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Direct energy consumption and CO_2 emission impact of the way of life in Côte d'Ivoire : case of the user of the Ivorian Interconnected Power Grid (IIPG)

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Abstract

In the general context of the search for solutions to reduce global warming, knowledge of the real emissions of electricity production of any network is essential. Indeed, for reasons of simplicity, the determination of the impacts is done using the default values of the Intergovernmental Panel on Climate Change (IPCC). The objective of this study is to determine over the period 2009 to 2019, the real direct specific CO_2 emissions of the user of the Ivorian interconnected power grid (IIPG). These emissions are due to the combustion of fossil fuels used in thermal power plants. The IIPG data for the period allow to determine the theoretical direct specific CO_2 emissions and energy consumed. With the real direct CO_2 emissions obtained with the CIPREL thermal power plant data, and the IPCC 2206 data, the theoretical results have been validated. Over the period 2009 to 2019, at the national level, the average specific direct CO_2 emissions of net production of the IIPG is 431.32 g of CO_2 per electrical kWh produced and 527.63 g of CO_2 per kWh of electrical energy consumed by a medium or low voltage user. The CO_2 emissions of the IIPG over this period are dominated by those of natural gas which represent 95.58 %. Over the period 2015 to 2019, the specific direct CO_2 emissions of the country and abidjanese users are 492.62 g CO_2/kWh and 524.44 g CO_2/kWh respectively, and in the country, the average fossil energy intensity is 8.81 MJ/kWh, less than Abidjan city consumers with an average of 9.38 MJ/kWh. The IIPG average CO_2 emission factor is 2.62 kg of CO_2/kg of fossil fuel consumed. These real results of direct CO_2 emissions from the IIPG will help to best estimate the environmental impact of energy in Côte d'Ivoire (Ivory Coast).

Keywords : *electricity Gird, Direct CO_2 emission, environmental impact, electricity consumption and production, Côte d'Ivoire, Ivory Coast.*

Résumé

Impact direct en consommation d'énergie et émissions de CO_2 du mode de vie en Côte d'Ivoire : cas de l'utilisateur du Réseau Électrique Interconnecté Ivoirien (IIPG)

Dans le contexte général de recherche de solutions pour réduire le réchauffement climatique, la connaissance des émissions réelles de la consommation électrique de tout réseau de production électrique est essentielle. En effet, pour des raisons de simplicité, la détermination des impacts se fait en utilisant les valeurs par défaut du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC). L'objectif de cette étude est de déterminer sur la période 2009 à 2019, les émissions spécifiques directes réelles de CO_2 de l'utilisateur du réseau électrique interconnecté ivoirien (IIPG). Ces émissions sont dues à la combustion de combustibles fossiles utilisés dans les centrales thermiques. Les données IIPG de la période permettent de déterminer la consommation spécifique en énergie fossile (MJ/kWh) et les émissions théoriques directes spécifiques de CO_2(g de CO_2/ kWh). Avec les émissions directes réelles de CO_2 obtenues avec les données de la centrale thermique CIPREL, et les données 2006 du GIEC, les résultats théoriques ont été validés. Sur la période 2009 à 2019, au niveau national, la moyenne des émissions spécifiques directes de CO_2 de la production nette de l'IIPG, est de 431,32 g de CO_2 par kWh électrique produit et de 527,63 g de CO_2 par kWh d'énergie électrique consommée par l'utilisateur de moyenne ou basse tension. Les émissions de CO_2 de l'IIPG sur cette période sont dominées par celles du gaz naturel qui représentent 95,58 %. Sur la période 2015 à 2019, les émissions directes spécifiques de CO_2 de l'ensemble du pays et des utilisateurs abidjanais sont respectivement de 492,62 g CO_2/kWh et 524,44 g CO_2/kWh. Au niveau de l'intensité moyenne en énergie fossile, les résultats sont de 8,81 MJ/kWh au niveau national et de 9,38 MJ/kWh pour les consommateurs de la ville d'Abidjan, soit une augmentation de 6,47 % par rapport à l'ensemble du pays. Le facteur d'émission moyen de CO_2 de l'IIPG est de 2,62 kg de CO_2/kg de combustible fossile consommé. Ces résultats réels des émissions directes de CO_2 de l'IIPG permettront de mieux estimer l'impact environnemental de la production et de la consommation de l'énergie électrique de réseau national en Côte d'Ivoire.

