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Environmentally Constrained Optimal Energy Mix Planning for the Egyptian Electric Grid

مخطط مزيج الطاقة المثلى بيئيا للشبكة الكهربائية المصرية

A. El-Sadat, M.M. El-Saadawi, S.S. Kaddah and N.M.A. Ayad

KEYWORDS:
Power generation mix, renewable, nuclear, CO_2 emission & levelized cost of electricity.

***الملخص العربي*:- في العقود المقبلة، سيواجه قطاع الطاقة في جميع أنحاء العالم مجموعة متزايدة التعقيد من التحديات المتشابكة - الاقتصادية والجيوسياسية والتكنولوجية والبيئية. وسيتطلب مواجهة هذه التحديات فترات زمنية طويلة جدا، خاصة بالنسبة لقرارات الاستثمار بشأن القدرات الجديدة لتغطية الطلب المتزايد على الطاقة وتحسين استخدام احتياطيات الطاقة الحالية والمستقبلية المتاحة. يقدم هذا البحث إستراتيجية مقترحة للحد من انبعاث ثاني أكسيد الكربون مع تقليل تكلفة التوليد من خلال حساب المزيج السنوي الأمثل من مصادر التوليد المتاحة والتي تعطي الحد الأدنى من التكلفة مع تلبية الحمل المتوقع. وتخضع الاستراتيجية المقترحة لأقصي قدرة على توليد كل نوع من أنواع الطاقات المتاحة سواء كانت الطاقة الشمسية وطاقة الرياح والطاقة النووية والتقليدية 'الحرارية والمائية' كما هو معطى من قبل السلطة المختصة، وباعتبار مزيج الطاقة الامثل للسنة السابقة من الطاقة المتجددة / النووية كأساس للسنة التالية. وقد تحقق الهدف من هذا البحث بحساب تكلفة توليد الطاقة مقابل ثاني أكسيد الكربون المنبعث. حيث تم تنفيذ الاستراتيجية المقترحة باستخدام الماتلاب وتم تطبيقها على الشبكة الكهربائية المصرية حتى عام 2030. وقد تأكدت فعالية الاستراتيجية المقترحة بمقارنة النتائج مع بيانات الحكومة المصرية.**

Abstract- **At the coming decades, the energy sector throughout the world will face an increasingly complex array of interlinked challenges; economic, geopolitical, technological, and environmental. Meeting these challenges requires very long times especially for investments decisions on new capacities to cover increasing energy demand and improve the utilization of current and future available energy reserves. This paper presents a proposed strategy to reduce the emission of CO_2 while minimizing the generation cost by calculating the optimal yearly mix of generation sources that gives minimum cost and satisfies the forecasted load. The proposed strategy is subject to the generation capability limit of each type of generation given by the authority. Then consider the previous year optimal mix from renewable/nuclear capacity as a base for the recent year. The objective of this paper is achieved by calculating the power generation cost versus the CO_2 emitted. The proposed strategy is implemented in Mat-lab environment and applied on the Egyptian electrical grid until 2030. The effectiveness of the proposed strategy is verified by comparing the results with the Egyptian government data.**

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I. INTRODUCTION

The electricity generation sector relies heavily on the use of fossil fuels and as a result, CO_2 emissions increase with time. Figure 1 shows that approximately 40% of these emissions are generated from the electricity generation sector. Carbon dioxide emissions reached 30 Gt in 2010 [1]. As a result of the increase in population density, the amount of carbon dioxide in the atmosphere increased from 280 to more than 380 ppm. This, of course, leads to global warming, where average surface temperature of the earth rose by 0.74 degrees Celsius. Carbon dioxide emissions must be controlled otherwise global warming will continue to pose a threat to the life of living organisms and may lead to large-scale melting of polar ice. Efforts to reduce carbon dioxide emissions are known to be inadequate and in most countries it is not a concern. These emissions should be reduced by 80 percent by 2050 [2]. In this paper we will focus on how to reduce the amounts of CO_2 emitted from electricity sector via calculating the optimal energy mix.

