Evaluation of CO₂ emission from Egypt's future power plants

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Abstract

Energy-related CO₂ emissions increased to a global peak of 33 Gt in 2019, resulting in an unprecedented level of “Global Warming”. Egypt emitted 250 million tons of CO₂ in 2018, thereby ranking 27th among the countries of the world in terms of energy-related CO₂ emissions. Approximately 40% of CO₂ emissions in Egypt originate from the electricity generation sector, which is predominately dependent on oil and gas (90%), followed by renewables (10%; solar, wind and hydroelectric). To achieve its development goals, Egypt plans to build new power plants with a total generating capacity of 30 gigawatts (GW). Added to the current generating capacity of Egypt's power plants (60 GW), the new power plants will enable electricity generating capacities to reach approximately 90 GW by 2030. Egypt has three scenarios to achieve this goal. In the first scenario, a diversified energy mix scenario, dependence on oil and gas will be decreased in favor of a more diversified energy mix of coal, nuclear power, in addition to renewables and hydro. The second scenario, a fossil fuel-based scenario, is based on recent discoveries of proven natural gas reserves, possibly shifting Egypt's vision towards more dependence on natural gas, as well as renewables, nuclear and hydro. These two scenarios might lead to increased amounts of released CO₂ into the atmosphere. Here we suggest a third scenario, the environmentally friendly scenario or the green scenario, in which more dependence is placed on renewables, hydro and nuclear power, in addition to natural gas, with no coal in the suggested energy mix. In this article, we analyze CO₂ emissions derived from electricity generation under these three futuristic scenarios. The results of our comparison show that building new power plants will lead to CO₂ emissions of 307, 330 and 128 million tons (Mt), respectively, according to the first, second and third scenario, respectively, compared to the current 100 Mt of emissions. These results clearly demonstrate that the third (green) scenario is the only scenario that allows the country to build new power plants to achieve its goals of development while only slightly increasing the amount of CO₂ emissions. In addition, this scenario may be incorporated into the Nationally Determined Contributions ratified by Egypt in the Paris Agreement to limit global warming.

Keywords CO₂ emissions · Electricity generation · Fuel mix · Egypt 2030

Introduction

CO₂ and global warming

For the first time in the history of climate negotiations, an agreement among the leaders of the world was signed in December 2015 at the United Nations 21st session of the Conference of the Parties (COP21) on climate change in Paris. The Paris Agreement has the objective of “holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels”. The production and use of energy are the two largest sources of global CO₂ emissions, indicating that the energy

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sector is crucial to achieving this objective (United Nations 2015).

Conventional methods to generate electricity involve burning (oxidizing) a fossil fuel to generate heat. In a steam power plant, this heat energy is used to convert water into steam in a boiler where the generated steam (working fluid) is used to rotate a steam turbine. In a gas power plant, the air is mixed with fuel in a combustion chamber and the gases resulting from the combustion (working fluid) are used to drive the blades of a gas turbine. The rotating turbine serves as the prime mover for an electric generator (transforming kinetic energy to electrical energy), with an overall thermal efficiency approximately equal to 40%. For example, let us assume that we have a certain amount of natural gas (or methane CH_4). Since methane is a hydrocarbon, a common way to convert its chemical energy into work is to combine it with oxygen (burn it) to release its chemical energy in the form of heat. The methane and oxygen undergo a chemical reaction and produce water and carbon dioxide, as shown in Eq. (1):

The amount of CO_2 released to generate 1 kWh of electrical energy depends on the carbon content in the fuel, as shown in Table 1 (International Energy Agency [IEA] 2016).

Despite the growth of non-fossil energy (such as nuclear, hydropower, solar and wind), the share of fossil fuels in the world energy supply chain has remained relatively unchanged. In 2018, fossil sources accounted for 80% of the world energy production. According to the IEA, the annual CO_2 emissions from fuel combustion reached 33 Gt of CO_2 in 2019 (IEA 2019). The concentration of CO_2 in the atmosphere has increased from 280 ppm in the pre-industrial era (1860) to about 415 ppm in May 2019 (Smil 2019). The development of CO_2 emissions in the atmosphere from pre-industrial levels to current levels is shown in Fig. 1 together with the concentration of atmospheric CO_2 (both in in ppm) over the same period (https://www.volker-quaschnig.de/datserv/CO2/index_e.php).