Mots-clés : *réseau électrique, émissions directes de CO_2, impact environnemental, consommation et production électrique, Côte d'Ivoire.*

1. Introduction

The International Energy Agency (IEA), whose mission is to guarantee global energy security and raise public awareness on environmental issues, provides information on the electrical systems of countries for which data is available. To assess the carbon intensity of the energy mix in different countries, as underlined by the Environmental and Energy Management Agency (Ademe) in France [1], the International Energy Agency (IEA) relies on the data of the effective emission factors of fuels and their net calorific value, provided by the Intergovernmental Panel on Climate Change (IPCC), in particular those provided by fuel emission factors in its guide on country GHG inventories [2]. Regarding the data provided, the basis for determining the carbon intensity of energy mixes, the authors indicate that these data are used as default emission factors for fuels with 95 % of confidence level; but if activity data are available, these values should be used directly, following a similar approach. As the authors say, the IPCC emission factors "are reliable because the calculations are based on a physical reaction", but contain uncertainties, however small. Thus, the IEA results will also include a margin of error compared to the actual field data of each electrical system. The impacts determined by the Ivorian Electricity Company “Compagnie Ivoirienne d’Electricité” (CIE), according to the method of Ademe in its 2019 annual report [3], will therefore present deviations from the specific realities of Côte d'Ivoire. In addition, this impact calculation does not take into account the CIPREL, Azito Energie and Aggreko thermal power plant and the Soubré hydropower plant, which are not under its responsibility. The Ministry of Environment and Sustainable Development of Côte d'Ivoire (MINEDD), during a training session for national experts on the mastery of the IPCC guidelines and the use of the IPCC 2006 software, in terms of GHG calculation, on March 17 and 19, 2021, in Grand-Bassam, in order to quantify GHG emissions [4], is also based on the same emission factors of the IPCC [2]. If the default fuel emission factors of the IPCC have the merit of allowing a less tedious estimation of the carbon intensity of the different electrical energy production systems and of having a low uncertainty, they are less precise in relation to the specific characteristics of each type of fuel used in each electricity production system, and in particular, in the case of the Ivorian interconnected power grid (IIPG). This study aims to provide of the IIPG, the real direct CO_2 emission factors and the specific direct CO_2 emissions and energy consumption of the national and abidjanese electrical energy consumed by medium or low voltage users.

2. Methodology

2-1. Presentation

In order to compare the IIPG to international power grids, CO_2 emissions are reported to the unit of electricity production or to the unit of electrical energy consumption by users (customers of the IIPG). This is referred to as intensity of CO_2 emitted [5, 6] or specific mass of CO_2 emitted, i.e. mass of CO_2 emitted per kWh of electrical energy, either produced or consumed by users. The basic Data was provided by CIE and Anare-ci companies from 2009 to 2019 [7, 8]. Thus, we first determine the mass of Natural Gas (NG) consumed and the theoretical mass of CO_2 emitted during the combustion of all the NG consumed by the IIPG, per year, from 2009 to 2019. Under real gas conditions, the ideal gas law is adjusted by a compression factor defined by ISO 6976 [9]. Then we determine the mass of liquid fuels (HVO : Heavy Vacuum Oil and DDO : Diesel Distillate Oil), followed by the theoretical mass of CO_2 emitted during their combustion. Before using all the theoretical masses of CO_2 emitted to assess the specific emissions, we proceed to validate them. This validation consists in comparing the theoretical results of CO_2 mass emitted, obtained with the real data collected from the CIPREL thermal power plant on the one hand, and the emission factors obtained with the NG consumed by the IIPG, and that obtained on the NG based on data provided by the IPCC [2] on the other hand. The various calculations of the theoretical mass of CO_2 emitted, either with NG and HVO together, or with NG, which represents approximately 96.90 % of all fossil energy consumption from 2009 to 2019 of the IIPG, allowed us to comment on the validity of these theoretical results.