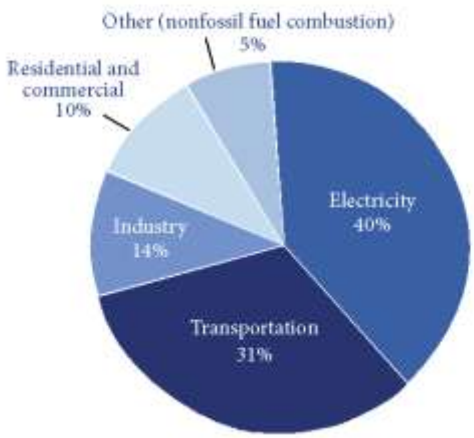

Fig. 1: Sources of CO2 emissions by sector (worldwide, 2009) [3].

II. LITERATURE REVIEW

Energy models for power generation technologies have been developed by numerous researchers. Z.A. Muis [4] proposed a Mixed Integer Linear Programming (MILP) model. The model was developed and implemented in general algebraic modeling to reduce the CO_2 emissions by 50 % for the fleet of electricity generation in Malaysia. Cedric De Jonghea [5] developed a static linear programming investment model to determine the optimal technology mix based on increasing the contribution of wind power in the electric generation system. That alternative methodology results in a reasonable reduction in the capacity of inflexible generation. Pereiraa [6] developed a model to solve the Generation Expansion Planning (GEP) problem in competitive electricity markets. The proposed model identifies the presence of several generation agents aiming at maximizing their profits. The planning environment is influenced by different factors including uncertainties affecting the demand, investment and maintenance costs, fuel and the electricity prices. The proposed approach used system dynamics to characterize the evolution of electricity prices and of the demand. Koltsaklis [7] proposed a mixed-integer linear programming model for optimal long-term energy planning of a national utility. The proposed model determines the optimal planning of the utility, the selection of the power generation technologies, the fuels' type and the plant locations so as to meet the expected demand, while satisfying CO_2 emissions constraints. The approach can provide policy makers with a systematic computer-aided tool to analyze different scenarios and technologies. Amaroa in [8] proposed a methodology to determine the optimal mix of renewable energy sources (RES) and fossil fuels in an electric power system by using the RES hourly production values and the electricity demand. The methodology was applied to the Mexican electricity system. Several combinations of RES that achieve a minimum of 35% electricity production were identified. Thangavelua [9] proposed a generic methodology to determine an optimal energy mix over a period of 15 years. The optimal energy mix is a right combination of energy sources that minimize the future energy sources uncertainties risk. The proposed methodology used stochastic optimization to address future uncertainties over a planning horizon and minimize the variations in the desired performance criteria such as energy security and costs.

The objective of this paper is to reduce the energy cost and to minimize the amount of CO_2 emitted via controlling the power generation mix. A general framework is developed to find the optimal energy generation mix which gives the minimum energy cost against the CO_2 emitted. This paper also, introduces a developed practical energy cost optimization model incorporating energy demand load forecasting. The proposed framework is applied to Egypt electrical grid and the results are compared with the Egyptian government data.

III. PROPOSED FRAMEWORK

The procedure of the proposed method can be summarized in the following steps:

1. Use the government forecasted load model data as an input to the proposed generation mix model
2. Compute levelized cost of electricity (LCOE) for each generation type.
3. Calculate sharing value for gas and oil sources.
4. Calculate the power generation cost (PGC) for the generation mix.
5. For a prescribed cost limit (x in \$/kWh), IF PGC < x, then go to step 8.
6. Otherwise if PGC > x, increase the nuclear source, the wind source and the solar source by a specified rate (n, w & s respectively) depending on the price factor of each source and then go to step 3.
7. Calculate the carbon intensity of electricity supply (CIES).
8. IF CIES > y, where y is the weight limit (g CO_2 /kWh) then increase the nuclear source, the wind source and the solar source by a rate that depends on the price factor of each source (as mentioned in step 7) and then go back to step 3.
9. IF CIES < y, then the optimal mix from generation sources is achieved.
10. Print Sharing % for each source, LCOE, PGC and CIES.

