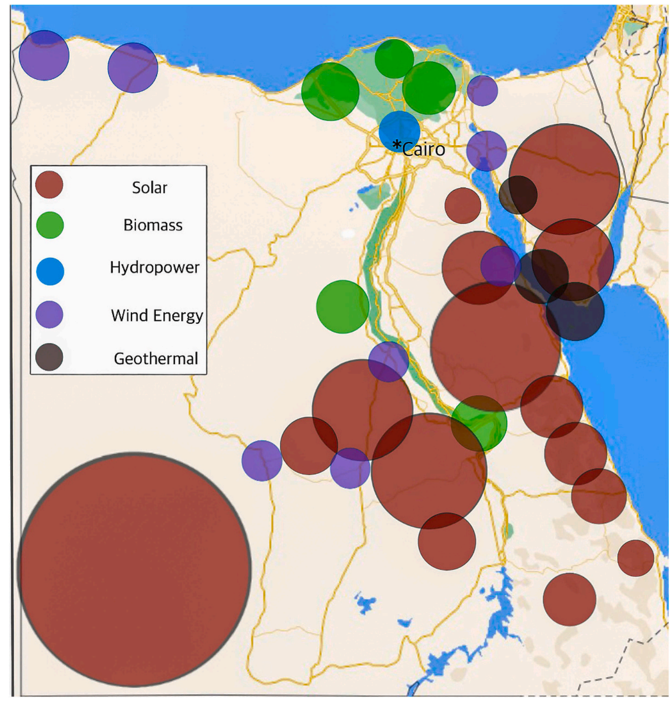



**Fig. 16.** Egypt's map of the potential renewable energy locations.

- The Gulf of Suez is the best location in Egypt which can supply 100% of its consumption from renewable energy because of the high potential of solar, wind and geothermal sources.

**Table 12**
Current RE projects in Egypt.

| RE Technology | Power (MW) | Location | Governorate |
|---|---|---|---|
| Hydro-power | 2100 | Aswan High Dam | Aswan |
| Hydro-power | 280 | Aswan 1 | Aswan |
| Hydro-power | 270 | Aswan 2 | Aswan |
| Hydro-power | 86 | Isna | Qena |
| Hydro-power | 64 | Naga Hamady | Qena |
| Hydro-power | 32 | Asyut | Asyut |
| Wind energy | 240, 220, 120 | Gulf of El Zayt 1, 2, 3 | Ras Gharib city, Red Sea |
| Wind energy | 545 | Zaafarana | Ras Gharib city, Red Sea |
| Wind energy | 250 | Gulf of Suez (under construction) | Red Sea |
| Wind energy | 250 | Ras Gharieb | Red Sea |
| Solar CSP | 20 | Al Kuraymat | Giza |
| Bioenergy | 10 | Algabal Alasfar | Qalyubia |
| Solar PV | 1465 | Benban Solar Park | Aswan |
| Solar PV | 250 | Kom Umbu (under construction) | Aswan |
| Solar PV | 50 | Zaafarana (under construction) | Ras Gharib city, Red Sea |
| Solar PV | 1465 | Benban Solar Park | Aswan |
| Solar PV | 26 | Kom Umbu | Aswan |
| Solar PV | 20 | Hurghada | Red Sea |
| Solar PV | 10 | Siwa | Matrouh |
| Solar PV | 6 | Marsa Alam | Red Sea |
| Solar PV | 5 | Shalateen | Red Sea |
| Solar PV | 5 | Al Farafra | New Valley |
| Solar PV | 2 | Halayeb | Red Sea |
| Solar PV | 2 | Abu-Ramad | Red Sea |
| Solar PV | 0.66 | Cairo University | Giza |
| Solar PV | 0.5 | Darb Al Arbaeen | New Valley |
| Solar PV | 0.5 | Abu-Minqar | New Valley |

**Table 13**
FIT values for renewable sources of energy.

| Reference | Source of electricity generation | FIT ($/kWh) | Location |
|---|---|---|---|
| Abdulrahman and Huisingh (2018) | Biomass | 0.13 | Delta |
| Lashin (2013) | Geothermal | 0.12 | Hammam Faraun |
| Aboulela et al. (2021) | Geothermal | 0.050–0.065 | Gulf of Suez |
| Desideri and Campana (2014) | Solar CSP | 0.19 | Luxor |
| Sadeq et al. (2020) | Solar PV | 0.076 | Alexandrea |
| Sadeq et al. (2020) | Solar PV | 0.035 | Aswan |
| Abdelhady et al. (2017) | Wind | 0.075 | Alexandria (off-shore) |
| Abdelhady et al. (2017) | Wind | 0.079 | El-Dabaa (off-shore) |
| Ahmed Shata and Hanitsch (2006) | Wind | 0.024 | El-Dabaa |
| Ahmed (2018b) | Wind | 0.0184 | Ras Seder |
| Ahmed (2018b) | Wind | 0.0422 | Nabq |
| Abd El Sattar et al. (2020) | Wind | 0.041–0.052 | Abo drag, Zafarana, Ras Gareb and Gulf of El-Zayt |
| Abd El Sattar et al. (2020) | Wind | 0.095–0.121 | Marsa Matrouh, Sidi Barrani, El-Suez and Hurghada |
| Abd El Sattar et al. (2020) | Wind | 0.326–0.941 | Alexandria, Port- said, Qena, Aswan |
| Ahmed and Abouzeid (2001) | Wind | 0.015 | Sharq El-Ouinat City |