2-2. IIPG mass of fuel

2-2-1. Natural Gas

2-2-1-1. Average molar mass of resulting natural gas

From 2009 to 2019, three companies provided all of the natural gas consumed by the electricity sector in Côte d'Ivoire (IIPG). These are FOXTROT International with 73.05 % market share average, followed by CNR (Canadian Natural Resources) with 22.50 % and PETROCI CI-11 with 4.45 %. Each thermal power plant receives a mixture of natural gas from the three gas suppliers for the IIPG. In the following, we define a natural gas with unique characteristics for all four thermal power plants, with an average molar mass M_{GNmoya}. The gas produced by each gas supplier has its own composition which related to the extraction well.

$$M_{GNmoya} = \sum_{F=1}^{3} T_F \times M_{GNF} \tag{1}$$

M_{GNmoya} : Annual average molar mass of natural gas supplied to the IIPG by all gas suppliers [g/mol]; M_{GNF}: Molar mass of natural gas from gas supplier F [g/mol]; T_F: Annual market share of gas supplier F in the whole of IIPG gas consumption.

Natural gas is a real gas whose equation is that of ideal gases and adjusted by a compression factor [9].

2-2-1-2. Mass of resulting natural gas

The natural gas to be considered in the follow-up of this study is therefore the resulting gas which is the combination of the different types of natural gas produced by the three gas suppliers of the IIPG, whose molar mass is M_{GNmoya}. Natural gas volume measurements are made under the standard conditions [10], at 101.325 kPa and 288.15 K. The equation of this resulting real gas, under standard measurement conditions, is presented according to the ISO 6976 [9] standard, as follows : The calculation of the compression factors allows to obtain the real mass of the resulting natural gas, from the formula on real gases of ISO 6976 [9]. This last result therefore allows us to calculate the actual mass of natural gas consumed annually by the IIPG, which is defined as follows :

$$m_{GNa} = \frac{M_{GNmoya}}{10^3 R} \times \frac{P_2 \times V_a}{Z_a(P_2, T_2) \times T_2} \tag{2}$$

Where *m_{GNa} : Annual Mass of natural gas consumed by all 4 thermal power plants in the IIPG [10^6 kg]; V_a : Annual volume of natural gas consumed by all 4 thermal power plants in the IIPG $10^6 m^3$]; M_{GNmoya} : Annual average molar mass of all the natural gases that supply the 4 thermal power stations of the IIPG [g/mol] ; P_2: Measurement pressure of natural gas under standard conditions at 101.325 kPa; R : Constant of ideal gases equal to 8.314 462 1 J mol^{-1} K^{-1} [9]; T_2 : Natural gas measurement temperature under standard conditions at 288.15 K ; $Z_a(P_2, T_2)$: Annual compression factor of real natural gas resulting at P_2 and T_2 define by ISO 6976 [9].*

2-2-1-3. Equivalent alkanes of resulting natural gas

The resulting natural gas used in the thermal power plants of the IIPG is composed of 15 chemical elements with 12 alkanes. The rest consists of carbon dioxide (CO_2), nitrogen (N_2) and water vapor (H_2O) which do not take part in the combustion reaction under theoretical stoichiometric conditions. Alkanes are the producers of CO_2 during combustion. The total carbon number of all these alkanes is essential in determining the mass of CO_2 emitted during combustion. The chemical formula of alkanes is : $C_{xa}H_{2xa+2}$. An equivalent alkane is determined per year with the 12 types of alkanes presented in the resulting natural gas. For each year, we define an equivalent alkane with the chemical *Formula* :

$$C_{x_a}H_{2x_a+2} \quad (3)$$

Where, *x_a: Number of carbon atoms in year a; C: Chemical element carbon with a molar mass of 12.011 g/mol [9]; H: Chemical element hydrogen with a molar mass of 1.007 g/mol [9]; M_{GNAa} : Annual molar mass of all the alkanes inside the resulting natural gas [g/mol].*

The annual molar mass of the equivalent alkane (M_{GNAa}) is :

$$M_{GNAa} = \sum_{f=1}^{3} t_{GNaf} \times M_{GNaf} \quad (4)$$

M_{GNAa} : Annual molar mass of the equivalent alkane from the resulting natural gas [g/mol] ; t_{Gnaf} : Annual volume distribution of gas for supplier f ; M_{Gnaf} : Annual molar mass of alkanes from natural gas produced by the gas supplier f [g/mol].

$$M_{GNAa} = 14.024x_a + 2.014 \rightarrow x_a = \frac{M_{GNAa}-2.014}{14.024} \quad (5)$$

The main goal is to determine the mass of alkane contained in the resulting natural gas. But to do that, we need the partial pressure of that alkane equivalent in the resulting natural gas. ***Table1*** shows the characteristics of the resulting natural gas consumed from 2009 to 2019 in the IIPG.

