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Greenhouse gases emission factors of mix electricity generation in Madagascar

M. P. Randrianarison[1]*, N. Randrianandrasana [1], N.A.T. Razafiarivony[1], B. Raheliarilalao [1]

[1]*Ecole Supérieure Polytechnique d'Antananarivo, Antananarivo PB 1500, Madagascar*
**Corresponding author : mino.randrianarison@gmail.com*

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- ✓ *mix electricity*

mino.randrianarison@gmail.com

Abstract

Greenhouse gases emission factors of electricity depend mainly on the primary energy sources. There are different sources of primary energy for electricity generation in Madagascar. They vary from year to year so the greenhouse gases emission factor of the mix electricity will also change over time. 81.58% of national electricity generation are provided by three principal interconnected grids: of Antananarivo, of Toamasina and of Fianarantsoa. Mix electricity of each interconnected grid is made up mainly of hydropower and thermal power using fossils fuels such as diesel fuel and fuel oil because of the season shortfall of the dam water. IGA is characterized by introducing solar power in 2018. The objective of this paper is to estimate the GHG emission factor for mix electricity delivered by the three main grids in 2017 and 2018 For this, appropriate tool is necessary, so Life Cycle Assessment methodology framework, commonly used in environmental impact assessment is applied. Our study is carried out from fossil oil extraction to mix electricity distribution including the transport and the production. One kilowatt-hour of delivered mix electricity is adopted as functional unit in the aim of comparing our results with other mix electricity and other energy sources greenhouse gases emission factors.

1. Introduction

The concept of sustainability appears with its three components: economic, social and environmental. The energy production is one of the most important aspects of sustainability [1]. In Madagascar, access rate to electricity (electric grid) is just only 11.4% in 2018 [2]: half of the population in urban areas and only 6% in rural areas. Although Madagascar has vast potential of renewable energy sources (hydro, solar, wind, biomass) [3], national energy consumption and supply is low. The energy sector is characterized by low access to modern forms of energy with only a quarter to third of adults having access [4] and the mix electricity is currently heavily dependent to fossil fuel imports [3]. The Malagasy electricity grid is dominated by JIRAMA, the country's vertically integrated sate-owned water and electricity company [4].

JIRAMA operates and oversees almost all production, transport and electricity distribution in Madagascar This company exploits most of the electricity power grid: interconnected grids: of Antananarivo (IGA), of Toamasina (IGT) and of Fianarantsoa (IGF) with greater respective line lengths of 278 km, 175km and 77km. These three interconnected grids provide 81.58% of the national electricity generation: 72.10% by IGA, 7.12% by IGT and 2.36% by IGF (data obtained by JIRAMA) **(Figure 1).** [4]

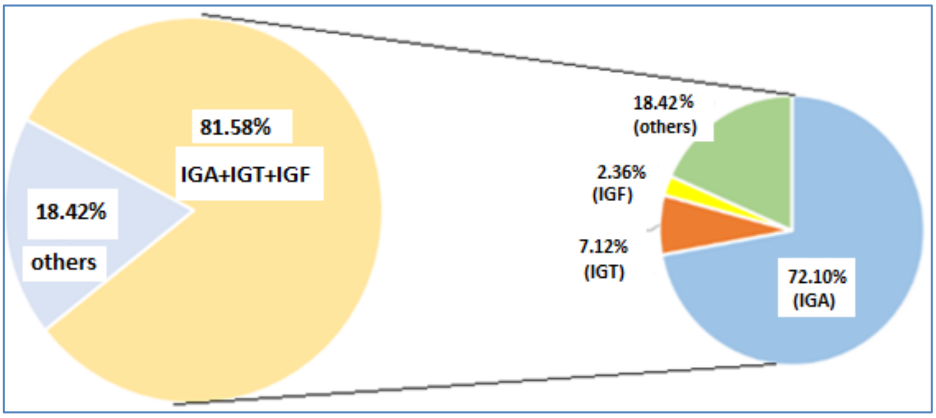

Figure 1. Temperature profile for biomass conversion

Mix electricity provided by the interconnected grids of Toamasina and Fianarantsoa are composed of hydro and thermal electricity using petroleum products (diesel and fuel-oil). In 2018, the interconnected grid of Antananarivo is characterized by introducing solar PV source, with 1.19% of his production. Electricity generation is a key contributor to global emission of greenhouse gases [5]. This last depends on the primary energy sources used for electricity generation.

