Assessment of the Planned Expansion of Renewable Energy in Egypt

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Abstract—In the continue of meeting the energy demand as well as decreasing the CO_2 emission and production costs, Egypt has expanded its power capacity of the renewable power plants. However, such expansion could lead to energy production failure due to the unreliable and unfeasible operation of such unconventional technology, if used without assessment. In this contribution, the planned expansion (till 2030) of renewable energy has been evaluated using an optimization model. The model has two phases, in which Phase-A estimates the cost and capacity of the PV, CSP, and Wind plants, while Phase-B optimizes the plants according to the required demand (i.e., the contribution of PV, CSP, and Wind). The available data (i.e., intensity, storage, and temperature effect) is used as an input to Phase-A, while the calculated cost and capacity are used as an input to Phase-B. The results are presented in terms of spatial and temporal distributions. The result successfully identified the promising renewable plants (i.e., type and location), as well as mix-installations of different renewable plants, were captured. Specifically, CSP plants contribute ≈20% of the power demand, especially in Upper Egypt, due to their higher capacities although their higher cost. Meanwhile, the PV plants are contributed ≈40% and are unpreferable for installation in Upper Egypt. Furthermore, it is recommended to install Wind plants near the Red-sea region with a ≈40% power contribution. This study is expected to insight our understanding into the planned expansion of renewable energies in Egypt; aiming to evaluate its potential.

Keywords—Renewable Energy Expansion; PV; CSP; Wind.

1. INTRODUCTION

In Egypt, the energy demand has rapidly increased due to the recent human consumption, which has doubled during the last decades, leading to significant growth in the installed power plants [1]. For example, the installed capacity has increased from ≈18 TWh (≈5 GW) in 1980 to ≈183 TWh (≈ 57 GW) in 2019. Such installed capacities have been dominated by fossil fuel based-plants (i.e., more than 90%), leading to a significant increment in fuel consumption [1]. However, the CO_2 emissions from such plants have increased global warming, which threaded human development. Besides, the fuel prices, which dominated the economic growth, have influenced the near-future of the electricity market, as the Egyptian gross domestic product has increased from USD 550 in 1980 to USD 2,930 in 2011 [1]. Thus, Egypt is looking for clean, cheap, and efficient power from renewable resources to further minimize the environmental impacts and contribute to the development of the green economy.

Recently, the Egyptian Renewable Authority has focused on the renewable energies, showing 9.5% renewable power generations (i.e., 48% hydro, 28% solar, 23% wind, and 1% biomass), as shown in Fig. (1a) based on the data of the US Energy Information Administration [1]. Although hydropower dominated renewable resources, most of the Nile River's hydropower potential has already been exploited. In contrast, there is no sufficient biomass resource to be considered for utility-scale power generation. Accordingly, the most promising renewable energies in Egypt are solar and wind resources, as they could continuously supply energy services; thereby improving energy security. This could be drawn from Fig. (1b); which shows a significant expansion of solar energy, especially in 2017. Considering solar energy, Egypt belongs to the global sun-belt, in which there is an advantageous position with solar energy. Based on the Solar Atlas, the annual global solar insolation is estimated to range from 1750 to 2680 kWh/m^2 and the annual direct normal solar irradiance is estimated to range from 1970 to 3200 kWh/m^2. Furthermore, the daily sunshine duration ranges from 9 to 11 hours with only a few cloudy days over the year [2]. This could vary according to the installed solar technology, either solar Photovoltaic (PV) or Concentrated Solar Power (CSP). For PV, Egypt has successfully expanded a 1.8 GW solar plant at Benban, which promises its future utility. For CSP, Egypt has successfully expanded a 140 MW combined cycle (20 MW CSP) power plant in the south of Cairo, resulting in more than 57,000 TWh [3] CSP electricity potentials. Thus, it is highly recommended to install such plants in Egypt [4]–[6]. Considering wind energy, the wind atlas of Egypt show minimum and maximum wind speeds of 4.4 km/h and 12.7 km/h, respectively [7]. It is a promising feature for future expansion of large-scale wind turbines. For example, with the current technology, the wind energy utilization for electricity generation is 65,000 MW, based on Mortensen et al. [7].

Consequently, the planned expansion of renewable plants has been developed through the Egyptian future vision, 2030. However, the renewable power plants are suffered from intermittency (i.e., non-controllable variability), as the renewable generation is varied according to the availability (e.g., wind speed and solar intensity) [8]. Such intermittency leads to net-load deformation not only in renewable power generation but in the conventional turbines as well [9]–[17].

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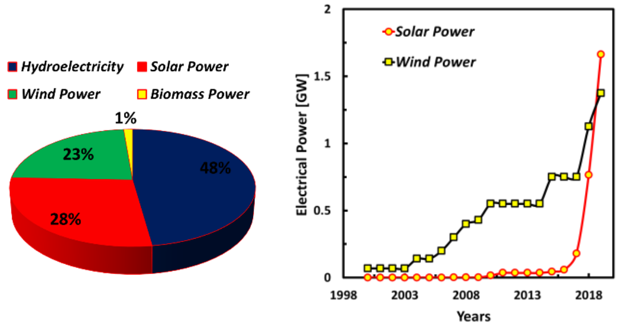
Accordingly, several techno-economic problems could be introduced, which probably threaten the stable and economic operation of the power system. The technical problems include supply/demand imbalances and cyclic operation of thermal generation units, which leads these units to work at their minimum stable generation levels with reduced efficiency and thus, increase their ramping requirements. This cyclic operation will also increase the mechanical stress on the internal parts, resulting in growing the maintenance requirements and reducing the lifetime of its thermal units. On the other hand, the economic problems include the economic losses in the national economy due to the shortage in electricity supplies, besides increasing in the operation and maintenance costs [18], [19]. Additionally, there will be frequent blackouts, if the energy expansion is not well planned. For example, it is obvious in recent years that most residential buildings are facing daily blackouts. This was obtained from the fact that the available power generation could not cover the steadily increasing demand, which resulted from the obvious lack of strategic planning. Thus, the assessment of the renewable expansion over Egypt to ensure sustainable operation is highly desirable.



(a) Renewable energy, 2019 *(b) Renewable energy Expansion*

Fig. (1) Renewable energy expansion of Egypt; reproduced from US Energy Information Administration [1].