A flowchart represents the proposed framework is shown below in Fig. 2.

Since the proposed algorithm is repeated for the entire period of study, it is useful to mention that the initial values of nuclear, wind and solar at any year (n+1) should be at least equal to their final values at the previous year (n) as they were already installed before.

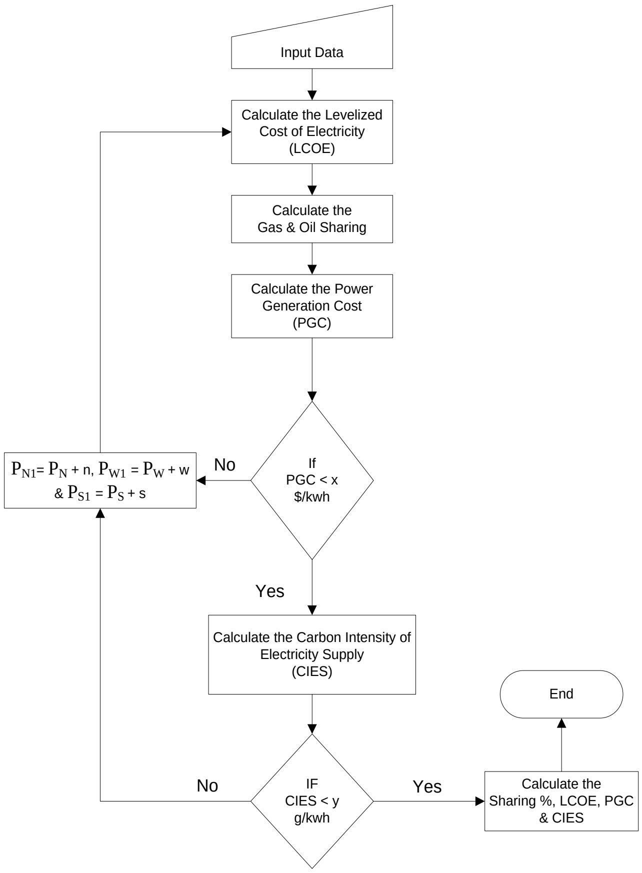

Fig. 2: A flowchart represents the frame work for one year.

3.1 Levelized Cost of Electricity (LCOE)

LCOE is defined as a fixed unit price ($ / kWh) to compare the power plants' costs. The power stations in this study differ in the technology used, capital expenditure paths, annual operating costs, taxes, carbon prices, fuel used, and life times. In general, LCOE can be determined by the following equations [10, 11 and 12]:

$$LCOE = \frac{\sum_T [(capital\ expenditure)_t/(1+r)^t]}{\sum_t [(electricity\ sold)_t/(1+r)^t]} \quad (1)$$

Where the capital expenditure is the expenditure per year (t), associated with the construction of the plant in dollars; the sold electricity is the net electricity produced and sold in one year (kwh/year); r is the annual rate used to discount the values taken as a necessary part to cover shares and the cost of debt.

The term levelized arises from the recognition that the accounts in (1) determine one current value of the total cost that can be converted into a series of standardized level and annual values through the use of so-called levelization factors. As commonly used in LCOE calculations, levelization factors are described differently when applied to different cost elements, as described later.

If the fuel costs, net electricity produced, operating and maintenance conditions, and net plant output are constant over the lifetime of the plant, then (1) can be reduced to (2) as follows:

$$LCOE = \left\{\frac{[(TCR)(FCF)+(FOM)]}{[(MW)(CF*8766)]}\right\} + (VOM) + (HR)(FC) \quad (2)$$

Where:

TCR Total capital requirements in base year ($);
FCF Fixed change factor (TCR levelization factor);
FOM Fixed operation and maintenance costs ($/year);
MW Net plant output (MW);
CF Capacity Factor (fraction)
VOM Variable operation and maintenance costs ($/kWh);
HR Net plant heat rate (MJ/MWh);
FC Fuel cost per energy unit ($/MJ).