Our objective is to develop in Madagascar a GHGEF database. In this paper, the aim of our study is to estimate the mix electricity GHGEF of the three interconnected grids. The estimations are carried out using Life Cycle Assessment (LCA). It's both a method and a tool that relies on the exhaustive accounting of environmental flows that are directly or indirectly linked with a well-defined product system: from fossil oil extraction to mix electricity distribution. LCA can help to quantify environmental burdens from "cradle to grave" and facilitate more-consistent comparisons of energy technologies [6]

2. Methodology

For this paper, LCA commonly used in environmental impact assessment [1] is adopted by following the methodological framework standardized by ISO 14040 to 14044 [7, 8, 9, 10, 11] **(Figure 2).**

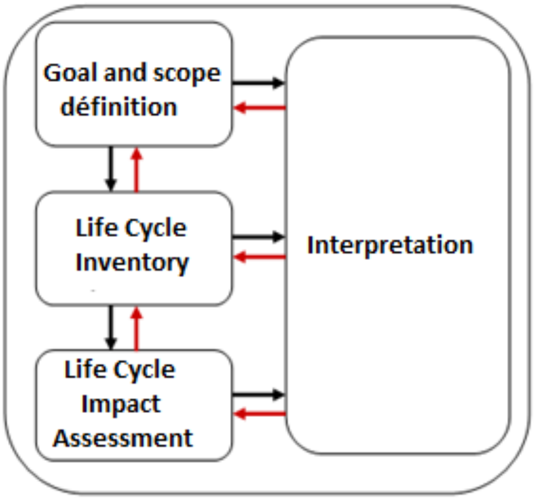

Figure 2. Temperature profile for biomass conversion

2.1 Goal and scope definition

This phase includes the specification of the aim of the study, the functional unit and the system boundaries. The aim is to estimate the GHGEF of the IGA, IGT and IGF mix electricity and to evaluate the changes of the GHGEF accounting the part of the electricity renewable source introduced into the electric grids. 1 kWh of delivered mix electricity is taken as functional unit in order to facilitate comparison of our results with other mix electricity GHGEF. The system boundaries are composed by background and foreground processes. Life Cycle Assessment includes these several steps: crude oil extraction and transport, transformation to diesel, fuel oil and lubricant, fossil fuels transport, mix electricity generation and distribution. Solar PV plant production is also considered **(Figure 3).**

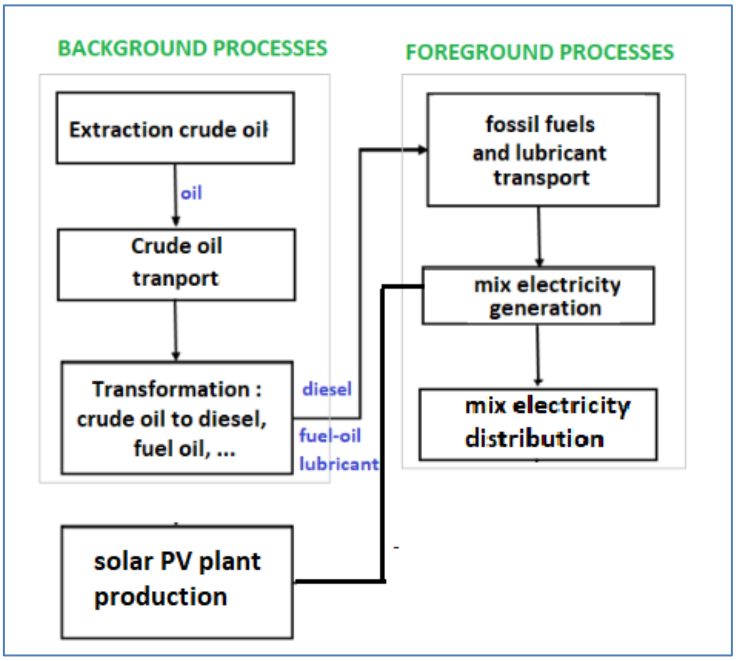

Figure 3. System boundaries of the IGA, IGT and IGF mix electricity

2.2 Life Cycle Inventory (LCI)

Life Cycle Inventory (LCI) of the LCA methodology is essentially the collection of the data [12]. Data used in this paper are based on information obtained by JIRAMA, GEMIS (Global Emission Integrated Systems) software and other study. The life cycle inventory is focused on:

- energy sources;
- quantity of electricity generation (delivered, loss, consumed by auxiliaries);
- GHGEF of renewable sources;
- GHGEF of diesel, fuel-oil and lubricant;
- specific petroleum products consumptions per kWh;
- fossils fuels transport distances since their acquirement until their distribution to the thermal plant;
- fossil fuels and lubricant transport types and
- line losses.

The main sources of electricity production are hydro and thermal powers. Cause by the season shortfall of the dam water, JIRAMA requires thermal plant (using petroleum products: diesel and fuel oi) and solar PV source in 2018 (IGA) **(Table 1).** The shares of energy sources of IGA, IGT and IGF mix electricity generations in 2018 are as follow **(Figure 4)**. Diesel, fuel oil and lubricant specific consumptions during thermal electricity generation are given in **Table 2.**

Table 1. Compositions of IGA, IGT and IGF electricity generation in 2018

	IGA	IGT	IGF
Hydro (kWh)	885 964 153	39 728 512	36 304 900
Thermal source using petroleum products (kWh)	359 909 351	84 824 529	4 904 045
Solar PV (kWh)	15 042 640	0	0
Total of electricity gross production (kWh)	1 260 916 144	124 553 041	41 208 945

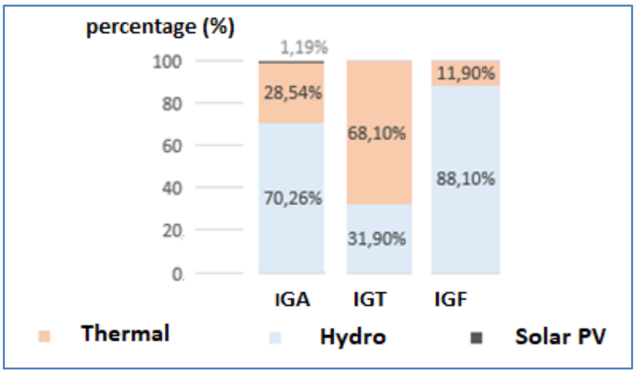

Figure 4. Shares of each energy sources of IGA, IGT and IGF mix electricity generations in 2018.

Table 2: Specific diesel, fuel oil and lubricant consumptions for thermal electricity generation

	IGA	IGT	IGF
Specific diesel consumption (g/kWh)	239.23	263.90	258.00
Specific fuel oil consumption (g/kWh)	219.93	247.30	0
Specific lubricant consumption (g/kWh)	0.065	0.470	1.790

Fuels and lubricant are imported from abroad and their transportations are carried out by sea and by road. 95% of the petroleum products used in Madagascar are from Persic Gulf, transported by sea and stored in Toamasina [13]. Then they are transported by road to the thermal power plants. The parts of transport type (sea and road) are shown in **Table 3**.

Table 3: Parts transport types

Transport type	IGA	IGT	IGF
Sea	94.14%	99.68%	88.66%
Road	5.86%	0.32%	11.34%

Emission factors values are taken from GEMIS software: sea transport: 0.005kg CO_2 eq/t.km took from « ship ocean 2020 (oil tanker) » process and road transport: 0.18 kg CO_2 eq/tkm took from « truck IN» process. These GHGEF comprise the processes of crude oil extraction, refinery step, transport and combustion of fuels during the transportation phases. Emission factor values of renewable sources have been investigated by Pehnt's paper [14] and GEMIS software: 0.013kg CO2 eq/kWh for electricity generated by solar PV and 0.10kg CO2 eq/kWh for hydroelectricity.

