

Multi-objective Optimization of Dynamic Electricity Generation-mix with CO₂ Reduction Target: A Case Study of South Africa

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Abstract

Carbon dioxide emissions is a global issue which has catastrophic consequences that beyond the universal climate change. Carbon emissions interact with other human demands on this planet, such as food, fibers, timber, and land for dwellings and roads. This paper presents a linear programming model for the optimal electricity generation-mix problem to meet a specified CO₂ emission target. The objective function minimizes the weighted sum of two terms: the electricity generation cost and the CO₂ emissions cost. Most of the electricity generation mix problem literature considers fixed and aggregated demand and capacity over the year. However, the electricity demand and generation capacity are dynamic parameters in hourly and/or daily basis. The proposed model contributes to the literature by modeling the hourly electricity demand, daily and hourly electricity generation capacity, and daily CO₂ emissions limit. The model is solved optimally with a case study derived based on the electricity sector 2030 plan in South Africa. Results show that the proposed model proposes generation-mix plans that could achieve the CO₂ reduction target. Furthermore, electricity generation cost and CO₂ emissions are eliminated.

Keywords

Electricity generation-mix, CO₂ emissions reduction, linear programming, optimization

1. Introduction

Electrical energy demand is increasing exponentially all over the world. For example, the total electricity consumption for South Africa recorded a growth of 17% from 265,457 GWh in 2013 to 310,410 GWh in 2017 (Department of Energy South Africa (DoE SA) 2013). Furthermore, this trend is expected to continue to record a growth of 34% by 2030 with increase from 310,410 GWh in 2017 to 416,410 GWh in 2030 (DoE SA 2013). Similarly, the grid peak load follows an increase pattern with growth of 37% from 37,500 MWh in 2017 to 61,596 MWh in 2030 (DoE SA 2013).

There are a limited number of solutions to meet the dramatic expansion of electricity demand. Most of contemporary solutions rely on the conventional idea of increasing the supply to match the demand by investing in new electrical power stations. Currently, the total installed electricity generation capacity in South Africa is about 50 GWh which is expected to expand up to 82 GWh by 2030, a growth of 64% (DoE SA 2013). Figure 1 shows the trends of annual electricity consumption, grid peak load, and generation capacity in South Africa from 2013 to 2030 (DoE SA 2013).

Due to the continual expansion in electricity generation capacity, the total CO₂ emissions from the electricity sector in South Africa is expected to increase by around 20% from 266 million tons in 2013 to 319 million tons in 2025 (DoE

SA 2013). The CO₂ emissions limit is originally indicated at 550 million tons per annum for South Africa starting from 2025 (DoE SA 2013). The Integrated Resource Plan for electricity sector in South Africa 2010-2030 (IRP-2010) assumed that the electricity sector accounts for around 45-50% of national CO₂ emissions. Thus, the CO₂ emission target is established in the IRP-2010 as 275 million tons per annum (DoE SA 2013).