Climate change mitigation actions require a reduction in emissions of 50–80% by 2050 compared to 1990 levels

Table 1 Emission factor of CO_2 in kilograms released to generate 1 kWh of electricity

Fuel	Coal	Petroleum oil	Natural gas
CO_2 released in kg/kWh	0.95 to approx. 1	0.75 to approx. 0.8	0.55

From the International Energy Agency (2016)

Fig. 1 Concentration of CO_2 in the atmosphere in parts per million (ppm) (blue line) and global CO_2 emissions from fuel combustion in million tons (Mt) (red line) (https://www.volker-quaschnig.de/datserv/CO2/index_e.php)

(World Bank Group 2016). The electricity sector has a key role to play in meeting these targets. In 2016, average emissions from electricity generation worldwide were in the range of 500 g $\text{CO}_2\text{eq/kWh}$ (Olivier and Peters 2019), which means that for each 1 kWh of electricity produced, 0.5 kg of CO_2 is released to the atmosphere.

CO_2 emissions in Egypt

In 2018 Egypt emitted 250 million tons (Mt) of CO_2 , thereby ranking 27th among the countries of the world in terms of energy-related CO_2 emissions, with a share of 0.75% of global emissions and 2.5 tons of CO_2 emissions per capita. The electrical power generation sector in Egypt is responsible for approximately 40% of the country's total CO_2 emissions, followed by the transportation (20%) and industry (15%) sectors, residential buildings (5%) and other sectors (20%), as shown in Fig. 2 (Crippa et al. 2019).

Fig. 2 Sources of CO_2 emissions in Egypt in 2018 (Crippa et al. 2019)

Table 2 Energy mix for electricity generation in Egypt in 2020

Energy source	Amount of electrical power generating capacity (GW)	Percentage of total electrical power generating capacity
Natural gas	51	85
Mazout	3	5
Hydroelectric	3	5
Solar	1.5	2.5
Wind	1.5	2.5
Total generating capacity (GW)	60 GW	100

From African Energy Reports 2020

According to the most recent report of 2020, Egypt has an electricity-generating capacity of 60 GW that is from a range of sources (natural gas, renewables), as shown in Table 2 (Africa Oil & Power 2020).

To achieve its goals of development, Egypt plans to build new power plants with a total electricity-generating capacity of 30 GW. Added to the current electricity-generating capacity of 60 GW, the country will have a power generating capacity of approximately 90 GW of electricity by 2030. Egypt has three scenarios to achieve this goal. The first is the diversified energy mix scenario in which dependence on the oil and gas will be decreased in favor of a diversified energy mix containing coal, nuclear in addition to renewables and hydro. The second scenario, a fossil fuel-based scenario, is based on recent discoveries of proven natural gas reserves, possibly shifting Egypt's vision towards more dependence on natural gas, in addition to renewables, nuclear and hydro. The authors of this paper suggest a third scenario, namely the environmentally friendly scenario or the green scenario (the third scenario) in which more dependence is placed on renewables, hydro and nuclear power, in addition to natural gas, with no coal in the suggested energy mix. In this article, we examine the CO₂ emissions from electricity generation under these three futuristic scenarios.

Reducing CO₂ emissions from the electricity sector in Egypt

Switch to low/no carbon fuels

Switching to low carbon fuels or to “carbon-free” generation (hydroelectric–nuclear–solar–wind) can be achieved by modifying the existing energy mix. A recent study of the optimal power generation mix in Egypt points out that, according to resource availability and future expected electricity needs, new power plants could be based on renewable resources or nuclear power plants (Farnoosh and Lantz 2015).

Although Egypt is the 25th largest oil producer in the world and has 4.5 billion barrels of crude oil reserves, resources have been declining rapidly; it is projected that only about 1.5 billion barrels of oil reserves will be available by 2030. Natural gas reserves are a favorable resource for power generation, and Egypt's new strategy is to accelerate the exploration and development of its gas fields. However, the current policy to expand natural gas use in all sectors (in place of petroleum products) in addition to natural gas exports will lead to a rapid decline in natural gas reserves (Mondal 2019).