The levelization factor is a factor that converts the total capital value to a single annual amount (annuity); it can be calculated as follows:

$$FCF = r(1+r)^t/[(1+r)^t - 1] \quad (3)$$

Where r is the interest rate and t is the economic age of the plant for the base year of the analysis used in the study. On the other hand, a modified version of (2) is needed if the annual cost of the plant changes over time, for example, when using nominal costs (current dollar) containing an assumed inflation rate or assuming 'real escalation rates' for fuel or other operation and maintenance costs, or when the level of plant production varies over time (different capacity factors are reflected). In such cases, LCOE ($ / kWh) can be determined as follows:

$$LCOE = \left\{\frac{[(TCR)(FCF_L) + L_1(FOM)]}{[(MW)(CF_L * 8766)]}\right\} + L_2(VOM) + L_3(HR)(FC) \quad (4)$$

L1, L2 and L3: are the levelization factors applied to the initial values of both fixed and variable operating costs and total fuel cost; respectively. Additional agents can be applied to any sequence of other annual costs, or to individual components for Fixed Operation and Maintenance cost (FOM) and Variable Operation and Maintenance cost (VOM).

In the next section we'll apply the proposed model to the Egyptian electrical grid as a case study using equation (2).

3.2 Gas and Oil Sharing

The sharing value of each gas and oil in (TWh) is calculated from the following two equations respectively, assuming that gas and oil are the only sources for CO_2 in this study:

$$P(gas) = [ED - (P_N + P_W + P_S + P_H + \cdots)] * \left[\frac{Pgas}{Pgas + Poil} * 100\right] \quad (5)$$

$$P(oil) = [ED - (P_N + P_W + P_S + P_H + \cdots)] * \left[\frac{Poil}{Pgas + Poil} * 100\right] \quad (6)$$

Where, ED is the total demand.

3.3 Power Generation Cost (PGC)

The cost of energy generated is expressed in terms of a unit cost ($/kWh) delivered at the boundary of the power station site. This cost includes both the capital cost of the plant and equipment; the cost of fuel burned (if applicable); and the cost of operation and maintenance [13]. It can be expressed mathematically as:

$$PGC = [(TPG.*LCOE) / ED] \quad (7)$$

3.4 Carbon Intensity of Electricity Supply "CIES"

There are many ways for computing CO_2 intensity (g CO_2 /kWh) emitted from electric power stations, according to the technique at which combined heat and power generation is taken into account. In this study the following formula is used to calculate CO2 intensity [14]:

$$CO_2 \text{ intensity} = \sum\left(\frac{1}{E_i} * C_i P_i\right) / \sum Pi \quad (8)$$

Where;

i Fuel source 1 ... n,

Ei Energy generation efficiency per fuel source,

Ci CO_2 emission factor per fuel source, (tone CO_2 /TJ), and

Pi Power production from public power plants per fuel source (MWh).

IV. CASE STUDY

The proposed framework is applied to optimal plan of energy mix for the Egyptian utility until 2030. The initial data for this study is obtained from the forecasted model developed by the Egyptian Ministry of Electricity. A computer program implementing the proposed framework is built in Matlab environment and is applied to the current Egyptian electrical grid until 2030. The results are then compared with the Egyptian government data.

4.1 Description of Egyptian Electrical Grid

Electricity generation in Egypt is mainly generated from hydro power plants and thermal stations. However, the proportion of energy generated by hydropower is gradually decreasing due to the installing new thermal and renewable power stations. Note that generation at thermal stations depends on the combined cycle and steam by up to 38% for the steam stations and up to 36% for the combined cycle as planned by the Egyptian Electric Holding Company (EEHC) [21].

Egypt has recently moved to produce electricity through large wind farms, particularly in the Gulf of Suez, to implement the principle of diversification of energy sources, where the average wind speed in the Gulf of Suez is 8 to 10 meters per second. Wind power plants can be built in the east and west of the Nile, down the capital and south because of the large desert areas.