Table 1 : *Characteristics of the resulting natural gas, consumed by the IIPG*

Study period	Average molar mass [g/mol]	Average molar fraction of hydrocarbons (Alkanes) [%]	Average molar mass of the hydrocarbons of the resulting natural gas [g/mol]	Chemical formula of the resulting natural gas [$C_{xa}H_{2xa+2}$]
2009 to 2019	17.86	97.61	17.06	$C_{1.07273069}H_{4.14546138}$

2-2-2. Liquid fuels (DDO and HVO)

For liquid fuels, the mass of the HVO is given and that of the DDO is calculated from its median density of 882.5 g/l.

2-3. Theoretical CO_2 emitted by the Ivorian interconnected power grid (IIPG)

2-3-1. CO_2 emitted by natural gases

With the substitution equivalent alkane, the combustion equation under theoretical stoichiometric conditions is as follows [11] :

$$C_{x_a}H_{2x_{a+2}} + \frac{3x_a+1}{2}(O_2 + 3.8N_2) \rightarrow x_a CO_2 + (x_a+1)H_2O + 3.8\frac{3x_a+1}{2}N_2 \quad (6)$$

From ***Equation (6)***, we deduce the total mass of CO_2 emitted into the environment by the combustion of all the natural gas consumed by the IIPG. In addition to the CO_2 resulting from the combustion of the equivalent alkane, we also have the fossil CO_2 contained in the natural gases which, of course, do not react to combustion, but are released into the environment. The content of this molar percentage of CO_2 (T_{xGN}) in natural gases from 2009 to 2019 average is 0.60 %. The total mass of CO_2 emitted using all the natural gases consumed by the IIPG is determined as follows :

$$m_{CO_2GNa} = M_{CO_2} \times \frac{m_{GNAa}}{M_{GNAa}} \times x_a + m_{GNa_{CO_2}} \quad (7)$$

With: m_{CO_2GNa} *: Total theoretical annual mass of CO_2 emitted by the combustion of natural gases consumed by the IIPG [kg of CO_2]; M_{GNAa} : Total annual mass of alkanes in the resulting natural gas [10^9 kg] ; M_{CO_2} : Molar mass of CO_2 of 44.0095 g/mol [9] ;* $m_{GNa_{CO_2}}$ *: Annual mass of CO_2 in natural gas and released into the environment [kg of CO_2].*

$$m_{GNa_{CO_2}} = M_{CO_2} \times \frac{m_{GNa}}{M_{GNmoya}} \times T_{xGN} \quad (8)$$

Hence :

$$m_{CO_2GNa} = \frac{M_{CO_2} \times m_{GNa}}{M_{GNmoya}}\left[\frac{m_{GNAa} \times M_{GNmoya} \times x_a}{m_{GNa} \times M_{GNAa}} + T_{xGN}\right] \quad (9)$$

However, the molar fraction of alkanes in the resulting natural gas consumed annually in the IIPG also has the following expression :

$$t_{Aa} = \frac{m_{GNAa} \times M_{GNmoya} \times x_a}{m_{GNa} \times M_{GNAa}} \quad (10)$$

Hence :

$$m_{CO_2GNa} = \frac{M_{CO_2} \times m_{GNa}}{M_{GNmoya}}[t_{Aa} + T_{xGN}] \quad (11)$$

2-3-2. CO_2 emitted by liquid fuels

From the mass composition of DDO and HVO given by the CIPREL thermal Power Plant and ADILCA Association [11], the theoretical stoichiometric combustion equation of HVO and DDO is as follows :

$$C_xH_yS_Z + \frac{4(x+z)+y}{4}(O_2 + 3.8N_2) \rightarrow x_aCO_2 + \frac{y}{2}H_2O + zSO_2 + 3.8\frac{4(x+z)+y}{4}N_2 \quad (12)$$

The number of moles of the chemical element carbon in the fuel is equal to that of CO_2 in the combustion products.

