Solar Energy in Africa - An Overview, with a Focus on Egypt

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Abstract. More than 85% of Africa's land area receives a high amount of solar energy, at least 2,000 kWh/m^2 per year, making it the most sunlit continent on the planet. Despite having the potential to produce 40% of the world's solar power, Africa currently contributes only 1.48% of the total global capacity for electricity production from solar energy. Many African counties currently focus on transforming their fossil-fuel powered electricity sector into a low-carbon system to reduce their CO_2 emissions and therefore solve the climate change problem. The aim of this paper is to present the current situation and future outlook of solar energy in Africa, focusing on Egypt. Egypt has a great opportunity for solar energy development, as it receives a high amount of solar radiation throughout the year, ranging from 9 to 11 h per day. It also hosts one of the largest solar energy projects in the world, the Benban Solar Park in Aswan.

Keywords: solar energy · renewable energy · Africa · Egypt

1 Introduction

Energy consumption affects our lives in many aspects such as industry, health, food production, security, and peace. Fossil fuels (such as coal, natural gas, and oil products) are the main sources of energy for most countries in the world. The percentage of electricity generated by renewable energy sources rose to nearly 13% in 2021, and they are likely to rise more in the future and take the place of the non-renewable ones [1, 2].

The increasing energy demands especially in times of the Ukraine-Russian war and increasing world population challenges abundance [3]. Moreover, the utilize of these fossil fuels as the main source of energy has also aggravated global warming [4].

The world population has grown by about 2,000 times since 12,000 years ago, as shown in Fig. 1, where the population since 1950 is displayed [5]. As the world population approaches 10.9 billion by 2100, with a yearly growth rate of less than 0.1% which cause a flattening in the world population in the next decades with increasing the world population and the rapid electrification of many processes, the global electricity demand is growing [6].

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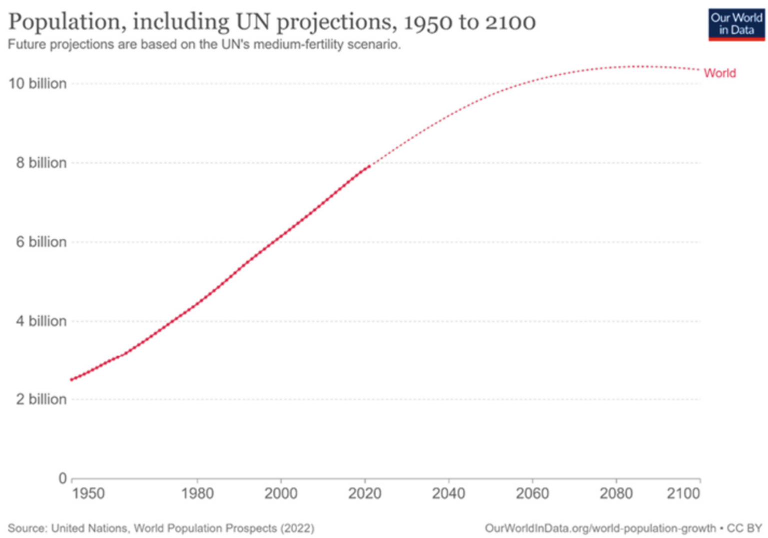

Fig. 1. The increasing number of people living on our planet since 1950 [7].

Leading researchers consider climate change as a major threat to the future of humanity [8, 9]. Since 2010, the world has experienced the ten hottest years on record, and 2022 ranked as the sixth highest in terms of global temperature since 1880, when the records began [10]. Climate change has resulted from the long-term use of fossil fuels as a primary energy source, and it will keep getting worse if we do not adopt alternative sources of energy. The environment and livelihoods are affected by the constant release of carbon dioxide (CO_2) and other greenhouse gases (GHG) such as Methane (CH_4), and Nitrous oxide (N_2O) [11]. Climate change, which is caused by the long-term use of fossil fuels as a main energy source, will alter the planet's geography, cause water scarcity, and accelerate the extinction of animals and the loss of biodiversity if we fail to slow down, control, and stop it. To solve these problems, we have to use low-carbon sources instead of fossil fuels [12].