It is known that Egypt enjoys the best solar radiation throughout the year among the countries of the world, where solar energy per square meter varies from 1970 to 2600 kWh. In 2007, the Supreme Energy Council (SCE) adopted a strategy to increase the proportion of electricity generated from renewable energy (wind and solar energy) to about 20%. However, the challenge remains to overcome the increased cost allocated.

The Egyptian nuclear program was activated in line with the energy diversification strategy. Egypt has two nuclear research reactors: the first is Russian, with a capacity of 2 megawatts, inaugurated in the early 1960s. The second is an Argentine origin with a thermal capacity of 22 MW, inaugurated in 1997. The first nuclear power plant is scheduled to be operational in 2026 with an electricity capacity of 1,200 MW per unit. It is known that Russia will build and develop nuclear energy in Egypt.

Table 1 summarizes the input generation mix for Egypt national grid according to the forecasted plan of Egyptian Ministry of Electricity, until 2030 [20].

TABLE 1:
INPUT GENERATION MIX FOR THE PROPOSED MODEL (GW)

Year	Hydro	Solar	Wind	Nuclear	Oil	Gas
2012	2.8320	0.0740	0.5450	0	4	25
2014	2.8320	0.1320	1.7150	0	4	30
2016	2.8320	0.1400	2.7150	0	5	35
2018	2.8320	0.1400	4.3150	1.0000	5	38
2020	2.8320	0.1400	5.6520	2.0000	6	42
2022	2.8320	0.1400	6.7520	3.0000	6	46
2024	2.8320	0.1400	6.8770	4.0000	7	51
2026	2.8320	0.1400	7.0320	4.0000	8	56
2028	2.8320	0.1400	7.2320	4.0000	9	63
2030	2.8320	0.1400	7.3320	4.0000	9	69

4.2 Results and Discussion

The developed computer program is applied to the current Egyptian electrical grid until 2030. The optimization analysis is performed among Nuclear, Wind & Solar generating sources to obtain the optimal sharing of Gas & Oil generating sources to keep both the power generation cost < 0.10 $/kWh, which is represented by (x) in the flowchart fig. 2 and to keep the carbon intensity of electricity supply < 500 g/kWh, which is represented by (y) in the same flowchart. A constant sharing of hydro power generation source is assumed during the plan duration. The reference scenario for the study is the data of the government model explained in Table 1. The resultant values of the generation mix after applying the computer program are shown in Table 2.

TABLE 2:
OPTIMIZED POWER GENERATION MIX (GW)

Years	Hydro	Solar	Wind	Nuclear	Oil	Gas
2012	2.8320	0.0	0.5000	0.0	3.4402	25.2278
2014	2.8320	0.1000	1.5000	0.0	4.1482	30.4198
2016	2.8320	0.1000	2.5000	0.0	4.7482	34.8198
2018	2.8320	0.1000	4.0000	1.0000	5.2882	38.7798
2020	2.8320	0.1000	5.5000	2.0000	5.8282	42.7398
2022	2.8320	0.1000	6.5000	3.0000	6.3082	46.2598
2024	2.8320	0.1000	6.5000	4.0000	7.0282	51.5398
2026	2.8320	0.1000	7.0000	4.0000	7.6882	56.3798
2028	2.8320	0.1000	7.0000	4.0000	8.6482	63.4198
2030	2.8320	0.1000	7.0000	4.0000	9.4882	69.5798

From this table, one can observe that the optimized solar power is 0.100 GW, the optimized wind power is 7.000 GW, whereas the optimized nuclear power is the same compared with the reference model. This will affect directly the power generated from gas and oil as illustrated in the table to supply the forecasted load. Table 3 includes the yearly levelized cost of each generation type over the planning period from each type.

This table clarifies the changes in levelized cost accordingly with the changes of generation mix obtained from the optimization process. It can observe that the cost increased with increasing the sharing of renewable sources in the generation mix. The percentage sharing of each type, during the planning period, is listed in Table 4.

