Renewable Energy Integration Considering Emission

Andi Dwiki Yulianto
Department of Electrical Engineering
King Fahd University of Petroleum and Miineral
Dhahran, Kingdom of Saudi Arabia
g202304190@kfupm.edu.sa

***Abstract*—In this paper, an optimization method to minimize the total cost for power system planning considering emission is proposed. The optimization method used in this paper is a mix integer linear programming (MILP) and it was simulated using General Algebraic Modelling Language (GAMS). Additionally, a future work will be discussed to address the limitations within this research such that this model could be more accurate and useful in real life implementation.**

***Keywords*—MILP, optimization, emission, renewable, integration.**

NOMENCLATURE

t	Year index
i	Generator type index
j	PV type index
a	Wind turbine type index
k	Time step (h)
PG(i)	Generator capacity (MW) of type i
Cost_inv(i)	Investment cost of generator type i (R/MW)
Cost_fuel(i)	Fuel cost of generator type i (R/MWh)
Cost_fixed(i)	Fixed O&M cost of generator type i (R/MW/Year)
Cost_var(i)	Variable O&M cost of generator type i (R/MWh)
Cost_ipv(j)	Investment cost of PV type j (R/MW)
Cost_iwt(a)	Investment cost of WT type a (R/MW)
Cost_fpv(j)	Fixed O&M cost of PV type j (R/MW/Year)
Cost_fwt(a)	Fxed O&M cost of WT type a (R/MW/Year)
Ro(t)	Carbon emission trading cost (R/tonne)
e(i)	Carbon emission rating of generator unit i (tonne/MWh)
Emax(t)	Maximum allowed emission in year t (tonne)
P(i,k,t)	Power generation of generator type i at hour k in year t (MWh)
PPV(j,k,t)	Power generation of PV type j at hour k in year t (MWh)
PWT(a,k,t)	Power generation of PV type j at hour k in year t (MWh)
Cinv	Capital investment cost of the system (R)
Cfuel	Capital fuel cost if the system (R)
Csalv	Total salvage value of the system (R)
Com	Capital O&M cost of the system (R)
Ccem	Penalty cost for carbon emission (R)
X(i,t)	Total generator type i installed in year t
Z(i,t)	Newly installed generator type i in year t
N(j,t)	Recommended capacity of PV type j in year t
M(a,t)	Recommended capacity of WT type a in year t
F	Objective function
D(k,t)	Demand at hour k in year t (MW)

I. LITERATURE SURVEY

Integrated standalone power system optimization involves utilizing renewable resources like solar, wind, and waste-to-energy technologies to meet energy demands efficiently while minimizing costs and environmental impact. Various studies propose optimization techniques using tools like Grey Wolf Optimization [1], and Hybrid Optimization Model for Electric Renewables (HOMER) to design and operate standalone microgrids with load demands in rural and urban settings [2]. These optimization methods consider factors like levelized cost of energy (LCOE), net present cost (NPC), and pollution emissions to achieve the most cost-effective and environmentally friendly power system configurations.

Additionally, linear programming optimization methods are proposed to streamline the startup and operation of power electronic systems within these integrated standalone power systems [3], [4].

Another approach which is proposed in [5], has a focus on maximizing the use of hybrid energy systems, which combine different renewable energy sources with storage systems to minimize costs, reduce grid dependency, and decrease emissions. Moreover, nowadays in designing power system, we really have to consider another important factor such as CO2 emission. In [6], The author proposed a method considering this factor by including a penalty cost for carbon emission in the objective function, and also put a limiting constraint to the thermal generator unit such that, the electricity production is bounded by how much CO2 emission allowed. A similar attempt in [7], the author introduces a system to penalize the emitted CO2 from the generation which is known as carbon trading system. In the formulation, they introduce a new decision variable which is the purchased carbon quota.

