

# CO<sub>2</sub> emission reduction and energy management for an integrated smart grid — Case of study: Rwandan electrical network

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**Abstract.** Many scholars have been focusing on the energy management by Integrating a smart grid into a conventional electrical grid. They have showed that to meet a certain power demand of the consumers, using energy management, the electric utility can turn on some generators, which may have the least operation cost, while the generators with high operation cost are left to supply extra load demand in specific peak periods. Henceforth, the operation cost of its generation units is minimized. The issue remains at a level of relating the energy management to CO<sub>2</sub> emission. The present paper briefly discusses the Rwandan electrical network that still integrates the use of diesel generators. It estimates the amount of CO<sub>2</sub> emission that can be avoided once a PV system is integrated into the electrical network. The paper as well proposes an algorithm for energy management with consideration of CO<sub>2</sub> emission.

## 1 Introduction

The main goal of applying energy management has been to minimize the economic cost and losses [1]. It has been shown that this cannot be achieved without integrating the renewable sources [2]. All of utility companies focuses more on energy management to regulate the power flow in a way to minimize the energy losses on the network and increase the penetration level of renewable energy sources (such as PV and wind farms) in an efficient way. Whereas the end-users use energy management to minimize their electricity bill and schedule their load demand in an efficient way. Few utilities and end users focus on the amount of CO<sub>2</sub> emission amount that they can avoid and achieve optimal operation cost while integrating the renewable sources. Some electrical networks intend to integrate diesel generator sets for meeting a high demand that can occur during a pick period. This the case of the Rwandan electrical network.

### 1.1 Modelling of CO<sub>2</sub> emission

#### 1.1.1 CO<sub>2</sub> emission delivered by a diesel generator set

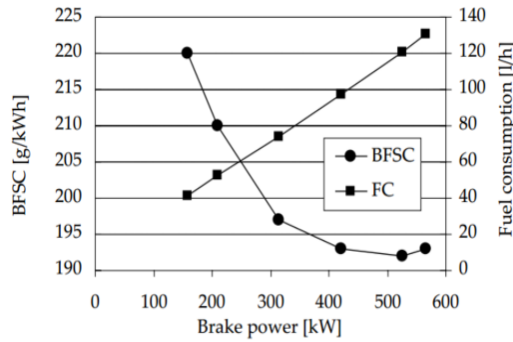
The previous section described clearly the role that diesel generators are playing in supporting the electricity production in Rwanda. The generators help to meet the

demand during peak periods. However, the diesel generator is not environmental friendly. It has high CO<sub>2</sub> emissions. The CO<sub>2</sub> emission can differ from one generator to another due to their efficiency. The diesel generators are characterized by their efficiency and rate of specific fuel consumption. The efficiency of the diesel generator is influenced by thermal and mechanical efficacy of the generator [3]. The quality of the diesel generator might increase or decrease the thermal efficiency. Most of the time, the mechanical efficiency of diesel engine is around 80% to 85% whereas the generator efficiency is around 95% to 98%. This efficiency is calculated with reference to the rated power of the diesel generator. It will be a mistake to operate the diesel generator at lower percentage of its rated speed because it will result to lower efficiency of the generator. This must be taken into consideration while connected the generator to the grid. The generator must operate at least at its 70 and 90 % of its rated power. Even though, the fuel consumption of diesel generators differ from one type of engine to the other depending on technologies used by manufacturers, an equation of fuel consumption rate for diesel generator is common. Figure 1 found in [4][5] was used to formulate Eq.1 that explains the fuel consumption of the diesel.

$$FC = a.P_B^2 + b.P_B + c.P_{BR} \quad (1)$$

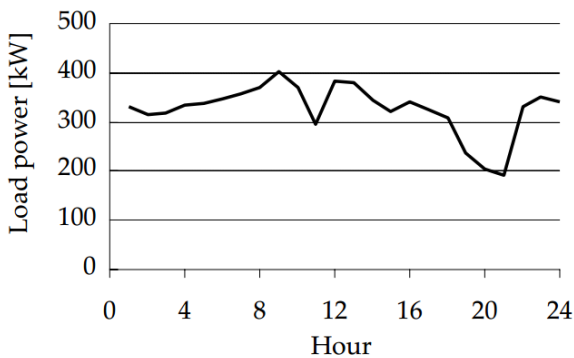
Where  $FC$  is the fuel consumption, in [l/h],  $P_{BR}$  is the rated brake power, in [kW], and  $a$ ,  $b$  and  $c$  are constants to be fitted for each particular engine.