The UN announced in 2015 a plan for Sustainable Development that consists of 17 objectives to be achieved by 2030. Goal 7 of the 17 goals that the UN set for the 2030 agenda for Sustainable Development is to "Ensure access to affordable, reliable, sustainable and modern energy for all". The aim of this goal is to increase the share of renewable energy and encourage investment in energy infrastructure and clean energy technology to create a green energy future (UN, 2015). The global CO_2 emissions from energy use dropped by 5.8% in 2020 due to COVID, according to the International Energy Agency's report in 2021. However, the global energy-related CO_2 emissions in the atmosphere did not change [13]. The global community has a long-term aim of reaching net zero CO_2 emissions by 2050, which requires various measures, such as changing from conventional fuels to low or zero carbon energy sources, as this is the most viable single way to stabilize the climate [14]. The report by IRENA in 2022 states that the percentage of renewable energy in electricity production needs to rise from 19% in 2019 to 79% by 2050 [15].

Renewable energy sources (such as wind, solar, hydro, tidal, biomass, geothermal, and wave) are gaining attention from many countries and international organizations. They think that these sources are vital for sustainable development, environmental protection, green gas emission reduction, and energy security [16–18]. Renewable energy technologies are becoming more common in both high-income and low-income countries as they are more affordable, dependable, and accessible [19]. Recently, more and more countries are getting interested in investing in renewable energy but developing countries start to show incredible attention toward investment in green energy sources (Fig. 2). Low-income countries surpassed high-income countries in renewable energy investment per capita in 2021, with 491 USD and 42 USD respectively [20].

Renewable energy systems are becoming more viable as the cost of renewable sources continues to decline. Solar energy is the most promising renewable energy source, as it can provide clean, dependable, and safe power. The solar energy that arrives the Earth's landmasses is over 27 times higher than the total annual commercial energy that humans use, making it a very attractive renewable resource [21, 22].

The amount of solar energy that the surface gets during a certain time period is related to solar radiation, which is the most important factor for scientists to decide where to install solar power farms [23, 24]. The total radiation that reaches the horizontal surface on the ground, called global horizontal irradiation GHI (kWh/m^2), is usually measured either daily or yearly. High GHI values indicate good locations for investing in photovoltaic (PV) farms [25–27].

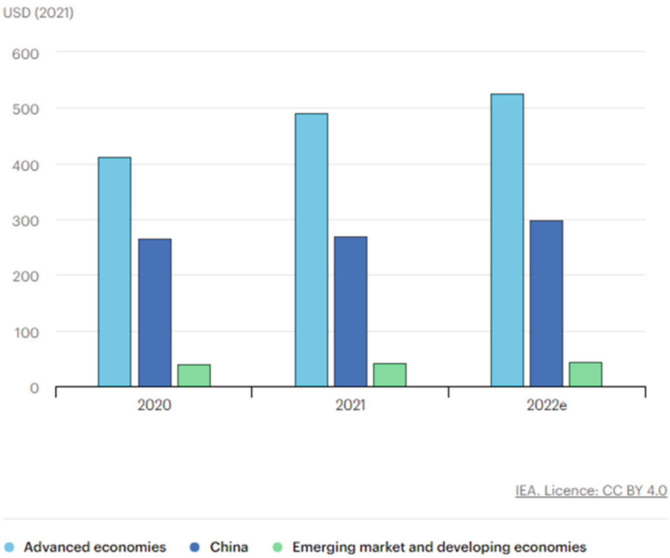

Fig. 2. Global New Investment in Renewable Energy per capita: advances and emerging economies [20].