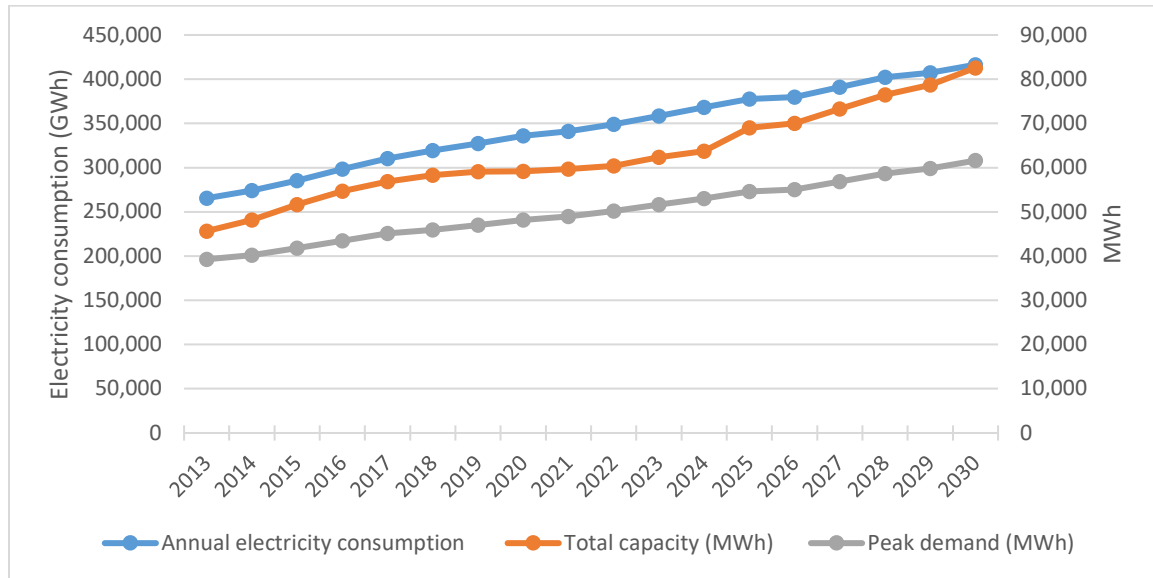


Figure 1. Grid demand and the generation capacity trends in South Africa.

In perspective of the quick growth in power generation capacity and the corresponding rise in CO₂ emissions in South Africa, there is a need for developing an electricity generation-mix that fulfills the expected electricity demand as well as achieves an overall reduction in CO₂ emissions. Henceforth, this paper aims to develop a mathematical optimization model for the Electricity Generation-Mix Problem (EGMP) with the objective function that minimizes the Electricity Generation Cost (EGC) and the CO₂ Emission Cost (CO₂EC). Meanwhile, the proposed model satisfies the hourly forecasted electricity demand constraint, the hourly generation capacity constraint for each energy source, and simultaneously fulfill a specified CO₂ emission target.

The majority of the publications in the EGMP considered aggregated demand and capacity over the year. However, the electricity demand and generation capacity are dynamic parameters in hourly and daily basis. For example, demand changes from peak to off-peak hours. Also, the demand changes over the weekdays, weekend, vacations, summer, and winter. Furthermore, the generation capacity may vary from day to day due to breakdowns and maintenance activities. Also, the capacity of some electricity generation sources may vary in hourly basis, such as the solar energy sources. Thus, there is a need to model the electricity demand and generation capacity in hourly and daily basis.

Muis et al. (2010) presented a mixed integer linear programming model for the optimal planning of EGMP to meet a specified CO₂ emission target. The model was implemented for the electricity generation in Malaysia. Zou et al. (2016) examined the impacts of CO₂ emission reduction targets on the structure of power generation in China. They developed a mathematical model to minimize the total EGC and selected the optimal energy technology while utilizing the learning curve concept.

Sithole et al. (2016) developed a policy-informed optimal electricity generation scenario to assess the sector's transition to 2050 with emission target in UK. They utilized an excel-based "Energy Optimization Calculator" to produce a least-cost generation mix. They focused mainly on the least-cost electricity generation portfolio, emission intensity, and total investment required to assemble a sustainable electricity generation mix. They concluded that low carbon technologies must be deployed on a large scale toward aligning the sector with 2050 targets.

Wang et al. (2018) proposed a deterministic optimization model for determining the optimal power mix through the introduction of environmental and carbon taxes. A case study of Hebei Province in China was provided to illustrate the effects of these two taxes. They concluded that such tax policies could significantly improve the power mix

adjustment as well as the surrounding air quality. Also, they concluded that tax levels would promote the development of renewable power generation.

The contribution of this paper is to modify and extend the models in the literature with two-fold aims. First, to formulate a practical, and easy to solve Linear Programming (LP) optimization model for the EGMP to determine the optimal electricity generation-mix for South Africa in 2030. In this model, the objective function minimizes the weighted sum of the EGC and the CO₂EC. This model would enable decision makers to control how they favor the minimization of the EGC and the CO₂EC over each other and produce the most suitable generation-mix for each scenario. Second, the proposed model generates an hourly-based generation-mix plan by considering both; the hourly electricity demand and the daily generation capacity. Where the hourly generation capacity is applied if applicable as for the PV source. Thus, the proposed model could be applied in both the strategic and operational generation-mix planning. Furthermore, it could help the decision makers to develop the best generation-mix plans for different hourly or daily loading and capacity scenarios. This could facilitate developing the best generation-mix and make it more flexible. Additionally, analyzing the generation-mix plan on an hourly basis enables us to provide data sets with hourly reporting of fuel type or energy source used in the generation mix. This could empower us to derive the dynamic hourly CO₂ intensity. Which could be used as a signal in demand response and electric load scheduling.