Alternatively, renewable sources of power generation can be used efficiently at very decentralized and local scales. However, due to their intermittent nature, renewable energy sources cannot provide a large-scale continuous base-load power.

Therefore, a power generation strategy based on gradual integration of nuclear and renewable has been suggested. A power generation mix, based on an optimal choice of natural gas, nuclear, hydroelectric and other renewable energy sources (solar and wind) is considered to be the most appropriate strategy to electricity production in Egypt.

Use combined cycle generation

The type of power generation technology also affects the CO₂ emissions. According to the 2017–2018 fiscal

Table 3 Effect of electricity generation technology on CO₂ emissions

Properties of power plant	Electricity generation technology					
	Steam turbines		Gas turbines		Combined cycle	
	< 300 MW	> 300 MW	< 50 MW	> 50 MW	< 400 MW	> 400 MW
No. of units	26	34	29	26	8	37
Total power (GW)	3	12.5	1	4.5	2	28
CO ₂ intensity (gCO ₂ /kWh)	725	591	923	612	510	384

year report by the Egyptian Electricity Holding Company (EEHC), of the turbines used to generate electricity, combined cycle gas turbines (CCGT) have the lowest fuel consumption and lowest generation of CO₂ emissions per kilowatt-hour and steam turbines have the highest. It should also be noted that power plants with larger capacities are generally more efficient than those with a small capacity. The outcomes of the 2017–2018 EEHC fiscal report (EEHC 2019) is shown in Table 3.

Energy efficiency in terms of transmission, distribution and utilization

In addition to generation decarbonization and installation of CCGT units, other strategies can be implemented to decrease current and future energy losses in the transmission and distribution system, expected to range from 12 to 15% by 2022 and to have decreased to 8% by 2030 (Egyptian Ministry of Planning 2016). Improved energy efficiency for end users can lead to a lower demand of energy services. Replacing 400 W sodium lamps in street lighting with equivalent 150 W LED lighting will reduce the current 6% share of consumed energy due to public lighting to approximately 2%. More reductions could be achieved for the residential sector, especially by increasing the use of LED lighting and high-efficiency appliances.

Proposed scenarios for power generation from 2020 to 2030

Diversified energy mix scenario

This scenario is introduced in Egypt's Vision 2030. In this scenario, the aim is to use a diversified (open to all possible sources of energy) energy mix by 2030. The proposed energy mix in this scenario will consist of 29% coal, 27%

oil and gas, 16% solar, 14% wind, 9% nuclear and 5% hydro (Egyptian Ministry of Planning 2016). This scenario, shown in Fig. 3, will not only introduce coal for the first time in Egypt as a source of energy generation, but also will make it proportionally the largest energy source in the energy mix.

Coal, the dirtiest source of fossil fuel, is found in Egypt in one small mine (ElMaghara) in the Sinai Peninsula, and it is of low heat quality. Consequently, the coal will be imported through some dedicated ports, and the government claims that the new coal-fired power plants will use “clean coal technology” (CCT). Seven coal-fired power plants are currently being constructed, with the first one to start operation by 2022.

An agreement with the Russian RosAtom Company was signed to build a nuclear power plant equipped with four 1.2 GW nuclear reactors. The first reactor ought to start operation by 2024, the second by 2025, the third by 2026 and the fourth by 2027.

Fossil fuel-based scenario

Between 2016 and 2018, the Egyptian government announced the discovery of several natural gas fields (especially in the Mediterranean Sea). The development of these fields may shift the country's vision towards more dependence on natural gas. Growing interest in renewables worldwide, together with the current global political situation and the drastic effects of coronavirus disease-2019 (COVID-19), has led to a sharp fall in oil price, which was approximately US \$30 per barrel as of May 2020. These developments may shift government interest in implementing its diversified 2030 vision towards a fossil fuel-based scenario that depends on natural gas and oil (60%), accompanied by a substantial contribution of coal (22%), nuclear power (6%) and renewables and hydro (12%) (The Egyptian Center for Economic and Social Rights & the Heinrich Böll Foundation 2016), as shown in Fig. 4.