Consequently, significant efforts have been done to evaluate the impact of national, regional, and global energy on the techno-economic policies to ensure sustainable strategies for the planned expansion using different optimization models. For example, Rout et al. [20] applied the long-term energy and emissions forecasting over China, Heinrich et al. [21] investigated the electricity supply industry for South Africa, Mondal et al. [22] performed technology selection for the Bangladesh power sector, and Panos et al. [23] assessed the policy and technology mixes required to achieve long-term energy security and environmental sustainability growth of Sub-Saharan Africa. The application of such models for Egypt can provide important insights into the implications of prospective conversion technologies and energy supply options that can be pursued by the government of Egypt in a cost-efficient and effective way. Additionally, the development of such comprehensive optimization models for the assessment of long-term energy strategies for Egypt is currently lacking; except very few studies. For example, Shaaban & Scheffran [24] developed a prototype model to assess energy security roadmaps. Riffai et al. [25] studied the economic development of solar and wind energies. Serverta & Cerrajero [26] and Shaaban et al. [27] assessed Egypt's CSP components and energy technologies, respectively. Recently, Mondal et al. [28] have performed an Egyptian future energy mixture according to actors' priorities.

While previous efforts have successfully assessed the planned expansion of renewable energies, very few studies have been conducted to model and study energy security performance. For example, Al-Ayouty & Abd El-Raouf [29] have drawn some policies that can pave the way toward greater energy security in Egypt. Based on that, Atlem & Rapiea [30] have modeled the future of energy security performance using a system dynamics approach (i.e., a comprehensive multi-dimensional modeling technique). It has the advantage to deal with complex and dynamic issues like energy security; simply and practically. However, those studies have not considered the temperature impacts on the plant performance. Based on the previous studies [31]–[33], the cell temperature has a negative impact on the PV efficiency. On the other hand, most of the previous studies have not considered the spatial distributions of the whole country, considering the current optimization method. Additionally, the optimization based-linear regression has not been presented in the open literature.

In this work, an optimization model is developed to access the planned expansion of renewable energy in Egypt till 2030; considering PV, CSP, and Wind energies. The optimization model has two phases, in which Phase-A estimates the cost and capacity of the PV, CSP, and Wind plants, while Phase-B optimizes the plants according to the required demand. The available data (i.e., solar intensity, wind speed, and ambient temperature) is used as an input to Phase-A, while the calculated cost and capacity are used as an input to Phase-B of the model. The results are presented in terms of spatial and temporal distributions.

Nomenclatures	
PV	Photovoltaic power plant
CSP	Concentrated Solar Power plant
Wind	Wind power plant
DNI	Direct Normal Irradiance
GHI	Global Horizontal Irradiance
PVGIS	Geographical Information System
a	Contribution of PV power [kW]
b	Contribution of CSP power [kW]
c	Contribution of Wind power [kW]
Alfa (α)	Learning rate
kWp	KiloWatt peak
η_{pv}/η_{ref}	PV efficiency compared with the reference
β	Temperature factor
T_{pv}	Cell temperature
T_{ref}	Reference temperature
T_{amb}	Ambient temperature
T_{NOCT}	Nominal operating cell temperature

2. METHODOLOGY

Considering the promising renewable power resources in Egypt, only PV, CSP, and Wind plants are considered in this study. However, installation of such plants is limited to different exclusion criteria (i.e., Topography, Hydrology, Terrain, Land Cover, Protected Areas, Population density, and Geomorphology). Such criteria have been developed by the Federal Republic of Germany's research Centre for aeronautics and space within the framework of the Middle East and North Africa Regional Water Outlook project [3]. Such geographic features were derived from remote sensing data and stored in form of GIS maps. The criteria considered for developing exclusion masks include [34];

- Terrain (i.e., any land with a slope greater than 2.1%).
- Land Cover (i.e., post-flooding, irrigated croplands).
- Protected Areas (i.e., Military regions).
- Population density (i.e., density >50 persons per km^2).
- Geomorphology (i.e., shifting sand with dunes).
- Hydrology (i.e., lake, reservoir, river).

Fig. (2) shows the exclusion map of Egypt, which is reproduced from Aly [34] and be used in the current study. The exclusion map is developed using MATLAB software; considering a 0.0 value as exclusion, while a 1.0 value is a useful site. It is obvious from Fig. (2) that the promising locations for installing renewable plants are located behind the Nile River. Noteworthy, the exclusion map is implemented in a matrix form so that all incoming figures accommodate similar concepts. The spatial resolution of the Egyptian map is considered as shown in Eq. (1) as 0.1 degrees on both the latitude and longitude axis.

$$Map = \begin{bmatrix} (25.0,32.0) & (25.1,32.0) & . & . & . & . & (36.9,32.0) & (37.0,32.0) \\ (25.0,31.9) & (25.1,31.9) & . & . & . & . & (36.9,31.9) & (37.0,31.9) \\ (25.0,31.8) & (25.1,31.8) & . & . & . & . & (36.9,31.8) & (37.0,31.8) \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ (25.0,22.2) & (25.1,22.2) & . & . & . & . & (36.9,22.2) & (37.0,22.2) \\ (25.0,22.1) & (25.1,22.1) & . & . & . & . & (36.9,22.1) & (37.0,22.1) \\ (25.0,22.0) & (25.1,22.0) & . & . & . & . & (36.9,22.0) & (37.0,22.0) \end{bmatrix} \quad (1)$$

2.1 Data Collection

Solar and wind energies have massive data that can be useful for statistical studies. Among all, the European Commission's science and knowledge service has shared such massive data via the Photovoltaic Geographical Information System (PVGIS) on their website [35]. The PVGIS maps the data by country and provides free open access to; full-time series of hourly values of nine climatic variables. Here, the data collection is limited to ambient temperature, intensities (i.e., wind speed for wind, direct normal radiation (DNI) for PV, and global radiation (GHI) for CSP), and average available hours. Accordingly, the country's map has been divided into 12,000 points, as the longitude is varied from 25^{o}E to 37^{o}E, while the latitude is varied from 22^{o}N to 32^{o}N, with a spatial resolution of 0.1x0.1 (see Eq. 1).