2.3 Life cycle impact assessment

For each interconnected, the GHGEf related to 1kWh of mix electricity (gross) is given by:

$$EF_{\ mix\ elec\ (gross)} = [\alpha_{hydro}\ \alpha_{sol}\ \alpha_{therm}] * [EF_{hydro}\ EF_{sol}\ EF_{therm}] \qquad \textbf{Eqn. 1}$$

Where α_{hydro} *:* ratio of electricity generated by hydropower (%);

α_{sol} *:* ratio of electricity generated by solar PV (%);

$\alpha_{thermal}$ *:* ratio of electricity generated by thermal power using petroleum products (%);

EF_{hydro} *:* GHGEF related to electricity generated (gross) by hydropower (kg CO_2 eq/kWh);

EF_{sol} *:* GHGEF related to electricity generated by solar PV (kg CO_2 eq/kWh) and

EF_{therm} *:* GHGEF related to electricity generated by thermal power using petroleum products (kg CO_2 eq/kWh).

Total GHG emission of thermal electricity is due to:

- crude oil extraction;
- crude oil transport and refinery (to diesel, fuel oil and lubricant);
- petroleum products (diesel, fuel oil and lubricant) transport to the power plants;
- electricity generation (based on fuels combustion) and electricity distribution (line loss included).

To account for greenhouse gases emission from electricity generation out of using diesel and fuel-oil, it is assumed that all fuels are combusted when used and emit greenhouse gases [15].

Knowing the diesel, fuel oil and lubricant specific consumptions per kWh of generated electricity for every interconnected grid, the GHGEF associated with the transport of these products is given by:

$$EF_{pet\ trans} = (CS_{diesel} + CS_{FO} + CS_{lub}) * [D * ((\alpha_{ST} * EF_{ST}) + (\alpha_{RT} * EF_{RT}))] \qquad \textbf{Eqn. 2}$$

Where : $EF_{pet\ trans}$: GHG emission factor related to petroleum products transportations (kg CO_2 eq/kWh g

CS_{diesel} : diesel specific consumption (kg/kWh);

CS_{FO} : fuel oil specific consumption (kg/kWh);

CS_{lub} : lubricant specific consumption (kg/kWh);

D : petroleum products distance transportation (km);

α_{ST} : ratio of sea transport (%);

α_{RT} : ratio of road transport (%);

EF_{ST} : GHG emission factor related to sea transport (kg CO_2 eq/kg.km);

EF_{RT} : GHG emission factor related to road transport (kg CO_2 eq/kg.km).

The GHGEF per kWh (gross) related to the thermal electricity production phase depends mainly on the specific consumptions and can be estimated by using the following equation:

$$EF_{therm\ prod} = [SC_{pet}] * [EF_{pet}] \qquad \textbf{Eqn. 3}$$

Where : $EF_{therm\ prod}$: GHGEF according to the production (gross) phase of thermal electricity (kg CO_2 eq/kWh);

$[SC_{pet}]$: line matrix composed by SC_{diesel} , SC_{FO} *et* SC_{lub} ;

SC_{diesel} : diesel specific consumption (kg/kWh);

SC_{FO} : fuel-oil specific consumption (kg/kWh);

SC_{lub} : lubricant specific consumption (kg/kWh);

$[EF_{pet}]$: column matrix composed by EF_{diesel}, EF_{FO} et EF_{lub} ;

EF_{diesel}: diesel GHGEF, related to crude oil extraction, crude oil transport and refinery (diesel), diesel transport to the power plants and combustion (kg CO_2 eq/kg diesel);

EF_{FO} : fuel oil GHGEF, related to crude oil extraction, crude oil transport and refinery (fuel oil), fuel oil transport to the power plants and combustion (kg CO_2 eq/kg fuel oil);

EF_{lub}: : lubricant GHGEF, related to crude oil extraction, crude oil transport and refinery (lubricant), lubricant transport to the power plants (kg CO_2 eq/kg lubricant);

$EF_{therm\ prod}$ can be expressed as:

$$EF_{therm\ prod} = [SC_{diesel}\ SC_{FO}\ SC_{lub}] * [EF_{diesel}\ EF_{FO}\ EF_{lub}] \quad \textbf{Eqn. 4}$$

So the GHGEF related to 1kWh of thermal electricity is as follow:

$$EF_{therm} = EF_{pet\ trans} + EF_{therm\ prod} \quad \textbf{Eqn. 5}$$

Transmission and distribution of electricity are often not included in LCA of power systems [15] but our study will show that the distribution network makes a significant contribution to the impacts of electricity delivered to customers.