In this paper, we propose a similar model used in [5] but with the addition of thermal generation units (diesel generator) as shown in Fig.1. However, it will be limited in the sizing of the generation units (without the battery system). Moreover, we will also take into account the emission factor as it was proposed in [6]. The structure of this paper is divided into several parts. The first one is Section I, the literature survey, which explains the literatures or the existing works which inspire this research. Second, the mathematical modeling of the system which will be discussed in Section II. Third, an elaborative explanation of the model by discussing the simulation and the result of the optimization, section III. Finally, we will discuss the final remarks of this research and possible future work and challenge in the field of power system optimization in Section IV.

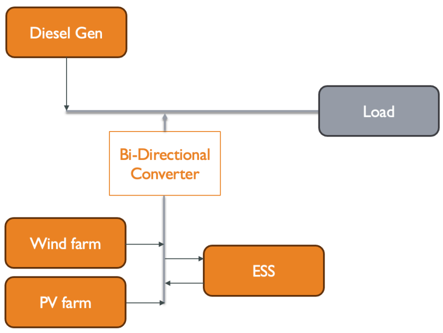

Figure 1 The schematic diagram of stand-alone system

II. Problem Formulation

A. Economic Components

Since the main objective in this paper is to minimize the overall cost of the system, the Objective function is formulated as in:

$$F = Cinv + Cfuel + Com + Ccem - Csalv \quad (1)$$

Where:

$$Cinv = \sum_t \left(\frac{1}{(1+disc)^{year(t)}} \sum_i cost\_inv_{(i)} . PG_{(i)} . Z_{(i,t)}\right) + \sum_j cost\_ipv_{(j)} . N_{(j,t)} + \sum_a cost\_wt_{(a)} * M_{(a,t)} \quad (2)$$

$$Cfuel = \sum_t \left(\frac{1}{(1+disc)^{year(t)}} \sum_{i,k} cost\_fuel_{(i)} . P_{(i,k,t)}\right) \quad (3)$$

$$Com = \sum_t \left(\frac{1}{(1+disc)^{year(t)}} \sum_i \left(cost\_fixed_{(i)} . PG_{(i)} . X_{(i,t)} + P_{(i,k,t)} . cost\_var_{(j)}\right) + \sum_j cost\_fpv_{(j)} . N_{(j,t)} + \sum_a cost\_fwt_{(a)} . M_{(a,t)}\right) \quad (4)$$

$$Ccem = \sum_t \left(\sum_{i,k} P_{(i,k,t)} . e_{(i)} . Ro_{(t)}\right) \quad (5)$$

$$Csalv = \sum_t \left(\frac{1}{(1+disc)^{year(t)}} \sum_i cost\_inv_{(i)} . PG_{(i)} . X_{(i,t)} . (1-\alpha)^{(To-year(t))}\right) + \sum_j cost\_ipv_{(j)} . N_{(j,t)} + \sum_a cost\_iwt_{(a)} . M_{(a,t)+} \quad (6)$$

B. Thermal Generation

The thermal units are consisted of three types of different diesel generator which the optimization will choose which units should be installed according to their parameter. The mathematical representation of this unit is:

$$P_{(i,k,t)} \le PG_{(i)} . X_{(i,t)} \quad \forall_{i,t,k} \quad (7)$$

$$Z_{(i,t)} = X_{(i,t)} - X_{(i,t-1)} \quad \forall_{i,t} \quad (8)$$

$$N_{(i,t)} = M_{(i,t)} - M_{(i,t-1)} \quad \forall_{i,t} \quad (9)$$

$$X_{(i,0)} \ge 0 \quad \forall_i (10)$$

C. Renewable Generation

The renewables consist of solar panels and wind turbine. The solar panel is modeled as:

$$PPV_{(j,k,t)} \le N_{(j,t)} . PVout_{(j,k,t)} \quad (11)$$

Here, $PVout_{(j,k,t)}$ represents the power output of an individual solar panel which is calculated beforehand using excel. This value is obtained using [5] :

$$PVout_{(j,k,t)} = PV_{(DC)} * \eta BOS \quad (12)$$

Where:

$$PV_{(DC)} = \eta c \; Aeff \; G \quad (13)$$

The PV type is Sharp poly-crystalline module with $Aeff = 1.47m^2$, $\eta c = 14.6\%$, G is the solar irradiance, and the BOS (Balance of System) is considered since it decreases the DC power by 15%, hence, $\eta BOS = 85\%$ [5].