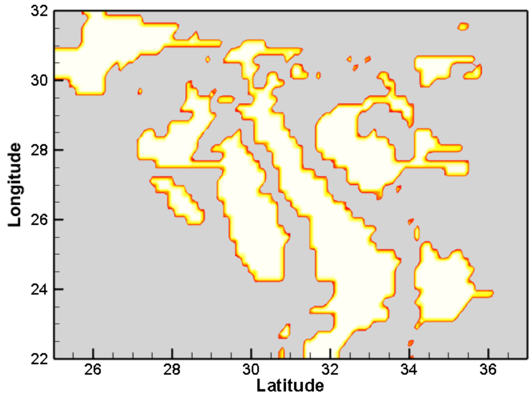
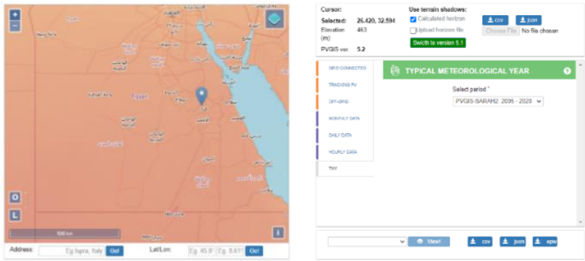


Fig. (2) Exclusion map of Egypt; reproduced from Aly [34].



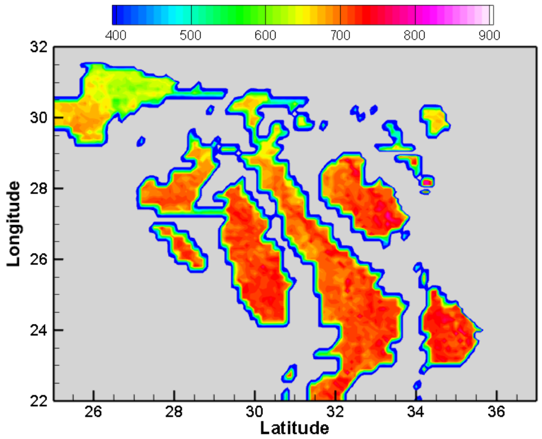
(a) Egyptian map *(b) Data selection*

Fig. (3) PVGIS system of Egypt for data selection and download.

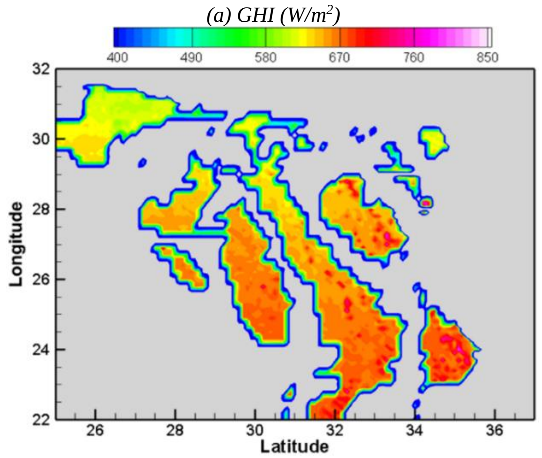
Fig. (3) shows the Egyptian map of the PVGIS system. To go through the website and download the available data, firstly, the site should be selected in both latitude and longitude directions. For example, the selection of Qena city (See Fig. 3a) shows 26.4 Latitude and 32.6 Longitude. Then, the methodology of data collection, as well as the average calculation, should be selected (see Fig. 3b). In this work, the data are collected from 2005 to 2020 yearly. Later, the download option will be provided via excel file. Fig. (4) shows the obtained intensities of GHI, DNI, and Wind powers over Egypt.

2.2 Optimization Model

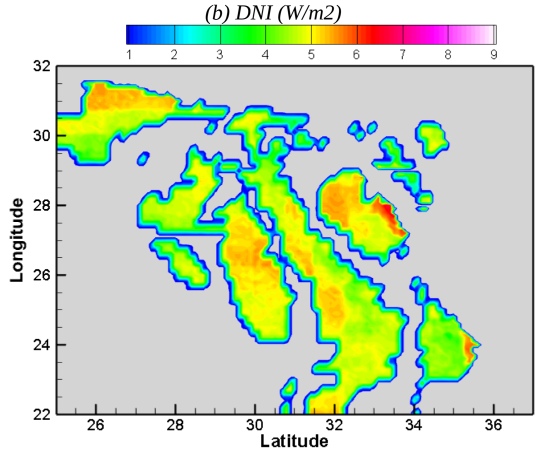
Throughout the current methodology, the main target is to assess the existing renewable plants besides obtaining the optimum future expansion based on minimum cost and maximum capacity; considering the future power demand over the whole country. Fig. (5) shows the schematic diagram of the optimization model. The model is running through two phases. In Phase-A, the exclusion, intensity, storage, and temperature data are fed into the model to calculate the cost and capacity of each plant. The intensity of PV and CSP plants are considered in the obtained global horizontal irradiance (GHI) and direct normal irradiance (DNI), respectively, while the intensity of wind plants is considered in the obtained Wind speed. Then, Phase-B provides the optimum mix between the renewable plants (i.e., a, b, c in Fig. 5), considering the cost and capacity, through the linear regression function of each year.



(a) GHI (W/m²)



(b) DNI (W/m2)



(c) Wind (m/s)

Fig. (4) Obtained data intensities (i.e., GHI, DNI, Wind speed) for Egypt.

However, Phase A requires the cost of each kWh and the energy production of each kWp. Based on the obtained data [36], Fig. (6) shows the energy production from the PV, CSP, and Wind power plants based on the already installed plants. For the PV plant (Fig. 6a), the output energy is describing the regularly available intensity for each square meter based on the Benban PV park. For the CSP plant (Fig. 6b), the output energy is describing the regularly available intensity for each square meter based on the Kyrimat CSP plant. For the Wind plant (Fig. 6c), the output energy is describing the regularly available intensity for each square meter based on the Zafarana Wind plant. Noteworthy, the capacity of PV and CSP plants (i.e., hours) is obtained from the PVGSIS website as an annual average data from the solar radiation. For Wind plant, the hour capacity is obtained from the running time of the turbine [36].

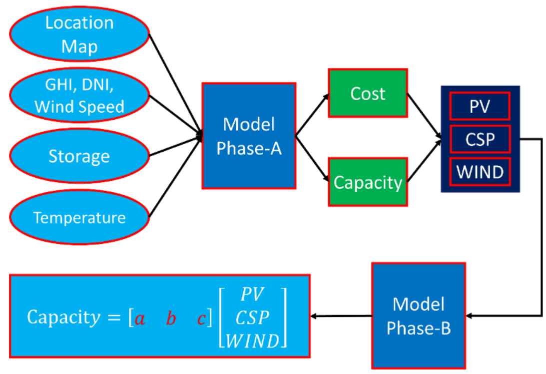
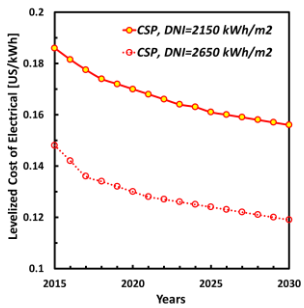
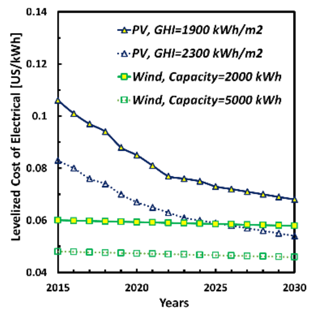


Fig. (5) Schematic diagram of optimization model of the current study.