2 A Quick Overview of Global Solar Energy

Figure 3 shows the GHI map for the Earth. To determine the best areas for PV farms investment, solar potential is classified according to GHI data into superb potential (annual GHI > 2221.8 KWh/m^2), outstanding (annual GHI from 2035.9 to 2221.8 KWh/m^2), excellent (annual GHI from 1843.8 to 2035.9 KWh/m^2), good (annual GHI from 1641.8 to 1843.8 KWh/m^2), fair (annual GHI from 1419.7 to 1641.8 KWh/m^2), marginal (annual GHI from 1191.8 to 1419.7 KWh/m^2), and poor (annual GHI < 1191.8 KWh/m^2) classes. From Fig. 3 we notice that almost 40% (60 mil km^2) of the land area on Earth has high solar resources with potential classes of superb, outstanding, and excellent (>1800 kWh/m^2 per year) for GHI. The analysis reveals that there are six main regions in the world with high GHI (Australia, Arabian Peninsula, eastern, northern, and southwestern Africa, and the western coast of South America). The solar resources in Africa are the highest in the world (Fig. 3), with 90% of the continental area is in superb, outstanding, and excellent classes. Furthermore, one-third of Africa's area (almost 10 mil km^2) has the highest potential for solar energy, based on GHI (Fig. 4) so, Africa is the best continent location for large-scale PV systems [28].

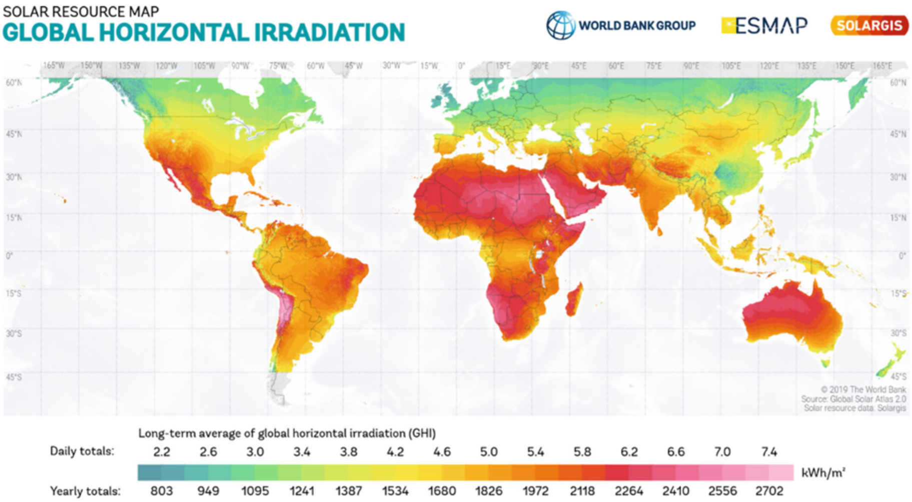

Fig. 3. Global horizontal irradiation map for the Earth [31].

Australia, the smallest continent on Earth (~8 mil km^2), has almost all of its area covered by the three highest classes of GHI (superb, outstanding, and excellent) (Fig. 4). The superb class, which has the highest solar energy potential, occupies a huge area of 2.4 mil km^2 (~30% of the total) [28]. More than 11 GW of solar PV capacity is installed on over 30% of Australian homes, which shows how Australians make use of the abundant solar energy available to them [29].

Asia has the biggest land area on Earth (~45 mil km^2), but only a small portion of it (almost 10 mil km^2, 22% of the continent's area) has high GHI resources compared to its size (excellent, outstanding, and superb GHI classes). However, it still produces a

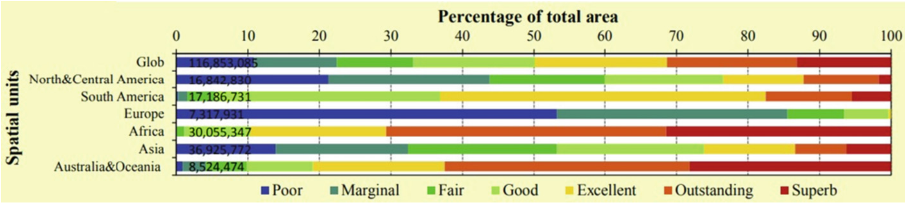

Fig. 4. Percentage classes' extent of GHI (kWh/m^2). Note: the absolute values on the left of the columns represent the total analyzed continental area (the global land area = 116,853,085 km^2, the land area of North & Central America = 16,842,830 Km^2, the land area of South America = 17,186,731 Km^2, the land area of Europe = 7,317,931 Km^2, the land area of Africa = 30,055,347 Km^2, the land area of Asia = 36,925,772 Km^2, and the land area of Australia & Oceania = 8,524,474 Km^2) [28].