2-3-2-1. Mass of CO_2 emitted by HVO

$$m_{CO_2HVOa} = \frac{\%C_{HVO}}{100M_C} \times M_{CO_2} \times m_{HVOa} \quad (13)$$

With : m_{CO_2HVOa} : *Theoretical annual total mass of CO_2 emitted by the combustion of HVO consumed by the IIPG [kg of CO_2]. $\%C_{HVO}$: Mass percentage of carbon element in HVO [%] ; M_C: Molar mass of carbon [g/mol] ; M_{CO_2} : Molar mass of CO_2 [g/mol] ; m_{HVOa} : Annual mass of HVO consumed by the IIPG [10^3 kg].*

2-3-2-2. Mass of CO_2 emitted by DDO

$$m_{CO_2DDOa} = \frac{\%C_{DDO}}{100M_C} \times M_{CO_2} \times m_{DDOa} \quad (14)$$

With: m_{CO_2DDOa} : *Total theoretical annual mass of CO_2 emitted by the combustion of DDO consumed by the IIPG [kg of CO_2] ; $\%C_{DDO}$: Mass percentage of carbon element in DDO [%] ; m_{DDOa} : Total annual mass of DDO for a median density [kg].*

2-3-2-3. Mass of CO_2 emitted by the IIPG

The CO_2 intensity of the IIPG is the total mass of CO_2 emitted by the consumption of fossil fuels (natural gas, HVO and DDO), either per unit of net electrical energy produced, or per unit of electrical energy consumed by users. For a given DDO density value ρ (minimum, median, maximum) the total annual mass of CO_2 emitted by the IIPG with the consumption of fossil resources is determined.

$$m_{CO_2IIPGa} = m_{CO_2GNa} + m_{CO_{2}HVOa} + m_{CO_{2}DDOa} \quad (15)$$

$$m_{CO_2IIPGa} = M_{CO_2} \times \left[\frac{mGNa}{MGNmoya}(t_{Aa} \times x_a + T_{xGN}) + \frac{m_{HVOa}}{M_C} \times \frac{\%C_{HVO}}{100} + \frac{m_{DDOa}}{M_C} \times \frac{\%C_{DDO}}{100}\right] \quad (16)$$

With m_{CO_2IIPGa} : *Total theoretical annual mass of CO_2 emitted by the IIPG [kg of CO_2].*

2-4. Real CO_2 mass emitted by the Ivorian interconnected power grid

2-4-1. Real CO_2 mass evaluation of natural gas combustion

The fumes gas ratio mass analysis results from natural gas combustion at the CIPREL thermal power plant of CO_2 (T_{xGfGN}) are between 5.05 % and 5.13 %, and the air of combustion ratio mass analysis (T_{xair}) is 0.05 % of CO_2. The mass of the fumes is given by the following ***Equation*** :

$$m_{Exh} = m_{air} + m_{GNa} \tag{17}$$

With, m_{Exh} *: Mass of fumes [kg].*

The mass of CO_2 emitted by the combustion of natural gas is the mass of CO_2 contained in the flue gases, subtracted from the mass of CO_2 contained in the air. The equation is :
The CO_2 mass emitted by the combustion of natural gas is the CO_2 mass contained in the flue gases, subtracted from the mass of CO_2 contained in the air. The equation is :

$$m_{GNVCO_2da} = \left[T_{xGfGN}\left(1 + \frac{1}{d_{rGN}}\right) - \frac{T_{xair}}{d_{rGN}}\right]\frac{m_{GNa}}{100} \tag{18}$$

With, m_{GNVCO_2da} *: Annual real mass of CO_2 emitted by the natural gas combustion of IIPG with fumes gas analysis results [kg]; T_{xair} : Mass content of CO_2 in the air (%) ; d_{rGN} : Real dosage of natural gas combustion ; T_{xGfGN} : Mass content of CO_2 in the natural gas combustion fumes (%).*

At CIPREL, the 111 MW gas turbines have a natural gas flow rate of 7 to 8 kg/s for an air flow rate of 380 to 400 kg/s. The real dosage (d_{rGN}) is therefore between a minimum value of 1/57.14 and a maximum value of 1/47.50. The median value of real dosage of natural gas combustion is 1/52.32.