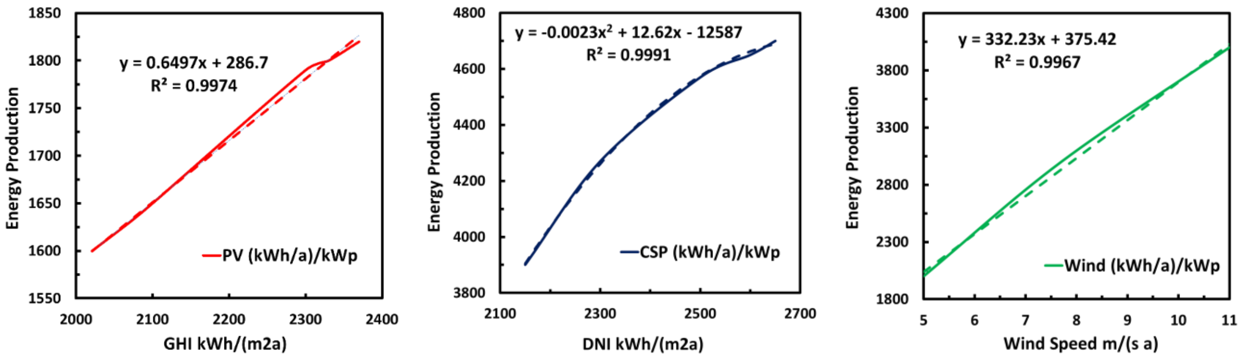




(a) CSP *(b) PV and Wind*

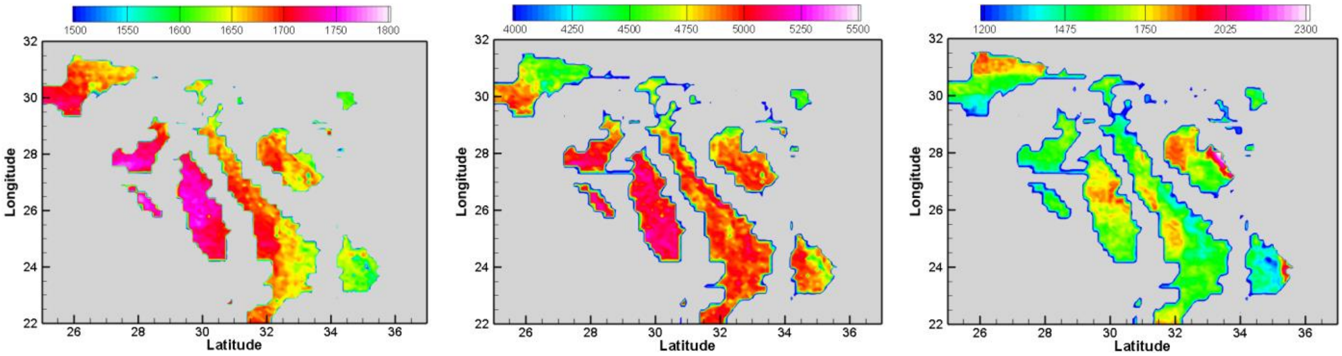
Fig. (7) Levelized cost of electricity for Egypt based on 2016 prices; reproduced from Noha et al. [37].

Considering, the cost calculation, Fig. (7) shows the unit price of the installed plants [37]. Here, the Levelized Cost of electricity is calculated, assuming an installation of the respective technology in Egypt today and for the future until 2030. To achieve that, the investment costs are determined: current investment costs are identified by detailed market analysis, and future investment costs are calculated out of the respective historic learning rate and a forecast of the market development. It is obvious from Fig. (7a) that the unit price of CSP plants continues to decrease in the next years, however, the higher DNI intensity shows lower prices. Similarly in Fig. (7b), the unit price of PV plants is also decreasing over the incoming years with higher prices of the lower GHI. Interestingly, the unit price of the Wind plants is quite stable with higher prices of lower intensity. Note that the plant prices are calculated based on data from Noha et al. [37] and implemented using fit-curve ploy-function estimation in Phase-A of the model.



(a) PV plants *(b) CSP plants* *(c) Wind plants*

Fig. (6) Yearly-average capacities for PV and CSP from available solar radiation.



(a) GHI intensity for PV plants *(b) DNI intensity for CSP plants* *(c) Wind intensity for Wind plants*

Fig. (8) Yearly-average intensity maps of Egypt, kWh/kWp.

Considering Phase-A calculations, the intensity, storage, and temperature are implemented into Phase-A of the model after exclusion. As a result, Fig. (8) shows the yearly-average intensities (i.e., kWh/kWp) over Egypt after being excluded from the exclusion map. Clearly, the DNI for the CSP map (Fig. 8a) shows promising hot spots in the Egyptian western desert. Specifically, the spots are quite close to the new cities, extending from New Aswan to New Assuit, showing higher intensities close to New Valley. On the other hand, Fig. (8b) shows the yearly-average GHI intensity for PV plants. The GHI map shows quite similar promising hot spots as the DNI map. This agrees well with the recent Egyptian plan, which focuses on installing such PV and CSP plants in Kom- Ombo, Qena, and Assiut. As for wind, Fig. (8c) shows the yearly-average Wind intensity. Clearly, the map shows promising hot spots close to the Egyptian Red Sea, which quite agree with the currently installed Wind plants.

Fig. (9) shows the unit prices [$/kWh] of the obtained maps through 2020. It is obvious from the figure that the prices of the CSP (Fig. 9b) are higher than PV (Fig. 9a) plants; as expected from Fig. (7). This could be the main reason behind the poor installation of such CSP plants in Egypt, although its higher energy intensities are shown in Fig. (8). However, the model could show another interesting result from the energy point of view through the incoming lines.