- The Mediterranean coast can be used for wind energy mainly in locations such as Sallum, Matruh and Port Saied.
- Southern Egypt also has a high potential in solar, wind and bioenergy but it is not as concentrated as the Gulf of Suez region.
- Biomass from agricultural waste has a significant energy generation potential and could contribute significantly to fulfilling the growing energy demand in Egypt, no much attention has been paid so far in this regard.
- Middle Delta has the highest potential for biomass power stations since most of the residues from agricultural, manure, sewage, and municipal solid wastes are the highest in this region, and this makes this region to be a perfect location to initiate biomass related power generation.
- The development of geothermal power plants across the coastal areas of the Gulf of Suez is a promising step forward for increasing the share of geothermal energy but this should be implemented carefully without damaging the nature.
- There should be more attention and extensive scientific works to develop new geothermal-fed communities around Hammam Faraun spring, for touristic purposes.
- The FIT initiative should be applied to all renewable energy sources including biomass and geothermal.
- Several actions should be taken to overcome the existing challenges that includes infrastructure challenges, fossil fuel subsidies and high-interest rates.
- The government should provide the necessary support for small and medium scale industries to actively contribute to local technology development and enhance renewable energy competitiveness in the energy market.
- New/modified legislation should be needed to support the implementation of renewable energy technologies and the interconnection with neighbour countries.
- Training programs should be structured and launched for local labours to enrich the knowledge of the workers in the field. Also, all investors, producers and consumers of energy should be responsible for following the required precautions and procedures to protect the environment and nature.
- There should be some nation scale programmes to educate the nation on the importance of moving towards the RE sources and to clarify their role in the NET-ZERO journey.

Ultimately, further development of the renewable energy sector in Egypt should allow for meeting the Kyoto agreement by reducing $CO_2$ emissions and actively participating in solving the global warming problem. This paper set some guidelines and information for the Egyptian authorities to realise their renewable energy goals and explore sustainable solutions for the existing energy challenges. More importantly, unlike most of the previously reported papers, this paper provides a clear and complete overview of Egypt's energy profile in all possible aspects. The details presented in the paper should be useful for the research community in the area of renewable energy technologies.

## CRediT authorship contribution statement

**Salma I. Salah:** Conceptualization, Writing – review & editing. **Mahmoud Eltaweel:** Conceptualization, Writing – review & editing. **C. Abeykoon:** Conceptualization, Writing – review & editing.

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## Nomenclature

*Acronyms*

| | |
|---|---|
| BSRD | Bioenergy Rural Development Project |
| BSPs | Bioenergy service providers |
| BOO | Build-Own-Operate |
| BCM | Billion Cubic Meters |
| BES | Battery Energy Storage |
| CAES | Compressed Air Energy Storage |
| COE | Cost of Energy |
| CSP | Concentrated Solar Power |
| CC | Combined Cycle |
| CDM | Clean Development Mechanism |
| COE | Cost of Energy |
| CAES | Compressed Air Energy Storage |
| DNI | Direct Normal Irradiance |
| DES | Seawater Desalination |
| EETC | Egyptian Electricity Transmission Co |
| EEHC | Egyptian Electricity Holding Company |
| EEAA | Egyptian Environmental Affairs Agency |

| | |
|---|---|
| EPC | Engineering, Procurement and Construction |
| ETC | Evacuated Tube Collectors |
| FIT | Energy Feed-in Tariff |
| FDP | Floating Desalination Plant |
| FPSO | Floating Production Storage and Offloading system |
| FIT | Feed-in Tariff |
| FC | Fuel Cell |
| FBES | Flow Battery Energy Storage |
| FES | Flywheel Energy Storage |
| GERD | Grand Ethiopian Renaissance Dam |
| GDP | Gross Domestic Product |
| GIS | Geographic Information Systems |
| GHI | Global Horizontal Irradiation |
| HESS | Hydrogen Energy Storage System |
| HPPEA | Hydroelectric Power Plants Executive Au- thority |
| ISCC | Integrated Solar Combined Cycle Power Plants |
| IRENA | International Renewable Energy Agency |
| IRR | Internal Rate of Return |
| IWMP | Integrated Water Management Program |
| IPH | Industrial Process Heat |
| KfW | Kreditanstalt fur Wiederaufbau |
| LFR | Linear Fresnel Collectors |
| LEC | Levelised Electricity Cost |
| MENA | Middle East and North Africa |
| MED | Multi-Effect Distillation |
| MTOE | Million Tonnes of Oil Equivalent |
| MOERE | Ministry of Electricity and Renewable Energy |
| MCA | Multi-Criteria Analysis |
| NPC | Net Present Cost |
| NPV | Net Present Value |
| NREA | New and Renewable Energy Authority |
| NBI | The Nile Basin Initiative |
| OWC | Oscillating Water Column |
| PV | Photovoltaic |
| PTC | Parabolic Trough |
| PHES | Pumped-Hydroelectric Energy Storage |
| RE | Renewable Energy |
| RO | Reverse Osmosis |
| SUMED | Suez-Mediterranean Pipeline |
| SDHW | Solar Domestic Hot Water |
| SET | Solar Energy Technologies |
| SWH | Solar Water Heating |
| SD | Solar dish |
| SCES | Supercapacitor Energy Storage |
| SMES | Superconducting Magnetic Energy Storage |
| SIPH | Solar Industrial Processing Heat |
| SPT | Solar Power Tower Systems |
| TDC | Thermally Driven Chiller |
| TPI | Turbine Performance Index |
| TESS | Thermal Energy Storage System |
| TDS | Total Dissolved Solids |
| UPHES | Underground Pumped-Hydroelectric Energy Storage |
| VVER | Water-Water Energy Reactor |
| WET | Wind Energy Technologies |
| WTG | Wind Turbine Generator |
| WEC | Wave Energy Converter |
| WWTPs | Wastewater Processing Plants |

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