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**Fig.1.** Variation of the Brake Fuel Specific Consumption (*BFSC*) and fuel consumption (*FC*) as a function of the brake output power of a rated 575kW, constant speed, commercial engine [6].

Brake specific fuel consumption (BSFC) is defined as a measure of the fuel efficiency of a diesel-fired generator whereas the brake power is developed by the engine at the output shaft. Figure 1 shows that the efficiency of diesel increases while its output power is closer to its brake output power [7]. In Rwanda, some diesel-fired generators are connected to slack busses and vary their corresponding generation capacities following the variation of power demand aiming at keeping the frequency within an acceptable limit; consequently, they are not always working closer to their nominal power ratings. This increases the fuel consumption as well as CO<sub>2</sub> emitted in atmosphere.



**Fig.2.** Example of a real load profile from a remote petrol exploitation field [2]

Some scholars do not consider the quadratic term and the equation is pure linear. However, the author in [3], added the quadratic term in order to improve the fuel consumption for variable speed diesel generators. Depending on a load profile, the fuel consumption can be calculated using Eq.1. Figure 2 gives an example of a load profile of some generations in Rwanda. This can be based on estimating the CO<sub>2</sub> emissions of the diesel generator in Rwanda. However, knowing the amount of CO<sub>2</sub> emissions per liter supports Figure 2 in calculating the CO<sub>2</sub> emissions using Eq.1. The fuel consumption of the diesel generator ranges between 2.4–2.8 kg of CO<sub>2</sub>/liter diesel [2]. Then considering the fuel consumption and the CO<sub>2</sub> emissions per liter the green emission (GHG) can be estimated as follow:

$$GHG = \sum_0^t FC * CO_{2\text{unit}} \Delta t \quad (2)$$

Where *FC* is the fuel consumption [l/h], CO<sub>2unit</sub> is the diesel CO<sub>2</sub> emissions [kg/l], and Δ*t* is time that the diesel is operating.

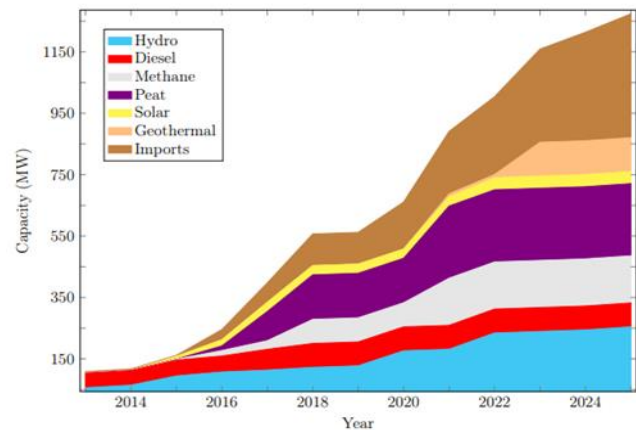
The same equation can be calculated using the energy consumed based on the load file in figure 2.

$$GHG = \sum_0^t P_r * t * CO_{2\text{unit}} \quad (3)$$

The Rwandan State-run Energy Development Corporation Limited (EDCL) has been working harder to increase the percentage of electricity access. Henceforth, the electrical generation capacity is being boosted using renewable and non-renewable sources. Among non-renewable sources, Heavy Fuel Oil, peat and methane gas fired power plants are being used [8]. These generations are being used as baseload generators, working 24 hours per day. Table 1 presents the figures of the installed capacity of thermal power plants.