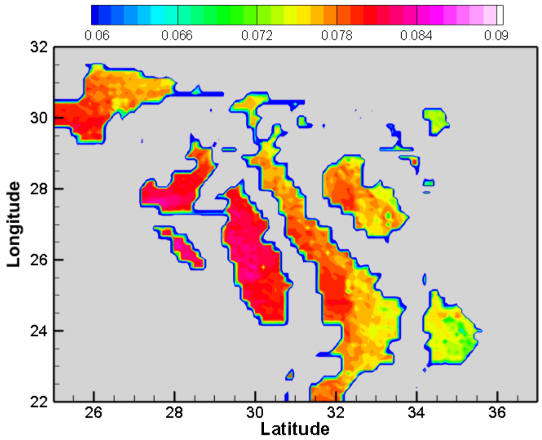
However, the weather temperature is quite an important factor for PV and CSP plants. The reason for using temperature data here is its negative impact on the PV efficiency, as discussed by Moharram et al. [31] and Jie et al. [32]. This is a new term that was introduced to the current study; showing the disadvantages of using such plants in high-temperature environmental conditions. Based on Tonui and Tripanagnostopoulos [33], the PV efficiency decreased by temperature factor, β, from the reference temperature T_{ref}; as shown in Eq. (2).

$$\eta_{pv}/\eta_{ref} = 1 - \beta(T_{pv} - T_{ref}) \qquad (2)$$

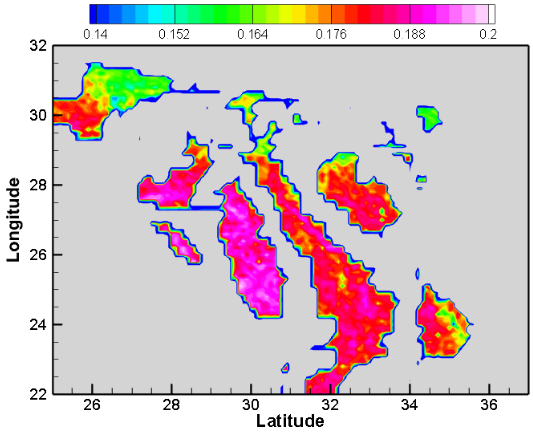
Considering the measurements of Tonui and Tripanagnostopoulos [33], the temperature factor can be taken as β= 0.0063/K for reference temperature of T_{ref}=25°C. However, the collected data represents the ambient temperature T_{amb}, while PV temperature is the cell temperature. Based on Moharram et al. [31], the cell temperature is calculated from the ambient temperature using Eq. (3); where T_{NOCT} represents the nominal operating cell temperature (i.e., 45° C in this study).

$$T_{pv} = T_{amb} + (GHI\ (T_{NOCT} - 20)/800) \qquad (3)$$

Fig. (10) shows the yearly-average cell temperatures based on Eq. (3) and collected ambient temperatures. Obviously, Upper Egypt is characterized by higher cell temperature, which negatively influences the PV performance as discussed by Moharram et al. [31] and Jie et al. [32]. Also, this introduced parameter would highly influence the contribution of the PV plants through Phase-B of the optimization model in such high-intensity regions.



(a) PV plants



(b) CSP plants

Fig. (9) Cost-based analysis of planned expansion in 2020, $/kWh.

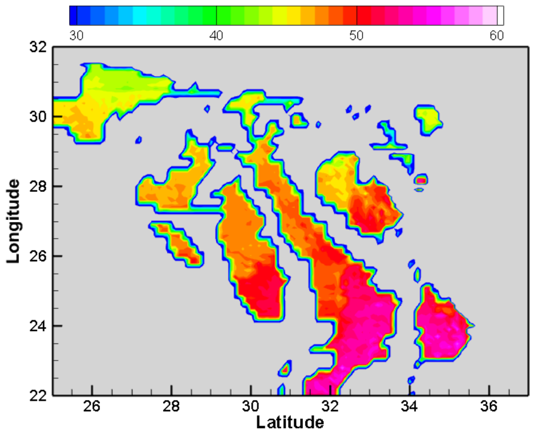
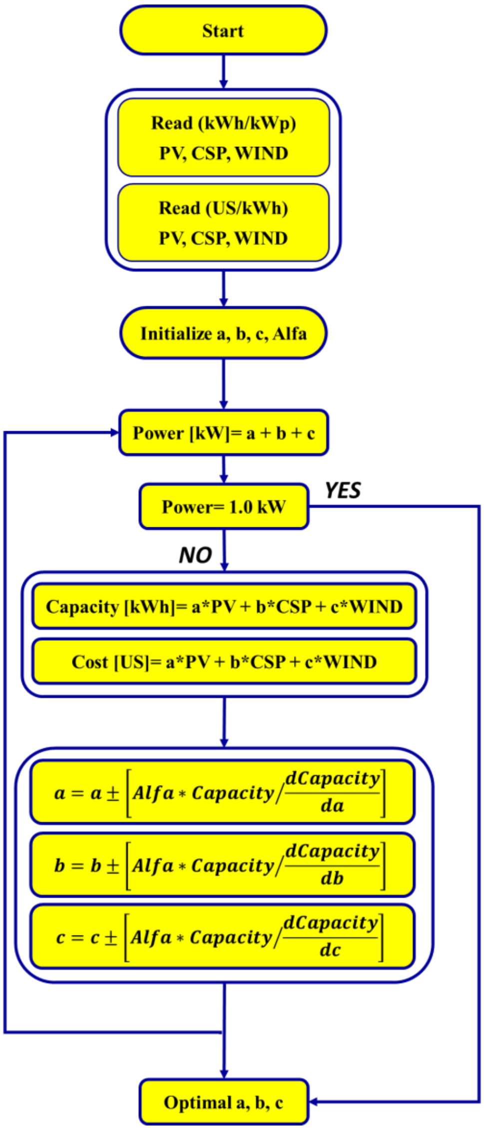


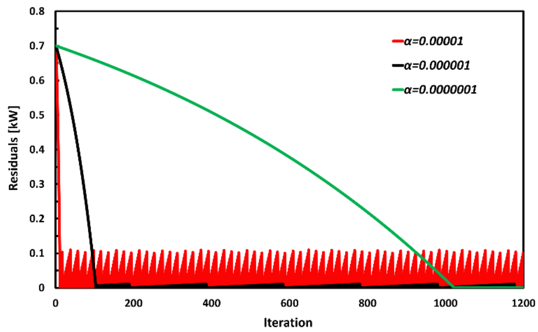
Fig. (10) Yearly-average cell temperature distribution over Egypt.