lot of PV power [28]. Over the last ten years, Asia added 40 GWp of solar PV each year and almost 80 GWp in 2020. This annual addition is expected to increase to 210 GWp through 2030. This great expansion concentrated in India and China. Solar PV production in North America and Europe increased twofold in 2020, and they are projected to have 19% and 14%, respectively, of the global solar PV installations by 2030. Africa and the Middle East have abundant GHI resources, but they have not invested much in the PV sector so far. They should prioritize solar PV projects, as they will need 70 GWp of yearly installations in this decade (IRENA, 2022) [30].

3 Africa's Solar Energy Prospects

The whole world is looking to Africa and the future of solar energy in it for many reasons. First, Africa occupies about one-fifth of the total land area of the Earth (the land area of Africa is approximately 30,365,000 km^2) [32]. Second, high population in Africa where the current population of Africa is estimated by the United Nations to be about 1.4 billion people and is expected to grow more than twice by 2050 reaching about 2.4 billion in a world where population growth is decreasing [33]. This increasing population has the lowest degree of electrification in the world. One of the areas most affected by this low in electricity in Africa is sub-Saharan Africa where more than two-thirds of people without access to electricity in the world live in this area So, we need new sources of energy to compensate this deficiency [34]. Third, The United Nations has identified Africa as the continent that is most susceptible (although the least responsible) to the impacts of climate change due to human activities, population growth, impending water shortages, and low capacity to adapt [35–37]. For example, the current electricity production in Africa mostly relies on fossil fuels (30% Coal, 9% Oil, and 40% natural gas), and continuing at this percentage increases the risk of climate change. The final reason is that Africa is blessed with solar energy in most of their countries (Fig. 5) [34].

Africa is the continent that receives the most sunlight on Earth, with more than 85% of its land area getting at least 2,000 kWh/m^2 of solar radiation every year [38]. Africa has the highest potential for solar power in the world, with 40% of it, but it only contributes 1.48% of the total global capacity for electricity production from solar energy [39]. Many

African countries have the goal of transforming their fossil fuel-based power sectors into low-carbon energy systems to lower their CO_2 emission. Almost all African countries have suitable solar resources but there are only 9 countries that are actual GHI hotspots taking into consideration that at least 50% of the area of the country has superb potential, those countries are Djibouti (52%), Libya (56%), Eritrea (58%), Chad (69%), Western Sahara (72%), Egypt (77%), Niger (84%), Sudan (86%), and Namibia (96%) (Fig. 5 and 6). However, the first 9 hotspots in terms of absolute areas in Africa are Sudan (~1.6 mil km^2), Niger (~1 mil km^2), Chad (~900,000 km^2), Libya (~900,000 km^2), Egypt (~800,000 km^2), Namibia (~800,000 km^2), Algeria (~700,000 km^2), Mauritania (~400,000 km^2), and Mali (~400,000 km^2) (Fig. 6) [28].