The remainder of this paper is organized as follows: Section 2 focuses on defining the problem and presenting the proposed LP optimization model. Section 3 introduces a case study based on 2030 energy plan in South Africa which is used in this paper. Results, comparisons and discussions are presented in section 4. Lastly, a conclusion is drawn.

2. The proposed mathematical model

In this research, a new LP model is developed to address the Generation Mix Problem (GMP) with CO₂ reduction target. As discussed above, the GMP is concerned with the decision of selecting an optimal generation-mix under given maximum capacities, the hourly grid demand and CO₂ emissions limit constraints. In other words, the GMP aims to define how much electrical energy are to be produced/generated from the different electricity generating sources over the day. The model is formulated using multi-objective function that minimizes the generation-mix cost and the CO₂ emissions cost.

Considering a time interval (t) of one hour over a study period (T) of 24 hours (full-day) and a power source (i), the main decision variable $x_{i,t}$ is defined. The $x_{i,t}$ defines the amount of power (KW) generated from a power source i at time period t . Table 1 summarizes the indices, parameters and decision variables used in the proposed mathematical model.

Table 1. Notation summary

Notation	Description
Indices:	
$i \in I$	Index of power source, where I is the set of the considered power sources.
$t \in T$	Index of time/ time period, $t = 1, \dots, T$, where T is the horizon.
Parameters:	
v_i	The levelized cost of electricity/energy (LCOE) rate of a power source i (R/KWh).
r_i	The CO ₂ emission rate of a power source i (Kg/KWh).
c	The carbon emission price (R/Kg).
UL_i	The upper bounds on electricity generated from a power source i (KW).
$UL_{PV,t}$	The upper bounds on electricity generated from the PV power source at time t (KW).
D_t	The total power demanded from the grid (KW) at time t .
CO_2DL	The daily limit of the CO ₂ emissions from all power sources (Kg/day).
ω	The weighting factor attached to the objective of minimizing the CO ₂ emissions cost.
Main decision variables:	
$x_{i,t}$	A real variable represents the electricity generated (KW) from a source i at time t .
Auxiliary decision variables:	

EGC	The total electricity generation-mix cost (R).
CO_2EC	The total CO ₂ emissions cost (R).

2.1. Model objective function

In order to obtain an optimal generation-mix that balances the objectives in (1), a weighting method is employed to integrate the sub-objectives into one. The advantage of this approach is that the government has an option to choose the objective to control the total electricity generation-mix cost (EGC) and the total CO₂ emissions cost (CO_2EC).

$$\text{Minimize } [(1 - \omega) \cdot EGC + \omega \cdot CO_2EC] \quad (1)$$

The first term in the objective function (EGC) is estimated by equation (2), where v_i is the levelized cost of electricity/energy (LCOE) rate of a power source i (R/KWh).

$$EGC = \sum_{i=1}^I \sum_{t=1}^T v_i \cdot x_{i,t} \quad (2)$$

The second term in the objective function (CO_2EC) is estimated by equation (3), where c is the carbon emission price (R/Kg) and r_i is the CO₂ emission rate of a power source i (Kg/KWh).

$$CO_2EC = c \cdot \sum_{i=1}^I \sum_{t=1}^T r_i \cdot x_{i,t} \quad (3)$$

2.2. Model constraints

Constraint 4 guarantees the hourly grid demand. The total electricity generation from whole electricity sources must be equal to or greater than the estimated total electricity demand at each time t . The total electricity generation results from the summation of the electricity generation from all the available electricity sources I as shown in equation (4), where D_t is the total electricity demanded from the grid (KW) at time t .

$$\sum_i x_{i,t} \geq D_t \quad \forall t \in T \quad (4)$$

Constraints 5 and 6 set the maximum capacity for the different energy sources. Constraint (5) sets upper bounds on electricity produced from the different electricity generation sources. Capacity of each generation sources must be less than or equal to its maximum capacity, where UL_i is the upper bounds on electricity generated from a power source i (KW).