2.3 Verification and Validation

After data collection, an in-house MATLAB code is developed to run the optimization model. Following the procedures shown in Fig. (11a), the model read the obtained data of PV, CSP, and Wind, considering capacity (kWh/kWp) and unit price ($/kWh). Then, the model initializes the promising shares of the renewable plants, such that (a, b, c), in which (a), (b), and (c) are the contributions of the PV, CSP, and Wind plants in kWp, respectively. The model calculates the plant capacity and cost functions using Eq. (4) and Eq. (5), respectively. Noteworthy, PV, CSP, and Wind are considered as kWh/kWp in Eq. (4) and as $/kWh in Eq. (5), while a, b, and c are kW.



(a) Schematic diagram



(b) Residuals

Fig. (11) Optimization model of the current study.

$$Capacity\ [kWh] = a * PV + b * CSP + c * Wind \quad (4)$$

$$Cost\ [US] = a * PV + b * CSP + c * Wind \quad (5)$$

Then, the model updates the contributions (a, b, c) until the residuals (i.e., 1- (a + b + c)) reaches zero (Fig. 11b). The updated weights of the contributions are calculated as shown in Fig. (11a).

$$a = a \pm \left[Alfa * Capacity / \frac{dCapacity}{da}\right] \quad (6)$$

$$b = b \pm \left[Alfa * Capacity / \frac{dCapacity}{db}\right] \quad (7)$$

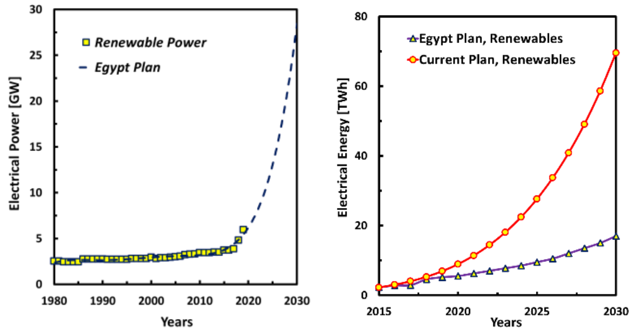
$$c = c \pm \left[Alfa * Capacity / \frac{dCapacity}{dc}\right] \quad (8)$$

Here, Alfa is used as a learning rate of the updated values. In statistics, the learning rate is a tuning parameter in an optimization algorithm that determines the step size at each iteration while moving toward a minimum of a loss function. Consequently, the value of Alfa is selected based on the closeness of the residuals. Fig. (11b) shows the model residual of the current study. Obviously, the learning rate of $\alpha=10^{-7}$ shows the best convergence. After 1200 iterations, the model is converged and shows the optimum contribution of the PV plant as (a=0.3939), the optimum contribution of the CSP plant as (b=0.2013), and the optimum contribution of the Wind plant as (c=0.4053). Here, the contribution is calculated as a mean value, where a, b, and c are calculated for each site and then the average is applied to get optimal conditions for the whole country. Meanwhile, such optimal conditions for each site could be considered for future works. However, these are quite interesting results, in which the contribution of the CSP exists. Unlike the previous planning, CSP plants could play a significant role in the future of renewable energy expansion

3. RESULTS AND DISCUSSION

3.1 Energy Expansion

Fig. (12) shows the Egyptian expansion plan from renewable sources (i.e., wind, solar) till 2030. For power expansion (Fig. 12a), the Egyptian plan was slightly increased from 1980 to 2016, which indicates the lack of renewable in the Egyptian plan during the last decades. However, Egypt has focused more and more on such renewable resources from 2017 till now. Furthermore, it becomes more promising through the plan till 2030. In this study, a typical Egyptian power plan is considered. Considering the energy plan, Fig. (12b) shows the energy expansion from 2015 to 2030. The current plan shows significant enhancement in the energy system compared with the Egyptian one. This could be obtained from the consideration of CSP plants, which have higher return kWh/kW. Although the planned power was the same (see Fig. 12a), this study provides ≈300% higher than the Egyptian one (i.e., ≈70 TWh by 2030).



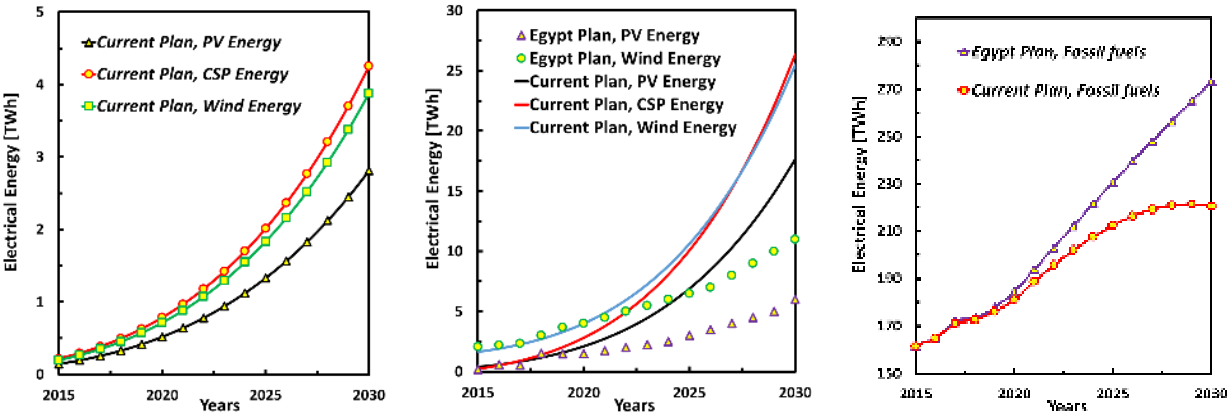
(a) Planned Power *(b) Planned Energy*

Fig. (12) Expansion of renewable resources; Current and Egypt Plan.