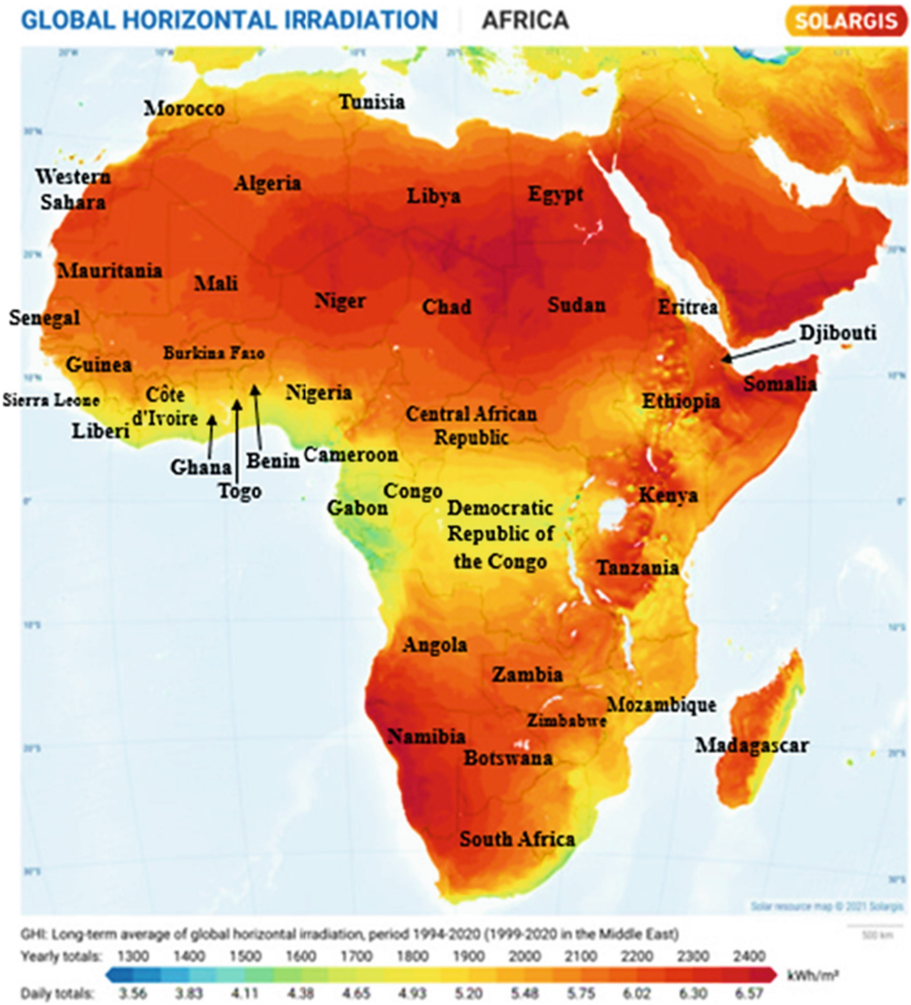

Fig. 5. Global horizontal irradiation map for Africa [40].

The continent's capacity for installing solar PV has grown from 8 GW in 2009 to 47 GWp in 2015 [41]. The Africa Solar Industry Association (AFSIA) reported that Africa's solar capacity increased by 989 MWp in 2022, a 14% growth compared to the previous year, and the continent's total solar capacity surpassed 10 GWp by the end of that year. However, The International Energy Agency predicts that Africa will need 497 GW of PV power by 2030 [42].

4 Solar Energy in Egypt

A region called the "Sun Belt" covers vast parts of the United States, North Africa, the Middle East, and the Mediterranean [43]. Egypt is part of this region, which belongs to the North Africa and Middle East area. The country gets direct solar radiation between 5.5 and more than 9.0 kWh/m^2 per day, and has a daily sunlight duration of 9 to 11 h [44]. According to IRENA, Egypt has one of the best conditions in the world for using solar energy for electricity and heating purposes [45]. The population of Egypt is 110 million and it is expected to grow to 160 million by 2050. The report by the Egyptian Electricity Holding Company in 2018 showed that only 10% of the total electricity generation capacity, which was around 54.5 GW, came from renewable energy sources [46]. By 2035, the Egyptian government has a plan to raise the percentage of electricity from renewable energy sources to 42%. Solar energy will provide 25% of this, wind energy will contribute 14%, and hydroelectricity will supply 2% (See Fig. 7) [47].

The highest potential locations in Egypt are Upper Egypt cities such as Asyut, Aswan, Luxor and around the Red Sea coast. According to Egypt-PV (2021), Egypt has over 125 solar PV power plants in operation, which can produce up to 9 GWp of electricity and decrease CO_2 emissions by about 9 t/y [48].