The table illustrates the sharing of each generation type as a result of the optimization process, where the total power of each year is the same as the total power each year related to the forecasted model. A Comparison between the optimized and reference cost of the generation mix over the planning period and the result is listed in Table 5.

TABLE 3:
YEARLY LEVELIZED COST OF ELECTRICITY "LCOE "$/KWH"

Years	LCOE $/kWh
2012	1.1814
2014	1.1814
2016	1.1814
2018	1.1686
2020	1.1686
2022	1.1686
2024	1.1686
2026	1.2306
2028	1.2306
2030	1.2306

TABLE 4:
PERCENTAGE SHARING OF EACH GENERATION TYPE:

Years	Hydro	Solar	Wind	Nuclear	Oil	Gas
2012	8.8500	0.0	1.5625	0.0	10.7505	78.8370
2014	7.2615	0.2564	3.8462	0.0	10.6363	77.9996
2016	6.2933	0.2222	5.5556	0.0	10.5515	77.3774
2018	5.4462	0.1923	7.6923	1.9231	10.1695	74.5766
2020	4.8000	0.1695	9.3220	3.3898	9.8782	72.4404
2022	4.3569	0.1538	10.0000	4.6154	9.7049	71.1690
2024	3.9333	0.1389	9.0278	5.5556	9.7613	71.5831
2026	3.6308	0.1282	8.9744	5.1282	9.8566	72.2818
2028	3.2930	0.1163	8.1395	4.6512	10.0560	73.7440
2030	3.0452	0.1075	7.5269	4.3011	10.2023	74.8170

TABLE 5:
COMPARISON BETWEEN OPTIMIZED AND REFERENCE GENERATION COST ($/KWH).

Years	Optimized	Reference
2012	0.0702	0.072
2014	0.0710	0.072
2016	0.0710	0.072
2018	0.0798	0.081
2020	0.0807	0.082
2022	0.0810	0.082
2024	0.0800	0.081
2026	0.0880	0.089
2028	0.0870	0.088
2030	0.0873	0.088

This table illustrates a comparison between the total cost of the power generated after optimization process versus the total cost without optimization (reference one), from which it is clear that the proposed optimization model provides a potential saving in $/kWh. The following figure illustrates a comparison graph between the optimized power generation cost and the reference power generation cost (MOE model).

Table 4 and Figure 3 explain that the obtained cost of the optimized scenario is a little lower than that of the reference one. A comparison of the emission values at both scenarios are listed in Table 6.

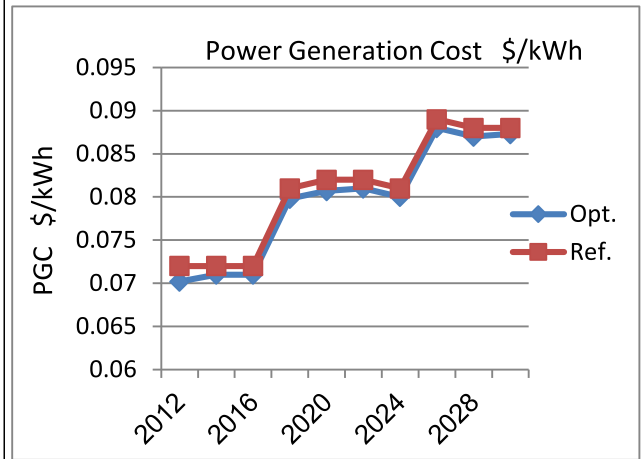

Fig. 3: The optimized power generation cost against the reference one

TABLE 6:
THE CO_2 EMISSION VALUES (G CO_2 /KWH).