Fig. 3 Diversified energy mix scenario

Fig. 4 Fossil fuel-based scenario

Green scenario

The Egyptian government announced its plan to increase its power generation capacity from renewable sources to 20% by 2022. This share is to increase to 37% in 2030 and to 42% in 2035. It also announced a Feed-In-Tariff (FIT) to encourage investors to invest in renewable energy, approaching several countries with high levels of solar irradiation and high wind speeds. However, although renewable sources of power generation can be used efficiently at very decentralized and local scales, the intrinsic intermittent nature of such technologies limits their use to provide large-scale continuous base-load power.

Therefore, a power generation strategy based on 58% CCGT, 37% renewables and hydro and 5% nuclear power may be realistic, as shown in Fig. 5. The CO₂ emission factor for CCGT is < 400 gCO₂/kWh of generated energy compared to approximately 600 gCO₂/kWh with conventional steam or gas turbine power plants. This scenario requires gradually decreasing the share of oil as a fuel, in addition to gradually installing CCGT into steam or gas power-generating stations.

Calculation of CO₂ intensity

Calculation formula

The intensity of CO₂ (gCO₂/kWh) can be calculated using Eq. (2) (Hussy et al. 2018):

Fig. 5 Green scenario

Table 4 Forecasted electrical energy consumption in Egypt up to 2030

Year	2020	2022	2024	2026	2028	2030
Energy consumption in million kilowatt-hours	186,000	216,000	252,000	294,000	344,000	400,000

$$\text{CO}_2 \text{ intensity} = \frac{\sum \left(\frac{P_i \cdot C_i}{E_i} \right)}{\sum P_i} \quad (2)$$

where P_i = electrical energy produced from fuel (i) in kilowatt-hours, C_i = emission factor of fuel (i) in grams per kilowatt-hours and E_i = generation efficiency during the production of P_i .

Determinants of the study

The three scenarios presented here are based on generating capacities (in GW). However, the CO₂ emissions are based on the actual energy consumed (in kWh). The total consumed energy Egypt during the fiscal year 2017–2018 was in the range of 160,000 million kWh (EEHC 2019). The annual increase in electricity consumption is in the range of 8%, based on the last 5 years of recorded consumption. Table 4 presents a 10-year forecast (from 2020 to 2030) for energy consumption in Egypt using an annual increase of 8%.

- As of May 2020, the peak load in Egypt was recorded as 32 GW, indicating that there is a reserve capacity of 28 GW (approx. 90%). This is a very high percentage and may decrease the speed at which the new power plants will be built. In our study, we assume that 6 GW of new generating capacities will be added every 2 years.
- Not all of the generating power plants will be actively operational. In our study, we assume that the priority for power generation will be given to renewables with almost no operating costs (but with availability of approx. 30% for wind and solar and availability of approx. 50% for hydro), followed by power supplied by the newly built plants (with availability of approx. 90%). Power from the latter source will be supplied mainly by the private sector under the auspices of a minimum purchasing agreement with the government. The remaining energy required will be supplied by the government-owned oil and gas generating plants.
- The CO₂ emission factor for CCGT is < 400 gCO₂/kWh generated energy compared to approximately 600 gCO₂/kWh with conventional steam or gas turbine power plants. Therefore, the emission factor in the third scenario starts with 600 gCO₂/kWh in 2020, with a gradual decrease to 400 gCO₂/kWh in 2030 through equal steps.
- Eq. (2) will be modified (as one of the authors' contributions) such that the numerator will be as follows: [$\chi \times$

$P_{\text{nat. gas}} \times C_{\text{nat. gas}}/E_{\text{nat. gas}} + (P_{\text{coal}} \times C_{\text{coal}})/E_{\text{coal}}]$ = Forecasted energy consumption (from Table 4). This equation will be solved for χ (the percentage of the natural gas to be used in the energy mix). This value of χ will be used in the denominator of the same equation to calculate the CO₂ intensity

Results

A modified Eq. (2) has been applied on the three scenarios, together with some of the estimated figures for generation capacities during the period from 2020 to 2030; missing values are interpolated. The results are shown in Tables 5, 6 and 7.