The significant energy production of the current study over the Egyptian one is obtained from the contribution of the PV, CSP, and wind plants. Specifically, Fig. (13a) shows the energy contributions of the current renewable resources, which are obtained from the individual power contributions (i.e., ≈40% PV, ≈40% Wind, and ≈20% CSP). Although the power contribution of the CSP is small, the energy production is significantly higher than PV plants. Furthermore, the CSP energy production is quite similar to the energy production of the Wind plants. This could highlight the importance of using the CSP plants in Egypt in the future. In addition, Fig. (13b) shows the total energy production based on Fig. (13a). Obviously, the current plan shows higher energy production compared with the Egyptian one. The PV and Wind plants start to deviate from the Egyptian plan from 2020 to 2030; showing higher values. This is based on the higher power contribution of both PV and Wind power in the current study. However, still the PV shows lower energy even in the current study. This is due to the lower energy return from the kWh/kW. Meanwhile, the CSP continues energy growth; showing even higher than the Wind energy production. This originates from the higher energy return from its kWh/kW. On the other hand, the current plan would save energy consumption from fossil fuels (see Fig. 13c), and thus decreases energy prices. Although both plans start in 2015 with the same values, the current plan suddenly decreases dependence on fossil fuels, especially from 2025 to 2030. This is caused by the massive energy production through this period from the renewable resources, especially CSP in the current plan. By 2030, the current plan could save about 19% compared with the Egyptian expansion. Such interesting results are promising soon with renewable sources. However, this could also provide some issues from the higher costs that were shown in the previous discussions. Consequently, the next part will discuss the energy-cost analysis of the obtained results.

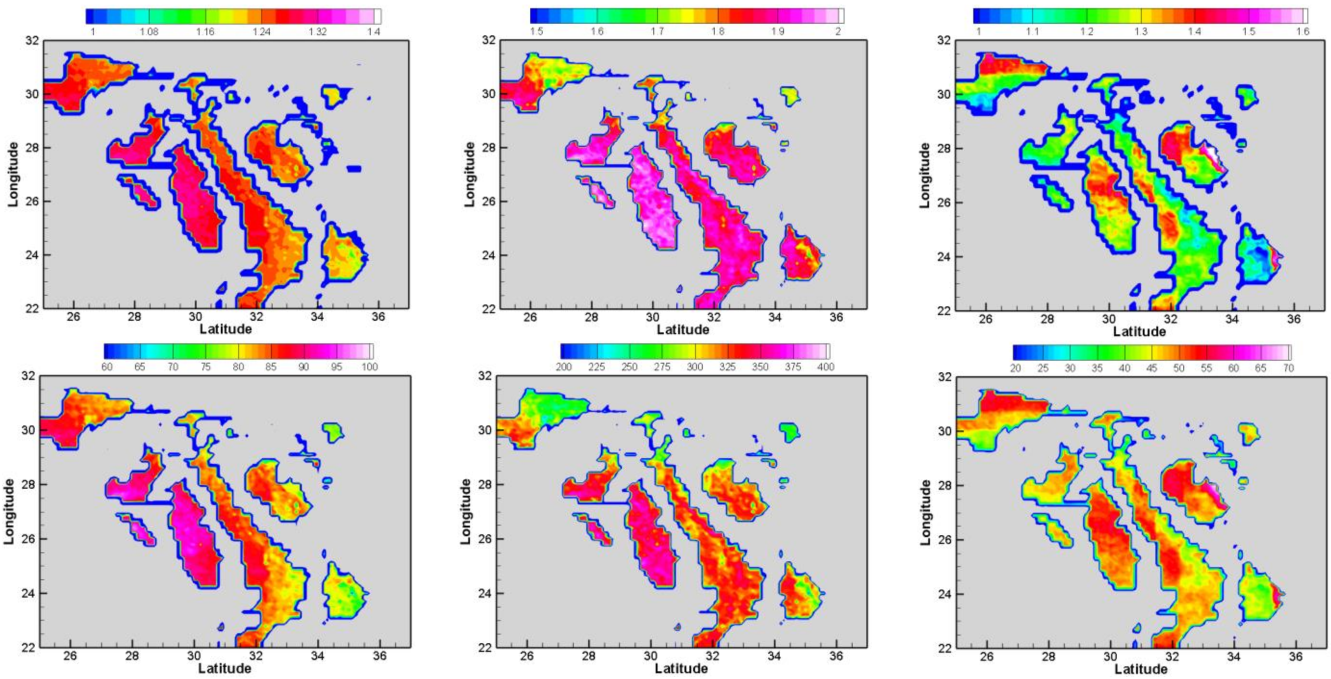
3.2 Energy-Cost Analysis

Fig. (14) shows the energy-cost analysis of the current plan, considering PV, CSP, and Wind renewable power plants. The result is obtained for a specific year, for example, 2025, in this figure. Noteworthy, the top maps show the energy production in TWh, while the bottom maps represent the cost of Million US$. For PV plants (Fig. 14a), the energy production varies from ≈1.0 TWh to ≈1.4TWh yearly. Specifically, the promising PV spots originate in the western desert. However, the cost of such plants is higher for those of higher TWh spots, as expected from Fig. (9a) shows higher US$ for higher kWh. Interestingly, the Aswan region (33ºE - 24ºN) is quite unsuitable for installing PV plants. This is inconsistent with the recent Egyptian installation in Benban with a ≈1.8 GW capacity. Considering the cost, the PV cost ≈95 million US$ for the current planned 750 MW of power through 2025 (≈1.3 TWh energy production). For CSP plants (Fig. 14b), the energy production varies from ≈1.5TWh to ≈2.0TWh yearly. The promising CSP spots are located in Upper Egypt, with more focus on the Upper desert. Specifically, Aswan city (33ºE - 24ºN) and New Valley (30.5ºE - 25ºN) are the most promising hot spots. However, the Egyptian plan ignores the future of CSP plants. The higher cost of such plants could be one reason, which is close to ≈350 million US$ for 380MW power in the current study through 2025 (≈1.9TWh energy production). For Wind plants (Fig. 14c), the energy production varies from ≈1.0TWh to ≈1.6TWh yearly.



(a) Renewable Energy contribution *(b) Renewable Energy production* *(c) Fossil fuel Energy production*

Fig. (13) Energy expansion of Egypt from PV, CSP, Wind, and fossil fuel plants.



(a) PV Plants *(b) CSP Plants* *(c) Wind Plants*

Fig. (14) Energy-cost analysis of the current plan during 2025; (top) Energy [TWh] and (bottom) Cost [Million US$].

The promising Wind spots originate close to the red sea as well as the Mediterranean-sea regions. The most promising hot spots are; Ras-Ghareeb (33.5ºE - 28ºN) and Marsa-Matrouh (26ºE – 30.5ºN). Similar to PV and CSP, the cost of Wind is also high for those hot spots. Typically for ≈770MW power generation in this study through 2025 (≈1.6TWh), the cost reaches ≈70 million US$.