Finally, the GHGEF of *mix electricity* generation, expressed in kg CO_2 eq/kWh (delivered electricity) in Madagascar in 2018 can be calculated using the following expression:

$$EF_{mix\ elec} = \frac{EF_{gross\ mix\ elec}}{\beta} \quad \textbf{Eqn. 6}$$

Where : β is the the ratio (%) of delivered mix electricity.

For IGA, IGT and IGF, the values of β are 91.06%, 90.84% and 95.35% respectively in 2018.

3. Results and Discussion

3.1 GHGEF of petroleum products

The GHGEF associated to the petroleum transport (used for production of 1kWh thermal electricity) from the provider country to the thermal plant are represented in **Figure 5**. The GHGEF associated to the petroleum transport varies from 8.94 kg CO_2 eq to 14.43 kg CO_2 eq. These emission factors are proportional to the fossil fuels consumed during the thermal electricity generation.

3.2 GHGEF of thermal electricity

The GHGEF relating to 1kw of thermal electricity are presented in Figure 6. 88.10% of IGF mix electricity are generated by hydropower that's why the GHGEF associated to this interconnected grid is 40% less than the GHGEF of GA. According to GEMIS, there are three types of thermal power (using petroleum products): small-scale, medium-scale and large-scale. The GHGEF depends on the scale of the power plant:

- electricity generated from big-scale: represented by "*dieselmotor big generic process"* (20MW) with 0.93 kg CO_2 eq/kWh of GHGEF;
- electricity generated from medium-scale: represented by "*dieselmotor medium generic process* "(5MW) with 1.089 kg CO_2 eq/kWh of GHGEF and
- electricity generated from small-scale: represented by "*dieselmotor small generic process" (*0.5MW) with 1.308 kg CO_2 eq/kWh of GHGEF.

It's noted that 99% of GES emissions of thermal electricity generation for IGA, IGT and IGF are allocated to diesel and fuel-oil combustion.

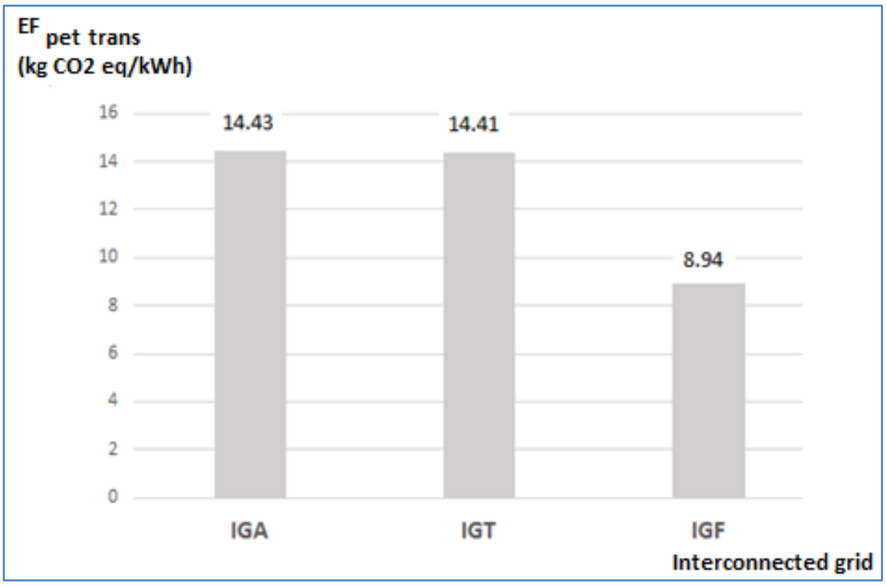

Figure 5. GHGEF associated to the petroleum products (diesel, fuel and lubricant) transport.