And the wind turbine is modeled as:

$$PWT_{(a,k,t)} \le M_{(j,t)} . WTout_{(a,k,t)} \quad (14)$$

For wind turbine, the $WTout_{(a,k,t)}$ represents the power output of the wind turbine which is also processed using excel. The windspeed data is converted into power output using:

Wind [m/s]	1	2	3	4	5	6	7	8	9	10	11	12
Power [kW]	0	0	0.15	0.37	0.78	1.38	2.25	3.48	5.12	7.2	9.25	0

Figure 2 wind turbine curve characteristics. (Adapted from [5])

D. Emission Factor

$$Emax(t) \ge \sum_{i,k} P_{(i,k,t)} . e_{(i)} \quad (15)$$

E. *Load balance*

$$D_{(k,t)} - \sum_j PPV_{(j,k,t)} + \sum_j PWT_{(a,k,t)} = \sum_i P_{(i,k,t)} \quad \forall_{t,k} \tag{16}$$

III. SIMULATION AND RESULT

In this section, method of acquiring the data is explained along with the results. Also, since gams could not handle the data points used in this simulation, we use an alternative server to run the program which is called NEOS.

A. *Data and Parameters*

Some parameters used in this are adapted from certain sources. For the thermal generation units, the data is acquired from an exercise problem. Meanwhile, for the renewables the data is adapted from [5] and [6].

- Load Data

The hourly demand at year 0 can be seen I Fig.3. It can be seen that the peak demand at that particular year is at 500MW. The hourly demand for year 1 is generated by multiplying each data point of the demand from the previous year by the factor of 600/500. Same applies to the hourly demand in year 2-4 using the factor of 700/600, 800/700, 900/800 respectively.

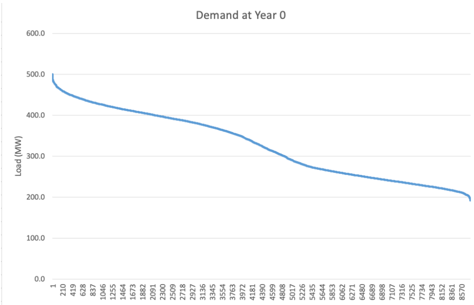

Figure 3 Hourly Demand at year 0

- Components Parameter

Unit Type	Capacity (MW)	Investment Cost(R/MW)	Fuel Cost(R/MWH)	Fixed O&M (R/MW.Year)	Variable O&M(R/MWH)	Emission Factor (tonne/MWh)
A	150	300000	20.409	12000	1	0.533
B	250	350000	14	36000	3	0.533
C	100	250000	25.953	30000	2.5	0.533
PV	-	1500000	-	29600	-	-
WT	-	2000000	-	34700	-	-

Figure 4 Component parameters

Fig. 4 shows the parameters of the generation units. Some other parameters used in the simulations are Emission Penalty cost is set to be 70 R/tonne, the discount rate is 10%, and the depreciation rate is 25%.

- Solar Irradiation and Windspeed

The data for the solar irradiance and the windspeed are hourly data ranging from 2013-2017 and it was obtained from Nasa data access viewer (power larc). Fig. 5 is the data profile sampled for the first 24 hours in year 2013.