2-4-2. Real CO_2 mass evaluation of HVO combustion

The results of the analysis of HVO combustion fumes gas from the CIPREL thermal power plant give the real dosage of HVO combustion (d_{rHVO}) value of 1/62, the mass content of CO_2 in the fumes gas (T_{xGfHVO}) is 5.86 % with a CO_2 mass content in the combustion air of 0.05 %.
The real total mass of CO_2 emitted is :

$$m_{HVOCO_2a} = \left[T_{xGfHVO}\left(1 + \frac{1}{d_{rHVO}}\right) - \frac{T_{xair}}{d_{rHVO}}\right]\frac{m_{HVOa}}{100} \tag{19}$$

With $m_{HVOCO2a}$ *: Annual real mass of CO_2 emitted by the combustion of HVO in IIPG [kg] ; d_{rHVO} : real dosage of HVO combustion ; T_{xGfHVO}: Mass content of CO_2 in the HVO combustion fumes (%).*

2-4-3. Real CO_2 mass evaluation of natural gas and HVO combustion

Assuming that these fumes gas and air analysis results are valid for the entire study period (from 2009 to 2019), we have :

$$m_{VCO_2da} = \left[T_{xGfGN}\left(1+\frac{1}{d_{rGN}}\right) - \frac{T_{xair}}{d_{rGN}}\right]\frac{m_{GNa}}{100} + \left[T_{xGfHVO}\left(1+\frac{1}{d_{rHVO}}\right) - \frac{T_{xair}}{d_{rHVO}}\right]\frac{m_{HVOa}}{100} \qquad (20)$$

With, *m_{VCO2da}: Annual real mass of CO_2 emitted with the consumption of natural gas and HVO, from the fumes gas analyzes of the CIPREL thermal Power Plant and for a given dosage of natural gas [kg of CO_2]; d_{rGN}: Real given dosage of natural gas combustion ; d_{rHVO}: Real given dosage of HVO combustion ; m_{air}: Annual mass of air consumed by the IIPG [kg] ; m_{GNa}: Annual mass of natural gas consumed by the IIPG [kg] ; m_{HVOa} : Annual mass of HVO [kg] ; T_{xair}: Mass content of CO_2 in the air (%) ; T_{xGfGN} : Mass content of CO_2 in the flue gases (%).*

2-5. Mass of CO_2 emitted validation study by the Ivorian interconnected power grid

This validation study consists of comparing the theoretical results of the CO_2 emission calculation by the IIPG with field data collected mainly from the thermal power plant CIPREL. From field readings, analyzes of exhaust smoke from the thermal power plant, analyzes of the composition of the oxidizer (air), the total mass of CO_2 emitted is calculated and compared with the theoretical results obtained. This validation also consists of determining the CO_2 emission factor for the combustion of natural gas, which accounts for 96.90 % of fossil energy consumed by the IIPG and comparing it with that of the Intergovernmental Panel on Climate Change (IPCC) [2]. DDO is a fuel that is only used for starting the thermal power plant. It represents only 0.06 % of the fossil energy consumption of the IIPG and has no field data at CIPREL. Validation will be done with natural gas and HVO.

2-5-1. Annual relative error between real and theoretical emission of CO_2

From ***Equation (15)***, excluding the DDO term, we obtain the reference theoretical CO_2 emissions witch is :

$$m_{RCO_2a} = m_{CO_2GNa} + m_{CO_2HVOa} \qquad (21)$$

Where m_{RCO_2a} *: Annual theoretical reference mass of CO_2 emitted with the use of natural gas and HVO by the IIPG [kg of CO_2].*