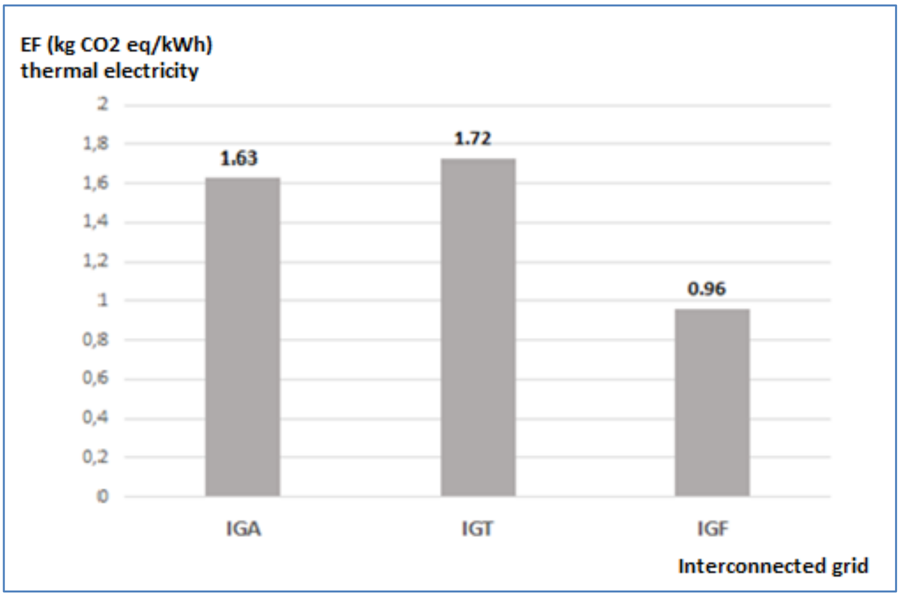

Figure 6. GHGEF associated to the petroleum products (diesel, fuel and lubricant) transport.

For IGF, his GHGEF is 0.96 kg CO_2 eq/kWh and coincides with the big-scale emission factor in GEMIS. For IGA, and IGT (1.63 kg CO_2 eq/kWh and 1.72 kg CO_2 eq/kWh respectively), their GHGEF correspond to small-scale factor emission in GEMIS however the available electrical powers of the groups vary from 8MW to 28MW. The values of GHGEF found in this paper results in the ages of the equipment. For JIRAMA, there's power group which his date of first use is 1982.

3.3 GHGEF of IGA, IGT and IGF mix electricity generation (gross)

GHGEF of IGA, IGT and IGF mix electricity generation (gross) are presented in **Figure 7**. For IGA and IGT, GHGEF of mix electricity are 0.47kg CO_2 eq/kWh and 1.17 kg CO_2 eq/kWh (gross) respectively in 2018. Thermal electricity is associated to 98.48% of the emission. For IGT, the GHGFE is 1.17 kg CO_2 eq/kWh and 99.57% of the emission are attributed to thermal electricity. For IGF, the

GHGFE is 0.12kg CO_2 eq/kWh. Despite the fact that 88.10% of mix electricity are generated by hydropower, 92.83% of GHGEF are caused by thermal electrity generation.

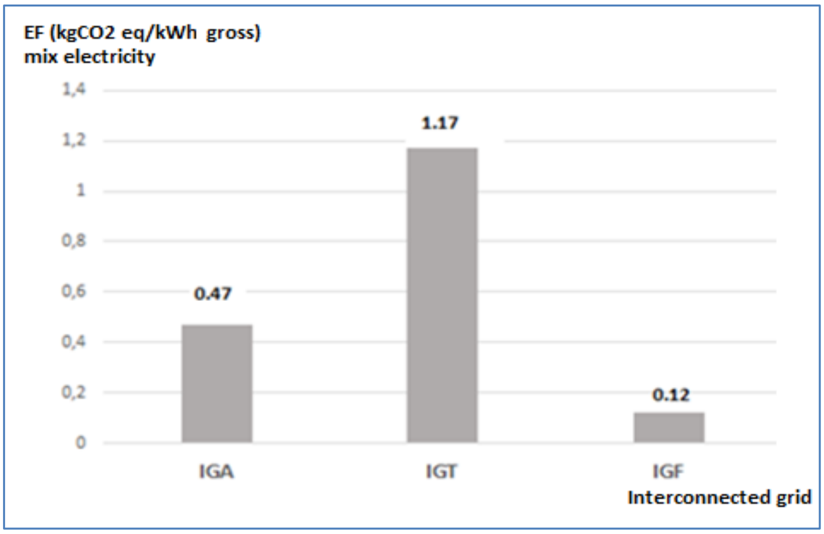

Figure 7: GHGEF of IGA, IGT and IGF mix electricity generation (gross)

3.4 GHG of 1kWh of delivered mix electricity

Taking into account the line loss and auxiliary consumption, the GHGEF, the GHGEF for mix electricity generation in 2018 for each grid are as follow **(Figure 8)**. Distribution network makes a significant contribution to the impacts of electricity delivered.