**Table 1.** Thermal power capacity in Rwanda

Sources	Installed capacity
Peat-fired power plant at Gishoma	15 MW
Diesel/heavy fuel oil fired power plant	57.8 MW
Methane gas	30 MW
Peat deposits	15 MW



**Fig. 3.** Projected installed power capacity in Rwanda by technology for the 2013–2025 period [9]

Figure 3 presents the projection that has been elaborated by the Rwandan State-run Energy Development Corporation Limited (EDCL) in order to meet the electrical demand. The present paper mainly focuses the diesel generators in order to investigate its contribution to CO<sub>2</sub> emissions. Based on the author in [1], the emission factor considered for a diesel generator is 1.27 kg CO<sub>2</sub>/kWh and using the Eq.3 and the information in given by Table 1, the CO<sub>2</sub> emission by the diesel generator is

1.761.744 kg per a day. This reveals that amount of CO<sub>2</sub> emissions by the diesel generator by a year is enormous. The integration of renewable sources could help to reduce the CO<sub>2</sub> emissions [10]. The following

section discusses the amount of CO<sub>2</sub> emissions once a PV system is integrated to the Rwandan electrical grid.

### 1.1.2 CO<sub>2</sub> emission reduction after integrating renewable sources in smart grid

There are still many diesel generators in Rwanda to locally support the electrical network. Apart from the high operation costs of those generators, the PV systems, on grid or off grid, reduce substantially the greenhouse gas emission, other pollutants generated by the combustion engines. A simple methodology for estimating the total amount of greenhouse gas emissions (GHG) once a PV system is integrated is as follows:

$$GHG_{old} = E_{eng} CO_{2\ eng} \quad (4)$$

$$GHG_{new} = ((E_{eng} - E_{enPV}) CO_{2\ eng}) + E_{enPV} CO_{2\ PV} \quad (5)$$

$$GHG_{avoided} = GHG_{old} - GHG_{new} \quad (6)$$

Where:

$E_{eng}$  and  $E_{enPV}$  are energy provide by a diesel generator and a PV system respectively.  $CO_{2\ eng}$  represents an amount of CO<sub>2</sub> emissions from a diesel generator per kWh and  $CO_{2\ PV}$  is amount CO<sub>2</sub> emissions from a PV system per kWh.  $GHG_{old}$  is amount of CO<sub>2</sub> emissions of a diesel generator set installed to cover a specific electricity demand without a PV system.  $GHG_{new}$  is amount of CO<sub>2</sub> emissions of a generator set installed to cover a specific percentage of electricity demand once a PV system is integrated into a grid. The difference between Eq.4 and Eq.5, expresses amount of CO<sub>2</sub> emissions that can be avoided while a PV system is integrated in order to support a diesel generator. The case study was carried out for Sub-Saharan countries. The estimation was done based on the GHG emissions of a stand-alone diesel-generator set without a PV system. Integrating the PV system, which can cover the same electricity demand as the diesel generator reduces the amount of GHG [11] given by Eq. 6. This shows the impact of PV system installation on the environment.

## 2 Energy management in a smart grid (SG) with a consideration of reduction of CO<sub>2</sub> emission

Many of the mathematical techniques have been used for managing the energy on both production and load sides. Moreover, optimization techniques in electrical engineering have been used for decades with a main objective to optimize investment and keeping the generated energy cost at minimum level [12].

The Figure 4 illustrates the existing optimization techniques among which engineers can choose techniques answering to specific research questions in field of smart grid management.

The flowchart of the proposed algorithm to solve the energy management in a smart Grid is given in Figure 5. The general steps intended to solve the objective constrained problem that aims to minimize the electricity cost and reduces the CO<sub>2</sub> emissions in a smart grids and find out operation modes of different loads with

organizing between the considered productions systems are described in Figure 5.