This relative error per year (Era) is calculated as:

$$Era = \frac{[m_{VCO_2da} - m_{RCO_2a}]}{m_{RCO_2a}} \times 100 \qquad (22)$$

Where : *E_{ra}: Annual relative deviation [%]; m_{VCO2da} : annual median value [kg of CO_2]; m_{RCO2a} : Annual theoretical reference mass of CO_2 emitted with the use of natural gas and HVO in the IIPG [kg of CO_2].*

2-5-2. CO_2 emission factors deviation

2-5-2-1. CO_2 emission factor of the IIPG net production

$$EF_{IIPGX} = \frac{m_{CO_2IIPGa}}{(m_{GNa}+m_{DDOa}+m_{HVOa})} \tag{23}$$

With : *m_{GNa} : Annual mass of natural gas consumed by the IIPG [kg] ; EF_{IIPGX} : CO_2 emission factor of the natural gas consumed in the IIPG [%] ; m_{DDOa}: Total annual mass of DDO consumed by the IIPG [kg] ; m_{HVOa} : Total annual mass of HVO consumed by the IIPG [kg] ; m_{CO_2IIPGa} : Total theoretical annual mass of CO_2 emitted by the IIPG [kg of CO_2].*

2-5-2-2. CO_2 emission factor of the IIPG natural gas

$$EF_{IIPG} = \frac{m_{CO_2GNa}}{m_{GNa}} \tag{24}$$

With : *m_{GNa} : Annual mass of natural gas consumed by the IIPG [10^9 kg] ; EF_{IIPG}: CO_2 emission factor of the natural gas consumed in the IIPG [%] ; m_{CO2GNa} : Total theoretical annual mass of CO_2 emitted by the combustion of the natural gases consumed by the IIPG kg of CO_2].*

2-5-2-3. CO_2 emission factor with IPCC (2006) natural gas

$$EF_{IPCC(2006)} = \frac{FE_{effective} \times PCI_{GN}}{10^6} \tag{25}$$

With : *$EF_{IPCC(2006)}$: CO_2 emission factor of natural gas with IPCC [2] [%] ; $FE_{effective}$: Effective CO_2 emission factor with IPCC [kg / TJ] ; PCI_{GN} : Net calorific value with IPCC [TJ / Gg].*

2-5-2-4. Natural gas emission factor Relative deviation between IIPG and IPCC

$$Er_{IIPG/IPCC(2006)} = \frac{EF_{IIPG}}{EF_{IPCC(2006)}} \times 100 \tag{26}$$

$Er_{IIPG/IPCC(2006)}$: Relative deviation of the theoretical natural gas emission factor of the IIPG compared to the natural gas emission factor of the IPCC [2] [%].

2-6. IIPG Intensity of CO_2 emitted.

2-6-1. CO_2 Intensity of electricity production

The intensity of CO_2 emitted by the IIPG for net electricity production is :

$$I_{CO_2NEP} = \frac{m_{CO_2IIPGa}}{E_{NXa}} \tag{27}$$

E_{NXa}: Net annual electrical energy produced by the IIPG (kWh).

2-6-2. CO_2 Intensity of medium and lower voltage customer's consumption

The medium voltage (MV) is between 1kV to 50 kV and the lower voltage (LV) is between 50V to 1kV. The Intensity of CO_2 emitted by the IIPG for the consumption of national MV and LV customers, is obtained :

$$I_{CO_2SNC} = \frac{m_{CO_2IIPGa}}{E_{NCNa}} \quad (28)$$

E_{NCNa} : Net annual electrical energy consumed by national MV and LV customers of the IIPG (kWh).

2-6-3. CO_2 Intensity of Abidjanese MV and LV electricity customer consumption

The intensity of CO_2 emitted by the IIPG for the consumption of Abidjanese MV and LV customers,

$$I_{CO_2SCAC} = \frac{m_{CO_2IIPGa}}{E_{NCAa}} \quad (29)$$

E_{NCAa}: Net annual electrical energy consumed by Abidjanese MV and LV customers of the IIPG (kWh).

3. Results and discussion

3-1. Mass of fuels consumed

Table 2 gives the average annual consumption of fossil fuel by the IIPG from 2009 to 2019. It stands at 1.314 million tonnes, including 1.265 million tonnes of natural gas.