$$x_{i,t} \leq UL_i \quad \forall i \in I, \forall t \in T \quad (5)$$

Giving that the solar generation profile changes over the day, a new parameter ($UL_{PV,t}$) is used to represent the upper bounds on electricity generated from the PV power source at time t (KW). Constraint (6) sets the potential upper bounds on solar generation source output on an hourly basis. This constraint guarantees that the potential capacity of the PV power source at time t is less than or equal to the $UL_{PV,t}$.

$$x_{i=Pv,t} \leq UL_{PV,t} \quad \forall t \in T \quad (6)$$

Constraint (7) calculate the CO₂ emissions from all electricity generation sources and guarantees that the produced emissions do not exceed the defined CO₂ daily limit (CO_2DL). Where CO_2DL is the daily limit of the CO₂ emissions from all power sources (Kg/day).

$$\sum_{i=1}^I \sum_{t=1}^T r_i \cdot x_{i,t} \leq CO_2DL \quad (7)$$

Finally, constraint (8) reflects the real properties of the main and auxiliary decision variables.

$$x_{i,t}, EGC, CO_2EC \in \mathbb{R}^+ \quad \forall i \in I, \forall t \in T \quad (8)$$

3. Case study

A case study involving electricity generation in South Africa is presented in this study. The case study data was obtained from several publications. Future projected data for electricity generation maximum capacity by each energy sources are based on Integrated Resource Plan for electricity (IRP) 2010-2030 (DoE SA 2013). Eight energy sources are included in the South African's IRP 2030, which are considered in this study. The case study includes four non-renewable energy sources— Coal, Nuclear, Open Cycle Gas Turbine (OCGT), and Closed/Combined Cycle Gas Turbine (CCGT); and four renewable energy sources—Wind, Hydroelectric (Hydro), Photovoltaic (PV), and Concentrating Solar Power (CSP). The maximum capacity for electricity generation by each energy sources is shown in Table 2.

The projected Levelized Cost Of Electricity/Energy (LCOE) for power generation sources are derived from forecasts of different organizations, such as the Department of Energy of South Africa (EPRI 2015), World Wide Fund for Nature in South Africa (WWF-SA 2014), and the U.S. Energy Information Administration (EIA 2017). The applied LCOE data is shown in Table 2.

For estimating CO₂ emissions from different electricity generation sources, CO₂ emission factors are derived based on a comparison of emissions of various electricity generation sources report published by the World Nuclear Association (WNA 2010). The estimated CO₂ emission factors used in the study are shown in Table 2. Based on the IRP 2010-2030 (DoE SA 2013), the CO₂ emissions limit is maintained at 275 million tons per annum. Thus, a daily emission target (CO_2DL) of 753,425 ton is established. In order to estimate the CO₂ emission cost, the CO₂ emissions are charged at $c = R0.1323/kg$ (Setlhaolo and Xia 2016).

Furthermore, the expected electricity demand in South Africa are derived based on Integrated Resource Plan for electricity (IRP) 2010-2030 (DoE SA 2013). The hourly grid demand profile is linearly scaled up according to the expected increases of the peak demand in the year 2030. The expected hourly grid demand profile (D_t) is shown in Figure 2.

Given that the maximum electricity generation capacity of the PV energy source changes over the day, a typical solar generation profile is used. It is derived from a technical report produced by the Electric Power Research Institute (EPRI) and the Department of Energy of South Africa (EPRI 2015). The solar generation profile on an hourly basis ($UL_{PV,t}$) is shown in Figure 2.

Table 2. Case study data.

Electricity generation source	Total capacity UL_i (MWh)	LCOE v_i (R/kWh)	CO ₂ r_i (g of CO ₂ /kWh)
1. Coal	41,071	1.37	888
2. Nuclear	11,400	1.06	29
3. Wind	9,200	0.86	26
4. PV	8,400	0.59	85
5. OCGT	7,330	1.99	733
6. Hydro	4,759	0.74	26
7. CCGT	2,370	1.18	499
8. CSP	1,200	1.21	52