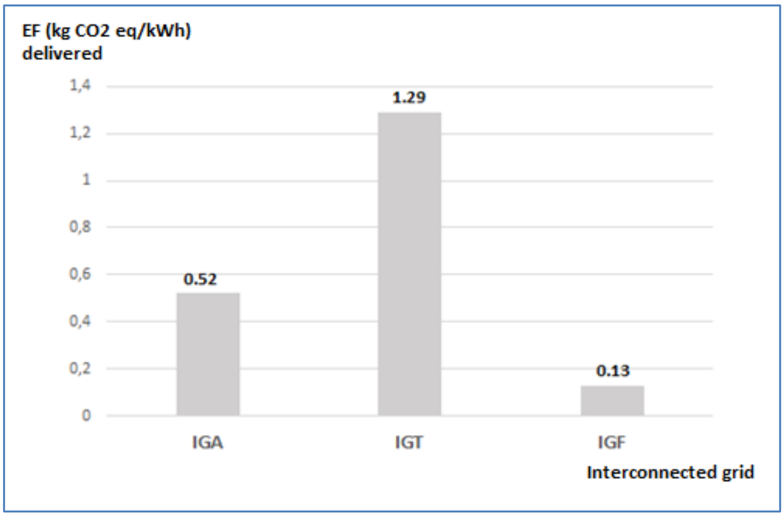

Figure 8. GHGEF of IGA, IGT and IGF mix electricity generation (delivered)

From the gross electricity to delivered electricity, an average increase of 7.57% of the GHGEF is observed. For French Guyana, with more than 60% of hydroelectricity, the emission factor of greenhouse gas is 0, 37kg eq CO_2 /kWh [16]. It is respectively 28,84% and 71,31% less than GHGEF of IGA and of IGT. Concerning the energy transition of Madagascar, we note that in 2023, the year of planned commissioning of the "Volobe" hydropower plant, there will be an average production of 750 GWh of electricity per year, with a power of 120MW). A decrease in thermal electricity generation will occur, which will certainly induce a reduction in GHG content per kWh. This result can be envisaged with the Malagasy government's project and the support of the providers of found, the connexion implementation of IGT and IGT. For Sahofika hydraulic power plant with 205MW of power, a production of 1650 GWh of electricity per year will be expected from 2024. Within a year, in 2023, the Tanambao solar park in Toamasina , with a capacity of 20 MW, will produce electricity for 3,000 households [17]. Further reductions in GHG content per KWh of electricity from the IGA and the IGT will then be undeniable because of this energy transition in Madagascar. Assuming that the GHGEF of thermal electricity is fixed (same as in 2018) and that the part of electricity from renewable sources increases, the predictions of changes of mix electricity GHGEF of the IGA, IGT and IGF are given respectively by the **Figures 9, 10** and **11**.

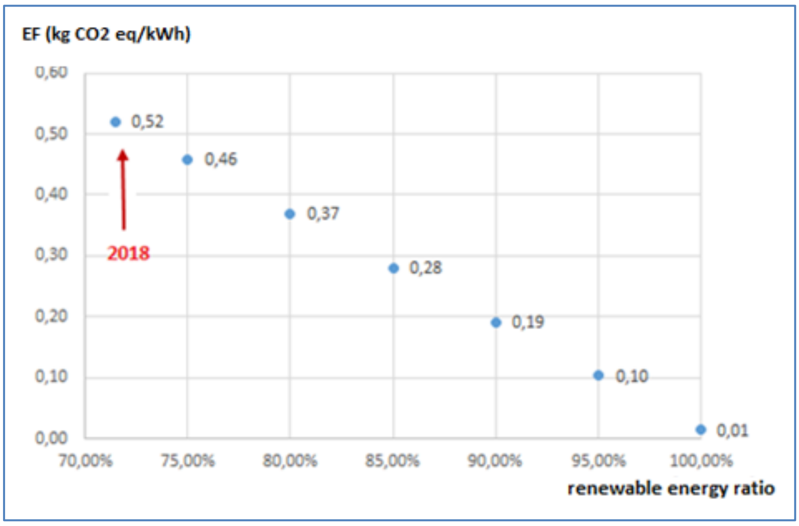

Figure 9. GHGEF evolution in terms of renewable source part introduced to the IGA.