Years	Optimized	Reference
2012	401	401
2014	**397**	**392**
2016	394	393
2018	**380**	**377**
2020	369	367
2022	**362**	**360**
2024	364	361
2026	**368**	**367**
2028	375	374
2030	**381**	**379**

Table 6 provides a comparison between the values of the emitted CO_2 (g/kWh) after optimization process versus the reference one (without emission optimization). With decreasing the power generated from gas and oil, the amount of CO_2 emitted will be decreased while increasing the price. Increasing the sharing from renewable energy in the generation mix will decrease the sharing from gas and oil power stations. This will lead to an increase in generation cost per unit. To control the price, there will be increases in the sharing from gas and oil power stations as explained by figure 4. In this figure there is a decrease CO_2 emission between year 2012 and 2022. After this year there is an increase in the amount of CO_2 emission.

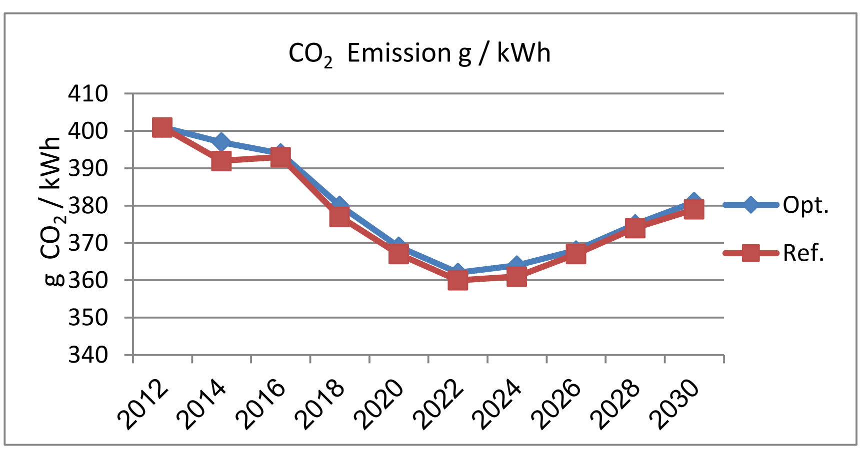

Fig. 4: Optimized CO_2 emission against the reference one.

The overall electricity cost of the whole Egyptian grid is calculated for both optimized and reference scenarios and the net saving due to performing the proposed strategy are shown in Table 7.

Table 7: Egyptian Annual Cost of Electricity Supply, billion $/year

TABLE 7:

Years	Optimized Scenario	Reference Scenario	Saving
2012	19.7	20	+ 0.3
2014	24.6	25	+ 0.4
2016	27.4	28	+ 0.6
2018	36.4	37	+ 0.6
2020	41.7	42	+ 0.3
2022	46.1	47	+ 0.9
2024	50.5	51	+ 0.5
2026	60.7	61	+ 0.3
2028	66.2	67	+ 0.8
2030	71.1	72	+ 0.9

This table provides a potential saving for each year which we can get when applying the proposed optimization process for the power generation mix.

4.2.1 Effect of Increasing Wind and Solar Generation on the PGC

In this section we will study the effect of increasing the sharing from Wind and Solar in the generation mix on the total power generation cost. The wind and solar energy are assumed to increase by 10%, and then by 20% versus the government model. This increase is assumed to start at year 2020. A comparison between the new scenarios and the reference one are illustrated in Figure 5 with respect to our proposed model.