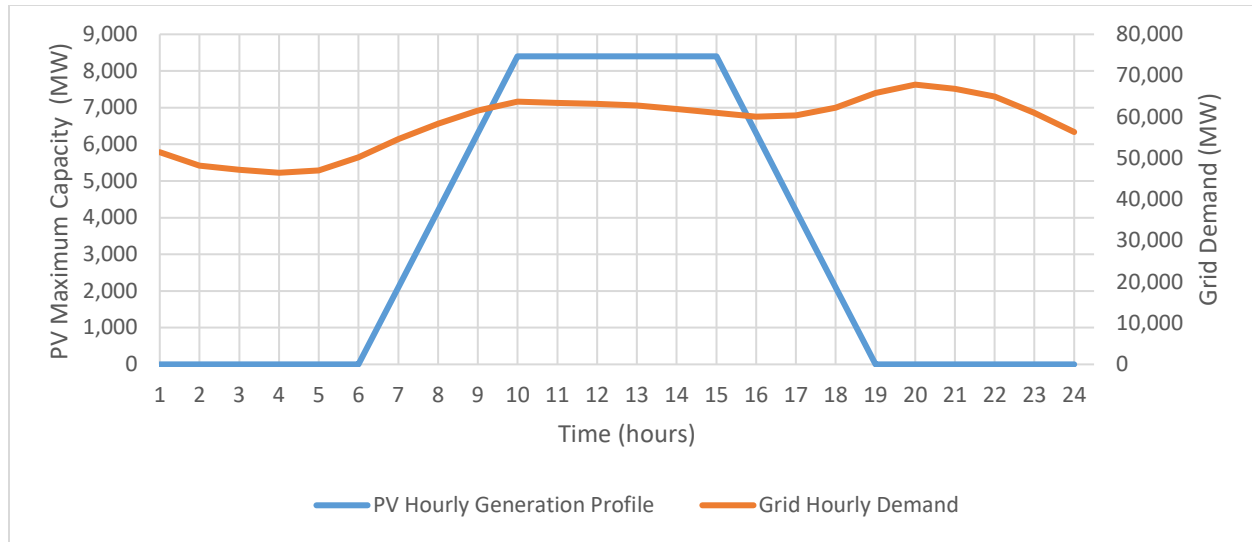


Figure 2. Grid demand and the solar generation hourly profiles.

4. Results and Discussion

This section presents and discusses the results of the proposed LP mathematical model for two different cases. The proposed model is solved optimally with the commercial optimization solver LINGO 12.0 (LINDO Systems Inc.). The proposed model aims to minimize the EGC and the CO₂EC. Thus, the proposed model is solved for two different scenarios of the weighting factor (w). The first case ($w=0$) ignores minimizing the CO₂EC and mainly aims to propose a generation-mix that eliminates the EGC. In other words, this case could be called “Minimum EGC driven generation-mix”. On contrast, the second case ($w=1$) ignores minimizing the EGC and mainly aims to propose a generation-mix that eliminates the CO₂EC. In other words, this case could be called “Minimum CO₂EC driven generation-mix”.

Table 3 shows comparisons between the two cases based on four measures—the EGC, the CO₂EC, the total CO₂ daily emissions (CO₂DE), and the peak CO₂ hourly emissions (Peak CO₂HE). The latter two measures are calculated based on the following equations, respectively.

$$CO_2DE = \sum_{i=1}^I \sum_{t=1}^T r_i \cdot x_{i,t}$$

$$Peak\ CO_2HE = \max_{t \in T} \left(\sum_{i=1}^I r_i \cdot x_{i,t} \right)$$

Table 3. Basic comparison between two proposed generation-mixes.

Weighting factor (w)	EGC (10 ⁶ R)	CO ₂ EC (10 ⁶ R)	CO ₂ DE (10 ⁶ Kg)	Peak CO ₂ HE (10 ⁶ Kg)
$w = 0$	1,582.29	81.72	617.70	36.46
$w = 1$	1,691.36	78.11	590.43	35.33

Results show that the minimum EGC driven generation-mix results in lower EGC by around 6.45% compared to the minimum CO₂EC driven generation-mix. However, the latter results in lower CO₂EC and CO₂DE by around 4.41% compared to the minimum EGC driven generation-mix. Furthermore, the proposed model could eliminate the CO₂DE, compared to the CO₂DL, by around 18% and 22% for the minimum EGC driven generation-mix and the minimum CO₂EC driven generation-mix, respectively. Moreover, the minimum CO₂EC driven generation-mix could reduce the peak CO₂HE by around 3.12% compared to the minimum EGC driven generation-mix.