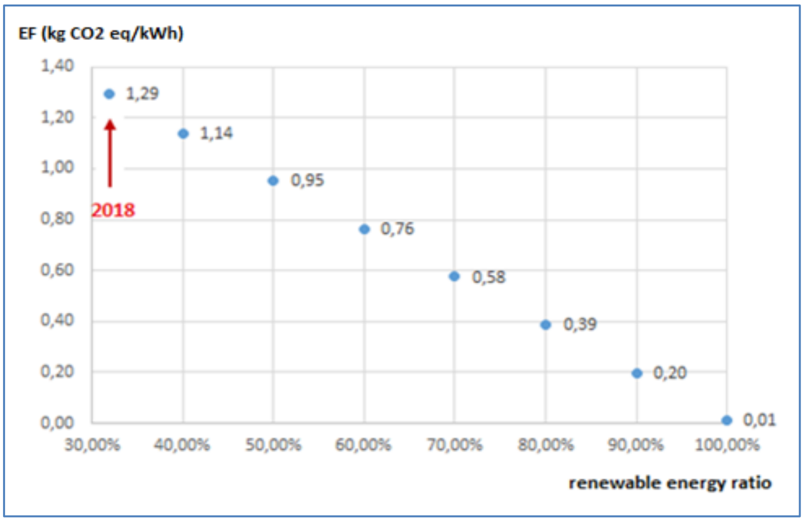

Figure 10. GHGEF evolution in terms of renewable source part introduced to the IGT.

Also taking into account the project, named PRIRTEM, including the realization of IGA and IGT interconnection by the construction of a 220 kV power line, having a capacity of 200 MW between Antananarivo and Toamasina (268 km) [18] and the electrification of two localities neighboring this same line. This operation will then have a great influence on the GHG emission factor of the electrical mix of the networks. Almost all regions of Madagascar receive than 2800 hours of sunshine a year. Average annual production is about 1600 kWh/kWp. The Malagasy potential is among the highest potentials in the world. Even the less areas show solar potential which is on to 4 times higher than the potential in western Europe [19]. So, it is benefic for Madagascar to use solar PV for electricity generation in Madagascar.

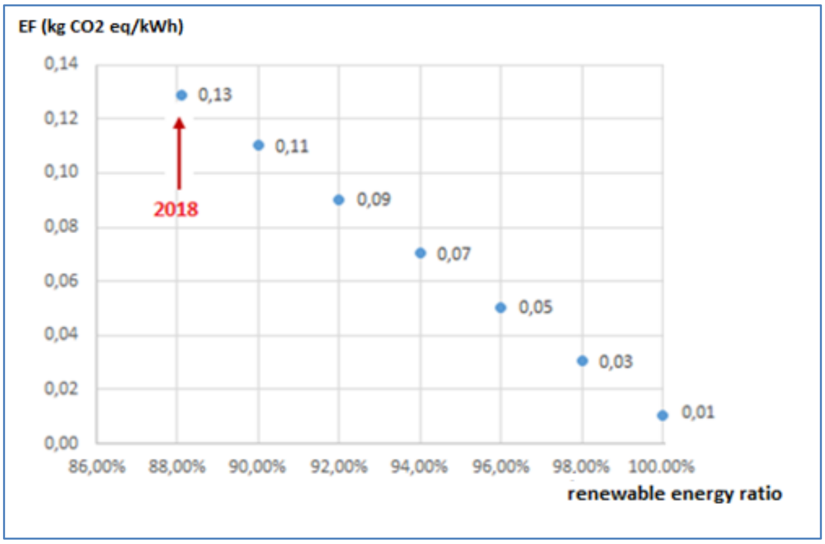

Figure 11. GHGEF evolution in terms of renewable source part introduced to the IGF.

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