IRENA reports that solar energy projects have great economic importance [49]. Egypt's solar energy plan aims to achieve 3.5 GWp of installed capacity by 2027, with 2.8 GWp coming from photovoltaic and 700 MWp from concentrated solar power. This is much higher than the current electricity production in Egypt from solar energy [50, 51]. Under the supervision of the Ministry of Electricity and Renewable Energy, Egypt has launched several solar energy projects such as Benban, Zafarana, Siwa, Farafra, Darb El-Arbayeen, and Shalten (Fig. 8) [52].

Benban Solar Park (Fig. 9) is one of the largest solar PV stations in the world (The table 1 shows the world's top five solar parks by size). On average, Benban Solar Park produces about 18% of Egypt's total electricity generation [53, 54]. The total capacity of the Benban Solar Park is 1650 MW and it occupies 37.2 Km^2 of land near Benban village in the Aswan Governorate in Upper Egypt. NASA studies and reports were used to choose the project site, which was recognized by the World Bank as the best project of 2019. The Benban Solar Park is projected to generate 3.8 TWh of electricity annually, which is almost equal to 90% of the power output of the high dam in Aswan [55]. The Benban solar park is made up of 41 solar power plants, with different capacities depending on the shape of the land. Most of them (31) can produce 50 MW_{AC} (64 MW_{DC}) each, while the rest (10) have varying capacities [56]. The project included 40 specialized companies, with 10 from global and Arab regions. It cost 3.4 billion euros, which is equivalent to 40 billion pounds. It generated 200 direct and indirect jobs and helped avoid 2 million tons of CO_2 emissions [57].