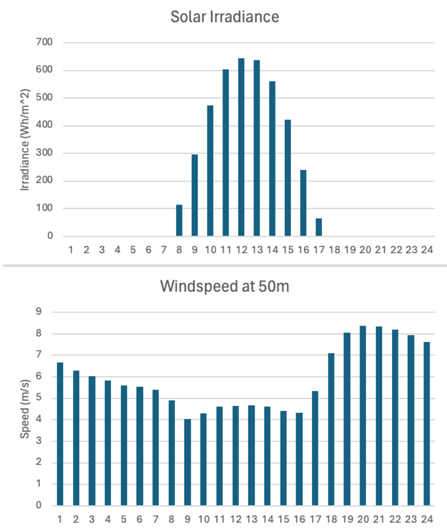

Figure 5 Solar and Wind data

B. *Simulation Result*

Two scenarios were conducted in the simulation. The scenario A is when we ignore the Emission limit, that way, we give some degrees of freedom for the optimizer to consider the thermal units. The second, scenario B, where we will set a limit for yearly carbon emission, thus, the optimizer will limit the power output of the thermal units.

Also, an important interpretation for renewable's result in the table, the newly installed capacity in year 1 is the capacity in in year 1 minus the capacity in year 0 (the result in the following table has not been subtracted yet, thus it does not represent the newly installed unit).

- Scenario A

In this scenario, where the thermal unit can operate freely without emission constraint, the optimization result is shown in Table 1 and the costs can be seen in Table 2.

Table 1 Unit Recommendation (Scenario A)

	Y0	**Y1**	**Y2**	**Y3**	**Y4**
Gen A	4	-	1	1	-
Gen B	-	-	-	-	-
Gen C	-	-	-	-	-
PV	-	-	-	-	-
WT	-	-	-	-	-

Table 2 Costs (Scenario A)

	Total (R)
Cinv	250,999,200
Cfuel	331,100,900
Csalv	340,864,000
Com	321,282,000,000
Ccem	746,027,400

As can be seen in Table 1, the optimizer recommends installing 4 units of type A (4*150MW) in the first year of the project and add 1 more unit in year 2 and 3. The optimization will maximize using thermal units since the overall cost is still cheaper inspite of the presence of the penalty cost.

- Scenario B

For this scenario, when setting the emission limit to 0, the optimization would not give any result and the model is considered infeasible since the constraint in Eq.16 where the power output of the generation unit should always meet the demand at every hour in the whole year. The problem with this model is that the power output of the renewables is not available all the time since the solar panel will only produce output at certain hours (can be seen from Fig. 4) and so does the wind turbine. Hence, since the thermal units is limited, the power output will never satisfy the demand at all times, and thus, the problem is infeasible.

Therefore, in order to make the program work, we make an assumption that the power output of the renewables will always be available, and since we do not model the energy storage, we can introduce a value (constant) for the PV (0.00015) and WT output (0.0023). These values were sampled from a certain hour in the solar irradiance and wind speed data. After applying this the result obtained from the simulation is shown in Table 3.

Table 3 Unit Recommendation (Scenario B)

	Y0	Y1	Y2	Y3	Y4
Gen A	-	-	-	-	-
Gen B	-	-	-	-	-
Gen C	-	-	-	-	-
PV	-	-	-	-	-
WT	217392 MW	260870 MW	304348 MW	347827 MW	391304 MW

Table 4 Costs (Scenario B)

	Total (R)
Cinv	2,469,330,000,000
Cfuel	0
Csalv	1,889,760,000,000
Com	42,843,000,000
Ccem	0

The result in Table 3 shows the capacity of the wind turbine needed to meet the demand. The value might seem really high because the power curve (power output) used in this simulation is a power curve from a 10KV wind turbine. Also, note that this value is definitely far from the real case scenario since the data is assumed. This challenge will be further discussed later in section IV.

To clarify if the emission constraint is indeed working appropriately, we set a limit for the yearly emission limit, and as can be seen from Table 5, the optimizer recommends integrating the generator type A with the wind turbine. And as shown in Table 6, compared to the scenario A, the penalty cost for the emission is reduced by 8.76%.