Figure 3 shows the proposed electricity generation-mix for two cases considered in the study. Results show that the proposed model compromises between the Coal and the OCGT electricity generation sources. The minimum EGC driven generation-mix relied more on Coal generation source to reduce the EGC. This result can be justified with the fact that the LCOE of the Coal generation source (R1.37/KWh) is lower than the LCOE of the OCGT generation source (R1.99/KWh). On contrast, the minimum CO₂EC driven generation-mix relied more on the OCGT generation source to reduce the CO₂EC. This result can be justified with the fact that the CO₂ emission rate (r_i) of the OCGT generation source (733 g of CO₂/kWh) is lower than the CO₂ emission rate of the Coal generation source (888 g of CO₂/kWh).

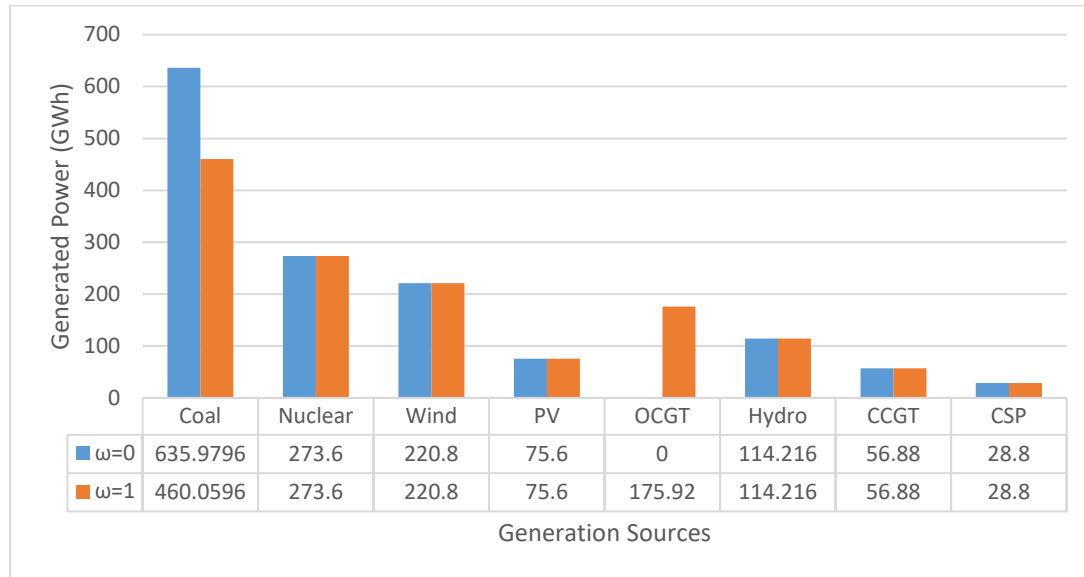


Figure 3. Two proposed electricity generation-mixes.

Figures 4 and 5 illustrate the breakdown for electricity generation-mix for the minimum EGC driven generation-mix case and the minimum CO₂EC driven generation-mix case on hourly basis, respectively.