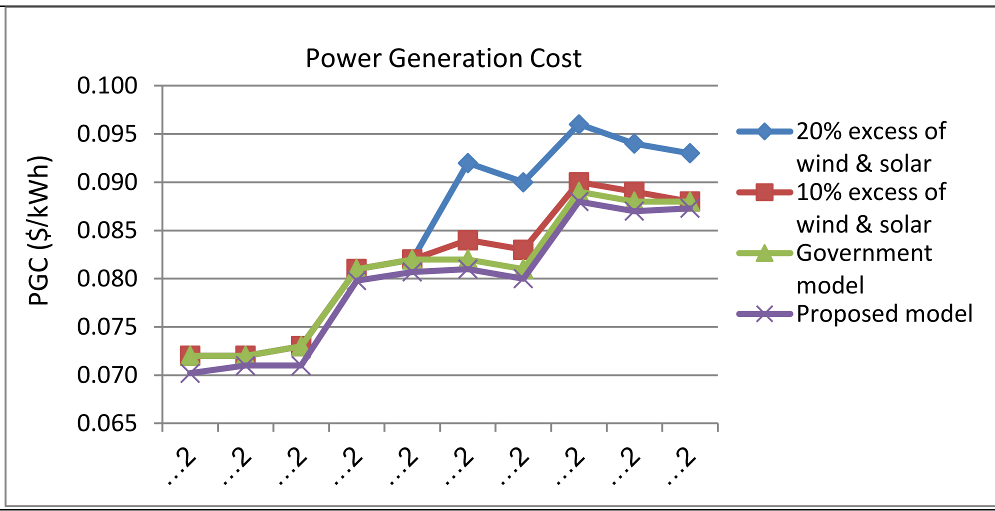

Fig. 5: Increasing the sharing of wind & solar against the PGC

From the above figure it can be observed that: increasing the sharing from renewable sources yields to an increase in the power generation cost, where our proposed model still has the best performance.

4.2.2 Effect of Increasing Wind and Solar Generation on CO_2 Emission

Also, the effect of increasing the sharing from Wind and Solar in the generation mix on the CO_2 emission will be studied. The wind and solar energy are assumed to increase by 10%, and then by 20% versus the government model. This increase is assumed to start at year 2020. A comparison between the new scenarios and the reference one are illustrated in Figure 6 with respect to our proposed model.

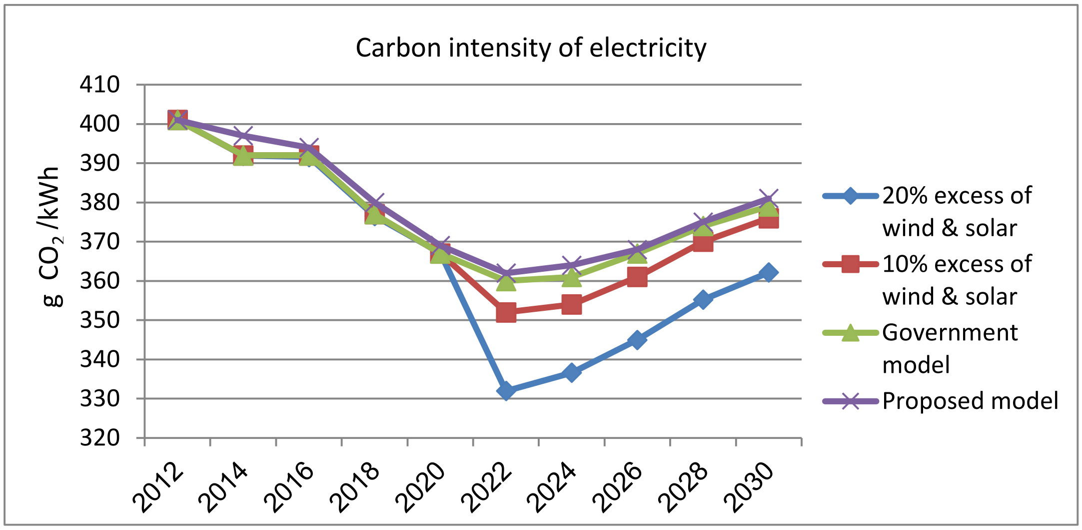

Fig. 6: Increasing the sharing of wind & solar against the CO_2.

V. CONCLUSION

This paper presents a general framework model that is capable of realizing the optimal mix of energy supply sources that meet current and future electricity demand, CO_2 emission control, and lower the overall cost of electricity based on an optimization technique. A Mat-lab program was built to represent the proposed model. The developed program was applied to optimal plan of energy mix for the Egyptian electric grid until 2030. In comparing with the current Egyptian plan, the results show that applying the framework leads to a potential saving of approximately $500,000 per year. Although this research focuses on certain types of power generation mix, the proposed framework can be extended to a wide range of power systems that use multi-source energy.

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