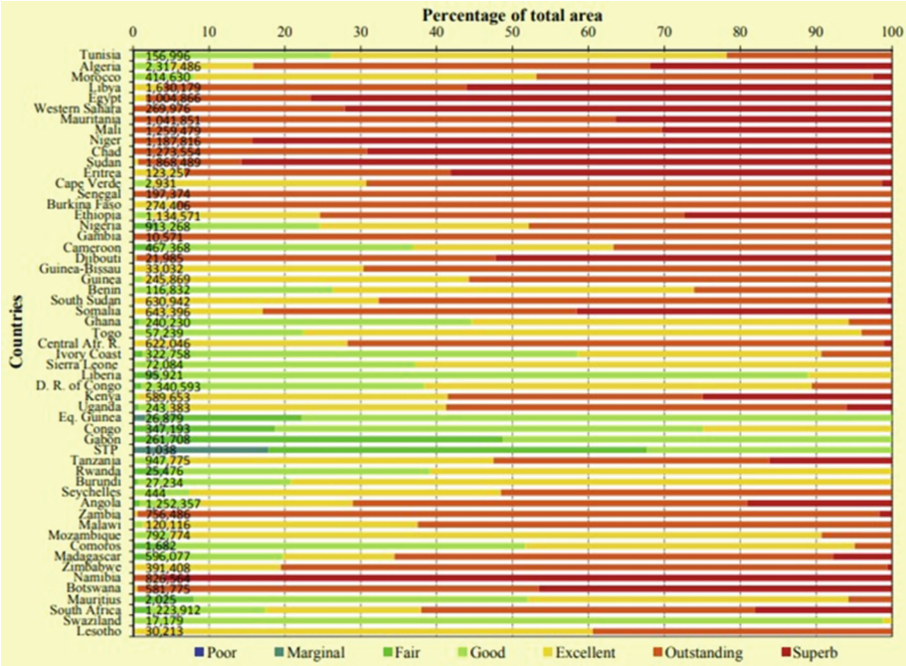

Fig. 6. Percentage classes' extent of global horizontal irradiation (kWh/m^2) in the countries of Africa. Note: the absolute values on the left of the columns represent the total national area (the land area of Tunisia = 156,996 km^2, the land area of Algeria = 2,317,486 Km^2, the land area of Morocco = 414,630 Km^2, the land area of Libya = 1,630,179 Km^2, the land area of Egypt = 1,004,866 Km^2, the land area of Western Sahara = 269,976 Km^2, the land area of Mauritania = 1,041,851 Km^2, the land area of Mali = 1,259,479 Km^2, the land area of Niger = 1,187,816 Km^2, the land area of Chad = 1,273,554 Km^2, the land area of Sudan = 1,868,489 Km^2, the land area of Eritrea = 123,257 Km^2, the land area of Cape Verde = 2,931 Km^2, the land area of Senegal = 197,374 Km^2, the land area of Burkina Faso = 274,406 Km^2, the land area of Ethiopia = 1,134,571 Km^2, the land area of Nigeria = 913,268 Km^2, the land area of Gambia = 10,571 Km^2, the land area of Cameroon = 467,368 Km^2, the land area of Djibouti = 21,985 Km^2, the land area of Guinea-Bissau = 33,032 Km^2, the land area of Guinea = 245,869 Km^2, the land area of Benin = 116,832 Km^2, the land area of South Sudan = 630,942 Km^2, the land area of Somalia = 643,396 Km^2, the land area of Ghana = 240,230 Km^2, the land area of Togo = 57,239 Km^2, the land area of Central African Republic = 622,046 Km^2, the land area of Ivory Coast = 322,758 Km^2, the land area of Sierra Leone = 72,084 Km^2, the land area of Liberia = 95,921 Km^2, the land area of Democratic Republic of the Congo = 2,340,593 Km^2, the land area of Kenya = 589,653 Km^2, the land area of Uganda = 243,383 Km^2, the land area of Equatorial Guinea = 26,879 Km^2, the land area of Congo = 347,193 Km^2, the land area of Gabon = 261,708 Km^2, the land area of São Tomé and Príncipe (STP) = 1,038 Km^2, the land area of Tanzania = 947,775 Km^2, the land area of Rwanda = 25,476 Km^2, the land area of Burundi = 27,234 Km^2, the land area of Seychelles = 444 Km^2, the land area of Angola = 1,252,357 Km^2, the land area of Zambia = 756,486 Km^2, the land area of Malawi = 120,116 Km^2, the land area of Mozambique = 792,774 Km^2, the land area of Comoros = 1,682 Km^2, the land area of Madagascar = 596,077 Km^2, the land area of Zimbabwe = 391,408 Km^2, the land area of Namibia = 826,564 Km^2, the land area of Botswana = 581,775 Km^2, the land area of Mauritius = 2,025 Km^2, the land area of South Africa = 1,223,912 Km^2, the land area of Swaziland = 17,179 Km^2, and the land area of Lesotho = 30,213 Km^2) [28].

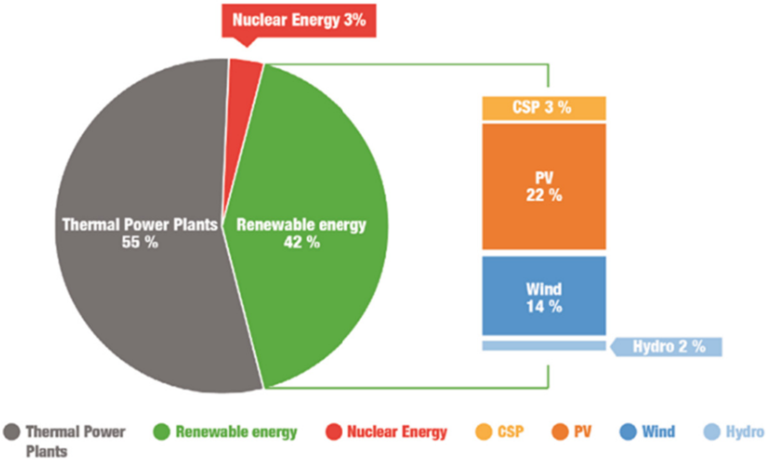

Fig. 7. Egyptian electricity target generation in 2035 [47].