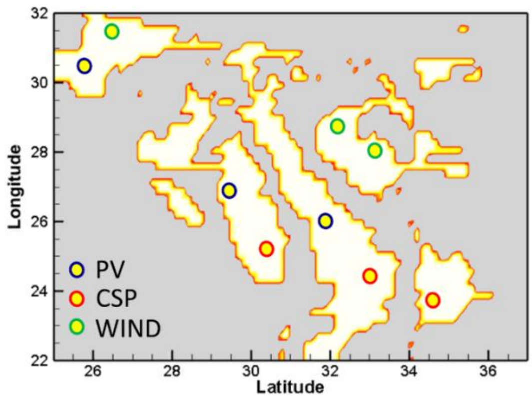
Specifically, Table (1) shows the maximum energy cost from the renewable plants through 2020, 2025, and 2030 for a better understanding of the current plan. Based on the obtained contributions, the CSP contributes higher energies, as discussed in Fig. (13), while contributing lower power over the years. However, the cost of CSP is significantly higher than other plants. For example, the cost of the CSP plant is ≈3.6 times the PV plant and is ≈5.6 times the Wind plant in 2020. Such cost is quite decreasing compared with the Wind plants; showing ≈5.32 times in 2030. Meanwhile, the cost of the CSP is continued increasing compared with the PV plant, showing ≈4.1 times in 2030. This could be the main reason for such limitation of installing the CSP plants in Egypt during the previous years. Additionally, the Wind plants dominate the previous Egyptian plan, while the PV plants dominate the near-future plan. However, the energy production per peak power of CSP plants is significantly higher compared with other plants, especially those dominated by PV plants. for example, the PV power is doubled compared with CSP during 2020. Thus, the current plan observes the challenge contribution of the CSP over other installed plants.

Table (1). Maximum energy-cost analysis of the current plan

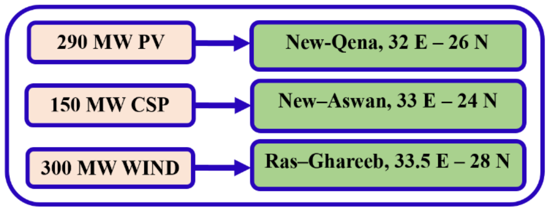
		2020	2025	2030
Power [MW]	*PV*	290	750	1580
	CSP	150	380	800
	WIND	300	770	1620
Energy [TWh]	*PV*	0.5184	1.3297	2.8098
	CSP	0.7844	2.0121	4.2519
	WIND	0.7148	1.8336	3.8747
Cost [Million US$]	*PV*	43.7134	96.8497	190.4136
	CSP	156.8106	380.9956	781.7541
	WIND	28.1121	70.8278	146.9562

3.3 Power Analysis

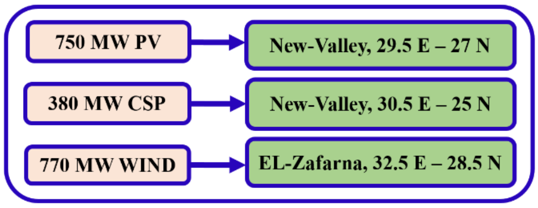
Fig. (15) shows the power analysis of the current plan for 2020, 2025, and 2030 over Egypt. The identified hot spots are shown in Fig. (15a), where the CSP originates in Upper Egypt, while the Wind originates beside the Egyptian seas. This is quite consistent with the Egyptian plan. The Egyptian electricity governorate provides some areas for PV plants in Faries-village and Kom-Ombo in Aswan, besides some areas for Wind expansion in Ras-Ghareeb. In Fig. (15b), the current plan for 2020 includes 740 MW power demand such that 290MW PV, 150MW CSP, and 300MW Wind power plants. Specifically, it is better to locate PV plants in New-Qena (32ºE - 26ºN), CSP in New Aswan (33ºE - 24ºN), and Wind in Ras-Ghareeb (33.5ºE - 28ºN). In Fig. (15c), the current plan for 2025 includes 1900MW power demand such that 750MW PV, 380MW CSP, and 770MW Wind power plants. Specifically, it is better to locate PV plants in New Valley (29.5ºE - 27ºN), CSP in New Valley (30.5ºE - 25ºN), and Wind in El-Zafarana (32.5ºE – 28.5ºN). Interestingly, the planned PV power (i.e., 750MW) and Planned wind power (i.e., 770MW) are quite consistent with Aly [34], who install a capacity of 896MW PV power and a capacity of 963MW wind power in his plan through 2027. In Fig. (15d), the current plan for 2030 includes 4000MW power demand such that 1580MW PV, 800MW CSP, and 1620MW Wind power plants. Specifically, it is better to locate PV plants in Marsa-Matrouh (26ºE – 30.5ºN), CSP in Shalateen (34.5ºE – 23.5ºN), and Wind in Matrouh (26.5ºE – 31.5ºN). The choice of these regions is mainly based on their near-to-population areas.



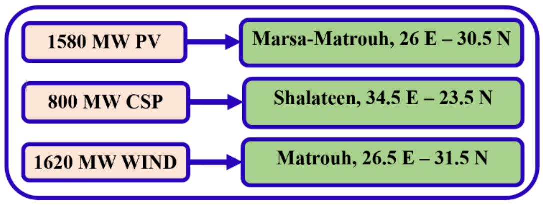
(a) Schematic diagram



(b) 2020 (740 MW)



(c) 2025 (1900 MW)



(d) 2030 (4000MW)

Fig. (15) Power analysis of the current plan throughout the years.

4. CONCLUSION

In this study, the planned expansion of renewable energy in Egypt has been assessed using an optimization model, to decrease the production cost and increase the capacity, as well as ensure reliable operation. Throughout two phases, the model has been carried out, in which Phase-A estimates the cost and capacity of the PV, CSP, and Wind plants, while Phase-B optimizes the plants according to the required demand (i.e., the contribution of PV, CSP, and Wind). The available data (i.e., intensity, storage, and temperature effect) is used as an input to Phase-A, while the calculated cost and capacity are used as an input to Phase-B. The results are presented in terms of spatial and temporal distributions. The main conclusion is;

- The result successfully identified the promising renewable plants (i.e., type and location) as well as mix-installations of different renewable plants.
- PV power is contributed ≈40% of planned power and mainly originated in New Valley with quite lower capacities as well as is not preferable for Upper Egypt.
- CSP power is contributed ≈20% of the power demand, especially in Upper Egypt, due to its higher capacities although its higher cost.
- It is recommended to install Wind plants near Red-sea regions, with a ≈40% power contribution.

This study is expected to insight our understanding into the planned expansion of renewable energies in Egypt; aiming to evaluate its potential.

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