Table 5 Unit Reccomendation (Scenario B2)

	Y0	Y1	Y2	Y3	Y4
Gen A	4	-	1	-	-
Gen B	-	-	-	-	-
Gen C	-	-	-	-	-
PV	-	-	-	-	-
WT	21740 MW	-	-	-	65217 MW

Table 6 Cost (Scenario B2)

	Total (R)
Cinv	121,973,000,000
Cfuel	306,068,000
Csalv	108,291,000,000
Com	42,843,000,000
Ccem	680,659,900

C. *Result Validation*

One way to verify whether if the result given by the optimization is correct or not, is to play with the parameters. Ideally, the program will always recommend the cheapest unit since the objective function is cost minimization. Therefore, the author of this paper repeatedly set the value of certain components (in this case the fixed cost and the investment cost of the renewable to R1). That way, without any fancy calculation, we already know what to expect i.e., the optimizer should maximize the renewables since it much cheaper that the thermal units.

IV. Conclusion and Future Work

From the simulation, it is shown that although renewable energy offers a cleaner and sustainable power, we cannot deny that the use of thermal generator is still preferable since the overall cost is much cheaper compared to renewable generator. However, it is possible to make.

As mentioned in scenario B, the renewables are assumed to be available all the time (will give power output every hour). For the future work, we can introduce energy storage such that, the result will become more accurate and closer to the real-world scenario. Also, we can vary the value of the emission constraint following regulation in certain countries. Additionally, since it is complicated to extract the detailed data since the code was ran using NEOS server, in the future, it is necessary to find a way to extract the result into excel format such that we can plot how the generators met the demand in every hour of the year.

ACKNOWLEDGMENT

The author would like to acknowledge King Fahd University of Petroleum and Minerals for providing the necessary resources and environment conducive to research. And we are also grateful for the advisor, Dr. Ali Al-Awami for the support and the guidance.

REFERENCES

[1] M. M. Kama, I. Ashraf, and E. Fernandez, "Optimal planning of renewable integrated rural microgrid for sustainable energy supply," *Energy Storage*, vol. 4, no. 4, p. e332, Aug. 2022, doi: 10.1002/EST2.332.

[2] U. A. Dodo, E. C. Ashigwuike, and J. N. Emechebe, "Optimization of Standalone Hybrid Power System Incorporating Waste-to-electricity Plant: A Case Study in Nigeria," *Proceedings of the 2022 IEEE Nigeria 4th International Conference on Disruptive Technologies for Sustainable Development, NIGERCON 2022*, 2022, doi: 10.1109/NIGERCON54645.2022.9803081.

[3] R. Khezri and A. Mahmoudi, "Review on the state-of-the-art multi-objective optimisation of hybrid standalone/grid-connected energy systems," *IET Generation, Transmission & Distribution*, vol. 14, no. 20, pp. 4285–4300, Oct. 2020, doi: 10.1049/IET-GTD.2020.0453.

[4] M. Starke, R. K. Moorthy, S. Campbell, and M. Chinthavali, "Start-up Optimization Considering Integrated Power Electronic Systems," *IEEE Power and Energy Society General Meeting*, vol. 2022-July, 2022, doi: 10.1109/PESGM48719.2022.9917140.

[5] M. Article, J. C. Alberizzi, M. Rossi, and M. Renzi, "A MILP algorithm for the optimal sizing of an off-grid hybrid renewable energy system in South Tyrol Standard-Nutzungsbedingungen: ScienceDirect A MILP algorithm for the optimal sizing of an off-grid hybrid renewable energy system in South Tyrol," pp. 22–25, doi: 10.1016/j.egyr.2019.08.012.

[6] A. Haseeb, M. M. Ashraf, and A. Arshad, "Emission Constrained Generation Expansion Planning considering Site-dependent Renewable Energy Sources of Pakistan," *2023 International Conference on Emerging Power Technologies, ICEPT 2023*, 2023, doi: 10.1109/ICEPT58859.2023.10152338.

[7] J. Zhong, Y. Qi, X. Hao, R. Liu, Z. Luo, and H. Lin, "Power Generation Planning Optimization Model Considering Carbon Emission," *I and CPS Asia 2022 - 2022 IEEE IAS Industrial and Commercial Power System Asia*, pp. 1050–1054, 2022, doi: 10.1109/ICPSASIA55496.2022.9949840.