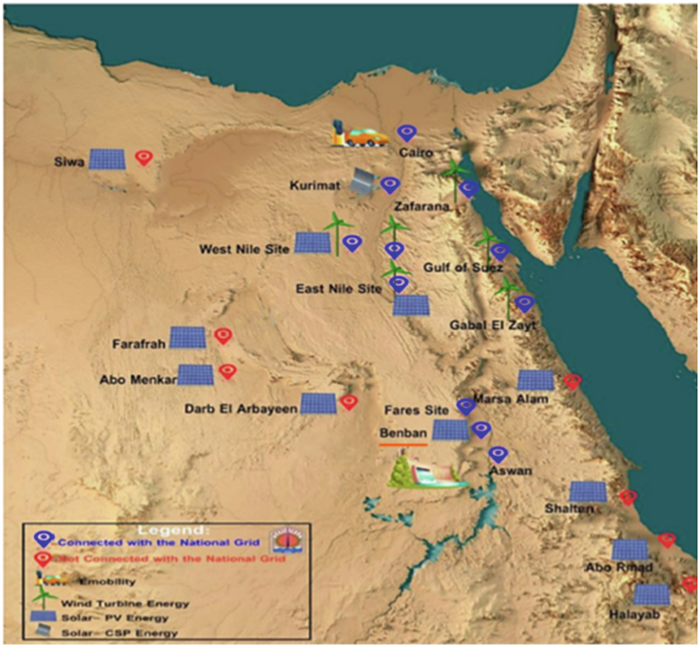

Fig. 8. Location of Benban Solar Park (We marked Benban with a red line, it is located 40 km northwest of Aswan city and has the coordinates 23.9786° N, 32.8739° E) [52].

The Web of Science database shows the trend of research articles on 6 renewable energy sources (i.e., wind, photovoltaic, concentrated solar, biomass, geothermal energies, and hydropower) in Egypt from 2010 to 2020 in Fig. 10. Researchers have shown great interest in renewable energy technologies in Egypt over the past decade. The

Fig. 9. Benban Solar Park [63].

Table 1. The world's five biggest solar parks, country, capacity, and area.

Name	Country	Capacity (MW)	Area (km^2)	Reference
Bhadla Solar Park	India	2,245	56	[58]
Pavagada Solar Park	India	2,050	53	[59]
Huanghe Hydropower Golmud Solar Park	China	2,200	42.5	[60]
Tengger Desert Solar Park	China	1,547	43	[61]
Benban Solar Park	Egypt	1,650	37.2	[62]

research papers on these technologies have a clear rising trend in Fig. 10, which indicates their importance for both the academic and industrial sectors. Another observation is that photovoltaic energy has received more attention than the other renewable energy sources in Egypt [64].

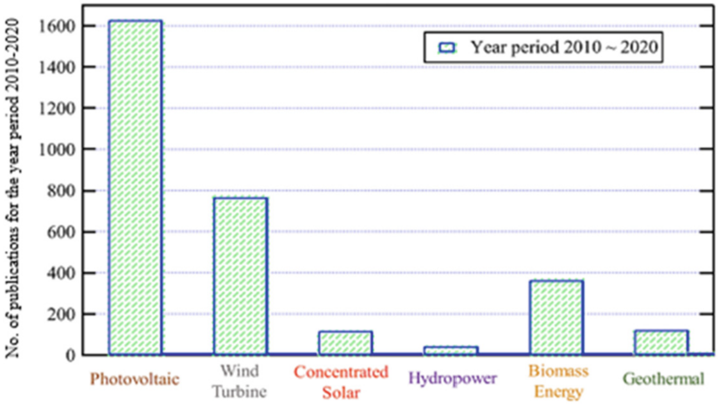

Fig. 10. The number of publications on renewable energy sources in the last 10 years [64].

5 Conclusion and Recommendations

This paper summarizes data of Africa's excellent solar resources, with a focus on Egypt. So far, these resources are not fully in use and its usage needs to get better. Egypt as example, has major GWp projects, yet not all possibilities of growth are explored. It is recommended that governments should integrate universities and research institutions beside industry to develop the renewable energy sector locally and regionally. This implies capacity building to make African researchers competitive on an international level and to increase the role universities play in technology development. Funds shall be more available for equipment and more recognition for research endeavors shall be anticipated. The future of research on this level in Africa and Egypt can be built through training, education, and increasing grant opportunities for researchers.

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