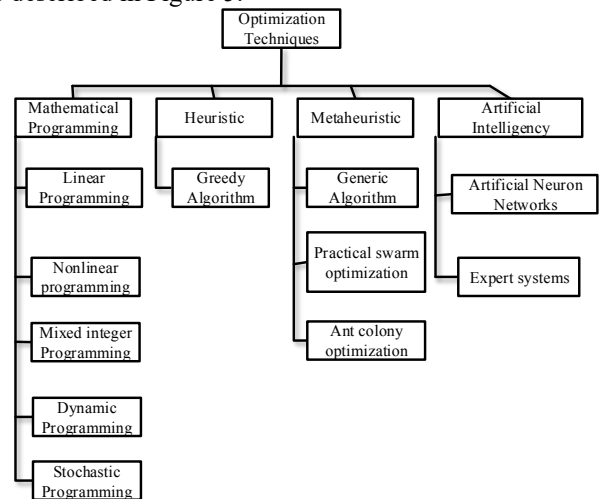


Fig. 4. Different optimization techniques [1]

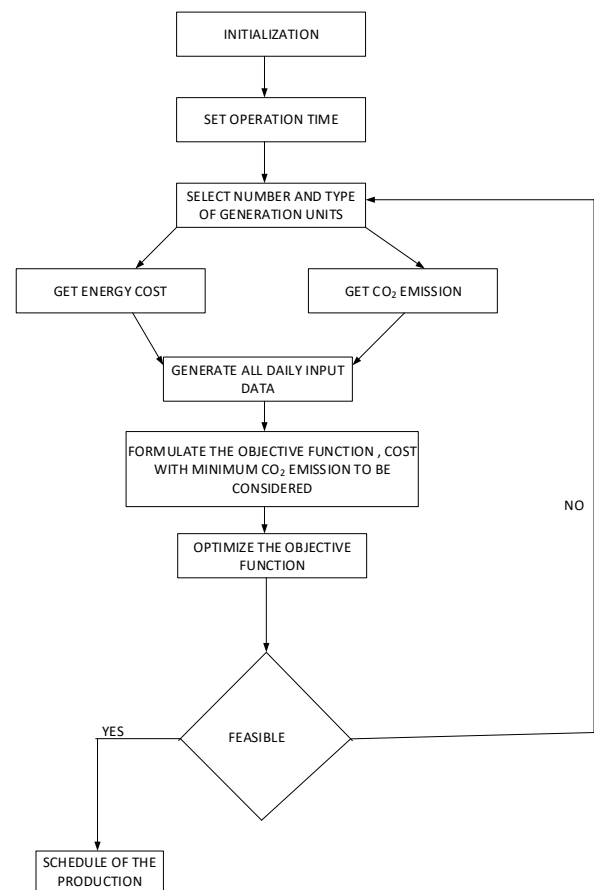
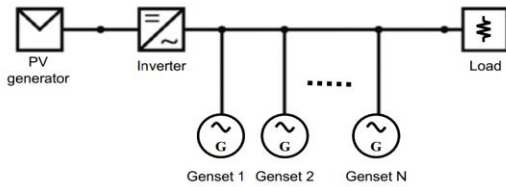


Fig. 5. Flow chart of objective function optimization for a PV-diesel hybrid system without energy storage.

The objective function is formulated based on the grid power balance. In other words, the production of electricity must meet the electrical demand as shown in equation 7. The Figure 6 shows the interconnection between diesel generators with a PV system. Most objective functions are formulated based on the cost constraints functions. This paper tries to incorporate the objective function with CO<sub>2</sub> emissions constraints.



**Fig. 6.**A PV-diesel hybrid system without energy storage[3]

$$P_v + \sum_{i=0}^N P_{gen,i} = P_{load} \quad (7)$$

Where  $P_v$ ,  $P_{gen,i}$  and  $P_{load}$  are production from a PV system, diesel generator production and power consumption at a load level, respectively. Eq.7 shows the balance of power between production and consumption. Based on the same power the objective function for the cost can be formulated.