Table 5 Diversified scenario for electricity generation up to 2030

Diversified scenario	2020	2022	2024	2026	2028	2030
Power generating capacity according to Energy sources (GW)						
Oil and gas	54.0	48.0	42.0	36.0	30.0	24.0
Hydro	3.0	3.0	4.5	4.5	4.5	4.5
Renewables	3.0	6.0	10.0	15.0	22.0	27.0
Coal	0.0	9.0	13.5	18.5	21.5	26.5
Nuclear	0.0	0.0	2.0	4.0	6.0	8.0
Electricity generation-associated factors						
Total power (GW)	60.0	66.0	72.0	78.0	84.0	90.0
Total energy (GWh)	160,571	216,337	252,814	294,862	344,268	400,507
CO ₂ emissions (ktons)	100,877	179,185	203,654	237,428	263,011	307,043
CO ₂ intensity (gCO ₂ /kWh)	628	828	806	805	764	767

Table 6 Fossil fuel-based scenario for electricity generation up to 2030

Fossil fuel-based scenario	2020	2022	2024	2026	2028	2030
Power generating capacity according to Energy sources (GW)						
Oil and gas	54.0	54.0	54.0	54.0	54.0	54.0
Hydro	3.0	3.0	5.5	5.5	5.5	5.5
Renewables	3.0	3.0	3.5	4.5	5.0	5.5
Coal	0.0	6.0	8.0	11.0	14.5	20.0
Nuclear	0.0	0.0	1.0	3.0	5.0	5.0
Electricity generation-associated factors						
Total power (GW)	60.0	66.0	72.0	78.0	84.0	90.0
Total Energy (GWh)	160,571	216,390	252,306	294,354	344,706	400,262
CO ₂ emissions (ktons)	100,877	170,358	191,466	223,129	264,172	330,085
CO ₂ intensity (gCO ₂ /kWh)	628	787	759	758	766	825

Table 7 Green scenario for electricity generation up to 2030

Green scenario	2020	2022	2024	2026	2028	2030
Power generating capacity according to Energy sources (GW)						
Oil and gas	54.0	53.5	53.0	52.5	52.0	52.0
Hydro	3.0	3.0	4.5	4.5	4.5	4.5
Renewables	3.0	9.5	13.3	17.4	22.7	28.7
Coal	0.0	0.0	0.0	0.0	0.0	0.0
Nuclear	0.0	0.0	1.2	3.6	4.8	4.8
Electricity generation-associated factors						
Total power (GW)	60.0	66.0	72.0	78.0	84.0	90.0
Total energy (GWh)	160,571	216,197	252,157	294,796	344,969	400,367
CO ₂ emissions (ktons)	100,877	120,158	117,804	116,227	120,740	128,863
CO ₂ intensity (gCO ₂ /kWh)	628	556	467	394	350	322

Fig. 6 Anticipated CO₂ emissions from the electricity sector in Egypt according to the different scenarios

Fig. 7 CO₂ intensity from the electricity sector in Egypt according to the different scenarios

The diversified energy mix scenario will increase CO₂ emissions from the electricity sector from a baseline value of approximately 100 MtCO₂ to approximately 307 MtCO₂. The fossil fuel-based scenario will increase CO₂ emissions from the electricity sector from a baseline value of approximately 100 MtCO₂ to approximately 330 MtCO₂. This scenario is worse than the diversified energy mix scenario in terms of CO₂ emissions due to its large dependence on fossil fuel. The green scenario will increase CO₂ emissions from the electricity sector from a baseline value of approximately 100 MtCO₂ to approximately 128 MtCO₂.

Discussion and conclusions

The CO₂ emission and intensity from the electricity sector under the three scenarios are compared in Figs. 6 and 7. It is evident that building the new power plants with respect to the first two scenarios (diversified and fossil fuel-based) will lead to a tremendous increase in CO₂ emissions that may exceed 300% of current emissions within 10 years. The third (green) scenario is the only scenario that allows the country to build new power plants to achieve its goals of

development while slightly increasing the current amount of CO₂ emissions by < 30% in the course of the same 10 years. In addition, this scenario is the only scenario that allows the emission intensity to decrease to almost half its current value (322 gCO₂/kWh instead of 628 gCO₂/kWh) while consumption rises by 250% (from 160,000 to 400,000 Million kWh). It is strongly recommended that Egypt should deploy this third scenario if it is serious about achieving its environmental pillar of Egypt's vision 2030 and its commitments to the Paris Agreement regarding reducing global warming. In future studies, we will look at evaluating the life-cycle cost analysis of these scenarios.

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