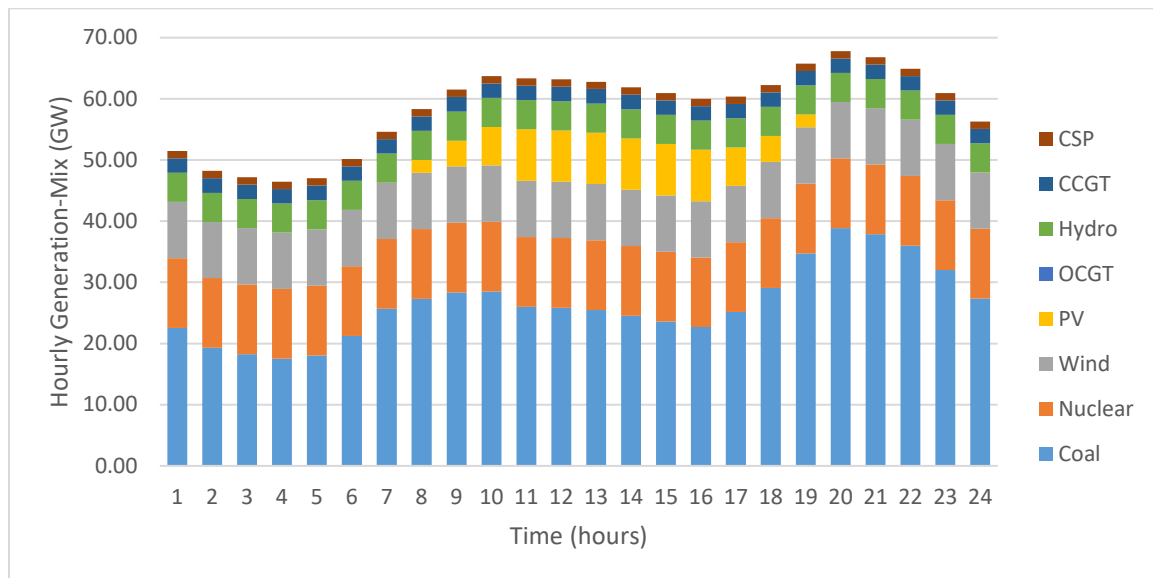


Figure 4. The proposed minimum EGC driven generation-mix.

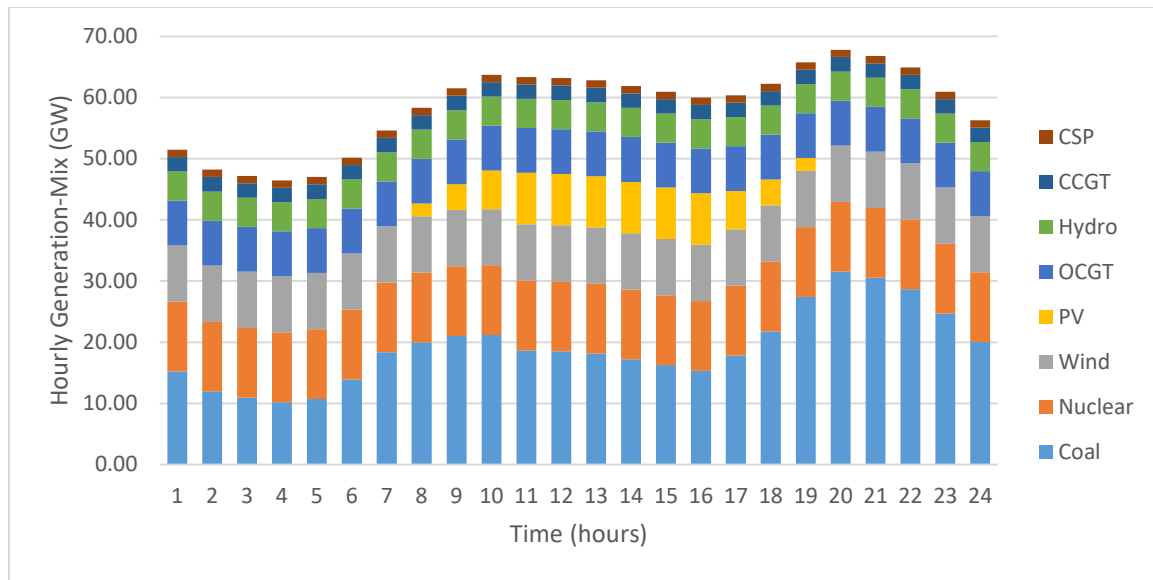


Figure 5. The proposed minimum CO₂EC driven generation-mix.

Figure 4 illustrates that the minimum EGC driven generation-mix fully utilized the cheapest generation sources and fulfilled the remaining hourly grid demand by the Coal generation source. However, it did not utilize the OCGT generation source at all because it is the most expensive generation source with LCOE of R1.99/KWh. However, figure 5 illustrates that the minimum CO₂EC driven generation-mix fully utilized the generation sources with the least CO₂ emission rate, including the OCGT generation source, and fulfilled the remaining hourly grid demand by the Coal generation source with the highest CO₂ emission rate of 888 g of CO₂/kWh.

Figure 6 illustrates the CO₂HE of each of the two cases considered in the study. Results show that the minimum CO₂EC driven generation-mix results in lower CO₂HE over the day. Results show that it could eliminate the CO₂HE by around 1,136.15 ton per hour compared to the minimum EGC driven generation-mix.