$$\sum_{i=0}^M C_{PV} P_{v,i} + \sum_{k=0}^N C_{gen} P_{gen,k} = Grid_{TC} \quad (8)$$

$$C_{PV}(X) = C_t(X) + M_t(X) \quad (9)$$

$$C_{gen}(X) = C_t(X) + M_t(X) + F_t(X) \quad (10)$$

Where  $X$  is the optimization problem design variable.  $C_{pv}$ ,  $C_t$  and  $M_t$  are respectively the present cost of Photovoltaic system, the manufacturing cost of the components of all system and maintenance cost. The same variables are applicable to the diesel generator plus the fuel consumption price. Once, Eq.9 is considered as objective function.  $C_t(X) = \sum_{i=0}^n C_i X_i$

With  $X_i$  and  $C_i$  are respectively the cost of a component and quantity of the components in the PV system.  $M_t(X) = \sum_{i=0}^n M_i X_i$  With  $X_i$  and  $M_i$  are respectively the cost of a component and number of maintenance required for in the PV system.

$\text{Min}(\sum_{i=0}^n X_i (M_i + C_i))$  Objective function

$$\sum_{i=0}^n X_i (M_i + C_i) \leq C_t(X).$$

$$X_i \geq 0,$$

This is the same at the diesel generator. However, the following constraints is related to the operating time for a PV diesel-hybrid system.

$$T_{pv}(h) + T_{gen}(h) \leq 24h \quad (11)$$

$$T_{pv}(h) \geq 0, T_{gen}(h) \geq 0$$

### 3 Conclusions

The Eq.8, 9 and 10 are true for the cost optimization but the fact is that Eq.11 can be used for letting generators in a network operate in average more than 14 hours a day. Moreover, if Eq.11 is applied the cost in Eq.8 is optimized. Furthermore, the Eq.6 is useful to evaluate the amount  $\text{CO}_2$  to be reduced. The future work is about the implement the flowchart in Fig.5.

### References

1. S. Member, O. Grunder, Z. Hammoudan, and B. Indices, "Energy Management in Electrical Smart Grid Environment Using Robust Optimization Algorithm," *IEEE Trans. Ind. Appl.*, vol. 54, no. 3, pp. 2714–2726, 2018.
2. Peter Ozaveshe Oviroh and Tien-Chien Jen \*, "The Energy Cost Analysis of Hybrid Systems and Diesel Generators in Powering Selected Base Transceiver Station Locations in Nigeria", MDPI, 2018
3. Ibrahim Dincer, Marc A. Rosen, "Generator efficiency", Science Direct, 2013
4. J. Muñoz and J. M. Carrillo., "Modeling and sizing of large pv-diesel hybrid systems without energy storage," no. 1, pp. 1–6.
5. V. A. Ani, "Design of a Reliable Hybrid ( PV / Diesel) Power System with," vol. 2016, 2016.
6. Lyes Tarabet, K. Loubar, Mohand said Lounici, Mohand Tazerout, "Experimental evaluation of performance and emissions of DI diesel engine fueled with eucalyptus biodiesel", WoodHead Publishing, 2011
7. Y.H. Teoh <sup>1,\*</sup>, K.H. Yu <sup>1</sup>, H.G. How <sup>2</sup> and H.-T. Nguyen <sup>3</sup>, "Experimental Investigation of Performance, Emission and Combustion Characteristics of a Common-Rail Diesel Engine Fuelled with Bioethanol as a Fuel Additive in Coconut Oil Biodiesel Blends", MDPI, 2019
8. Ministry of Environment and Rwanda Environment Management Authority (REMA), Third National Communication under the United Nations Framework Convention on Climate Change (U.N.F.C.C.C), Government of Rwanda, 2018
9. E. S. Overview, G. Capacity, and E. Environment, "Rwanda," 2017.
10. Kim HanhNguyen, MakotoKakinaka, "Renewable energy consumption, carbon emissions, and development stages: Some evidence from panel cointegration analysis", Elsevier/Science Direct, 20 August 2018
11. Franco Davoli, Matteo Repetto, Carlo Tornelli, "Boosting energy efficiency through Smart Grids", ITU, 2012
12. Mariana Resener, Sérgio Haffner, Luís A. Pereira & Panos M. Pardalos, "Optimization techniques applied to planning of electric power distribution systems: a bibliographic survey", Springer, 2018