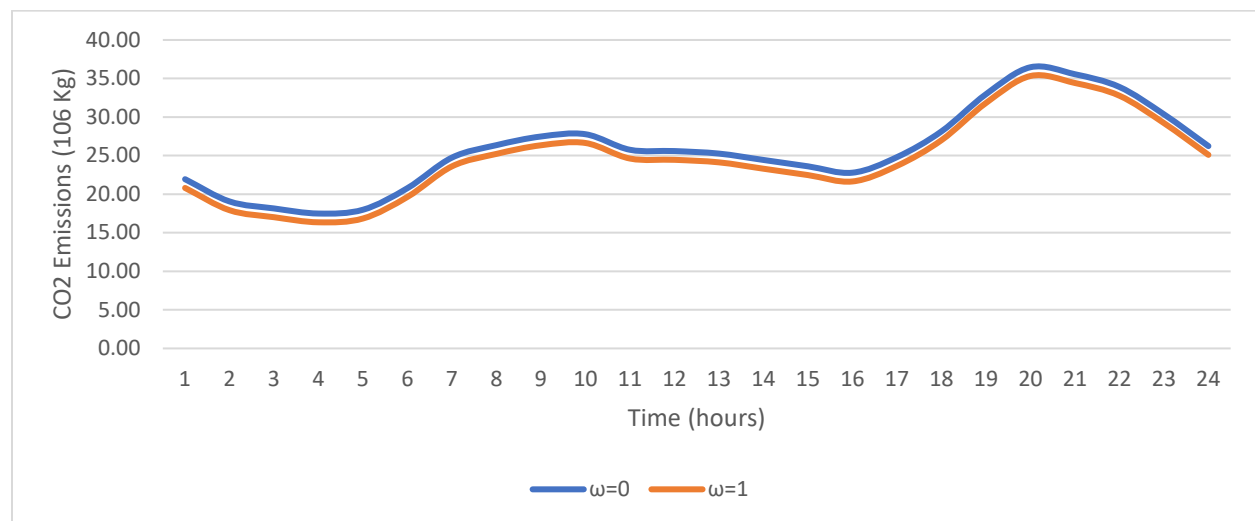


Figure 6. Comparison between two proposed generation-mixes in terms of the CO₂HE.

5. Conclusion

The majority of the literature in the EGMP considers fixed and aggregated demand and capacity over the year. However, the electricity demand and generation capacity are dynamic parameters in hourly and/or daily basis. This paper proposed a linear programming model for the optimal EGMP to meet a specified CO₂ emission target. The objective function minimizes the weighted sum of two terms: the EGC and the CO₂EC. The model was solved optimally with a case study based on the electricity sector 2030 plan in South Africa. Solving the proposed model at two weighting scenarios resulted in two generation-mix plans; a minimum EGC driven generation-mix and a minimum CO₂EC driven generation-mix. The former is with a lower EGC by around 6.45% while the latter is with lower CO₂EC and CO₂DE by around 4.41%. Both could eliminate the CO₂DE, compared to the CO₂DL, by around 18% and 22%, respectively. Furthermore, the minimum CO₂EC driven generation-mix results in lower CO₂HE over the day by around 1,136.15 ton per hour compared to the minimum EGC driven generation-mix. Further analysis may investigate the performance of the model at different points and the most compromise point is to be identified. Future extension to this model may focus on developing a stochastic model to consider the uncertainty in demand and renewable energy sources, and variations in prices.

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Biographies

Zakaria Yahia received the M.Sc. and Ph.D. degrees in Industrial Engineering from Cairo University, Giza, Egypt, in 2012 and Egypt-Japan University of Science and Technology (E-JUST), Alexandria, Egypt, in 2015, respectively. As a visiting Ph.D. student, he spent one academic year at the Tokyo Institute of Technology (TITECH), Tokyo, Japan, working on the research project “Developing a Design and Engineering Methodology for Organization (DEMO)-based simulation model for surgery room system”. From 2015 to 2017, he was an Assistant Professor with the Department of Mechanical Engineering, Fayoum University, Fayoum, Egypt. Currently, he is a Post-Doctoral Researcher with the Department of Quality and Operations Management, University of Johannesburg, South Africa. His research interests include the areas of Applied Operations Research & Simulation, Scheduling, Healthcare Management, Smart Grid Management and DEMO-Enterprise Ontology.

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