Table 2 : *Mass of the different fossil fuels consumed annually by the IIPG*

Year		Mass of natural gas [10^6 kg]	Mass of HVO [10^6 kg]	Average mass of DDO [10^6 kg]	Total mass consumed [10^6kg]
2009		877.52	0.84	0.01	878.37
2010		1016.88	22.25	0.03	1039.16
2011		1004.68	8.08	0.08	1012.85
2012		1 103.80	124.59	0.14	1 228.54
2013		1 335.92	57.13	0.11	1 393.16
2014		1 387.26	151.62	0.13	1 539.00
2015		1 448.08	146.26	0.07	1 594.41
2016		1 575.28	20.80	0.01	1 596.09
2017		1 461.13	0.12	0.79	1 462.05
2018		1 316.34	0.67	0.32	1 317.33
2019		1 381.42	3.11	0.26	1 384.78
Average of the period	Mass [10^6 kg]	1 265.39	48.68	0.18	1 314.25
	[%]	96.28	3.71	0.01	100.00

Natural gas is, by far, the most consumed by the thermal power plants of the IIPG with 96.28 %, followed by HVO with 3.71 %.

3-2. Mass of CO_2 theoretical emitted by the IIPG by type of fuel

The mass of CO_2 emitted by the IIPG from 2009 to 2019 breaks down as follows: 95.58% for natural gas, 4.40% for HVO and 0.02% for DDO ***(Table 3)***. So the IIPG uses essentially NG. Natural gas and HVO are responsible for 99.98% of the theoretical CO_2 emissions of the IIPG.

Table 3 : *Annual theoretical mass of CO_2 emitted by the various fuels consumed in the IIPG*

	Theoretical mass of CO_2 emitted by the IIPG [10^6 kg of CO_2 / year]				Ratio [%]		
Year	Total	Natural Gas	HVO	DDO	Natural Gas	HVO	DDO
2009	2271.01	2268.37	2.61	0.02	99.88	0.12	0.00
2010	2706.56	2637.34	69.13	0.10	97.44	2.55	0.00
2011	2635.15	2609.79	25.11	0.25	99.04	0.95	0.01
2012	3 248.82	2 861.25	387.12	0.45	88.07	11.92	0.01
2013	3 649.68	3 471.82	177.51	0.35	95.13	4.86	0.01
2014	4 078.14	3 606.63	471.11	0.40	88.44	11.55	0.01
2015	4 218.19	3 763.52	454.45	0.22	89.22	10.77	0.01
2016	4 158.01	4 093.36	64.62	0.03	98.45	1.55	0.00
2017	3 795.94	3 793.04	0.38	2.51	99.92	0.01	0.07
2018	3 422.54	3 419.44	2.08	1.02	99.91	0.06	0.03
2019	3 600.70	3 590.23	9.66	0.82	99.71	0.27	0.02
Average	3 435.78	3 283.97	151.25	0.56	95.58	4.40	0.02

3-3. CO_2 theoretical mass emitted by the IIPG by type of fuel

The set of natural gas and HVO values is a range between a minimum value and a maximum value. The representative median value of real CO_2 emissions is compared to the theoretical reference value of natural gas and HVO emissions with a relative error calculation. ***Figure 1*** presents the range of real direct values of CO_2 emissions per year, with the combustion of natural gas and HVO in the IIPG, based on field data from the CIPREL thermal power plant in the one hand, and the median real direct CO_2 emission values per year, in the other hand. Within the real direct limit values of CO_2 emissions per year, we have the theoretical reference mass value per year. The maximum difference between the theoretical reference mass value and the real values corresponds to 14.16 % relative deviation in relation to the theoretical reference value. The maximum average relative deviation is 13.72 % and corresponds to an average annual CO_2 emission of 472,497.90 tons. Between the two extreme real values, there is the median real value, the basis of comparison. The relative annual deviation of the mass of theoretical CO_2 emitted compared to the median value of the CO_2 really emitted for the use of natural gas and HVO is between 3.26 % and 5.20 %, with an average of 4.01 %. Only in 2012 the value of the relative error is greater than 5 % (5.20 %). The statistically acceptable limit being a 5 % margin of error, we can say that the theoretical approach adopted to assess the real CO_2 emissions for the consumption of natural gas and HVO in the IIPG is acceptable.

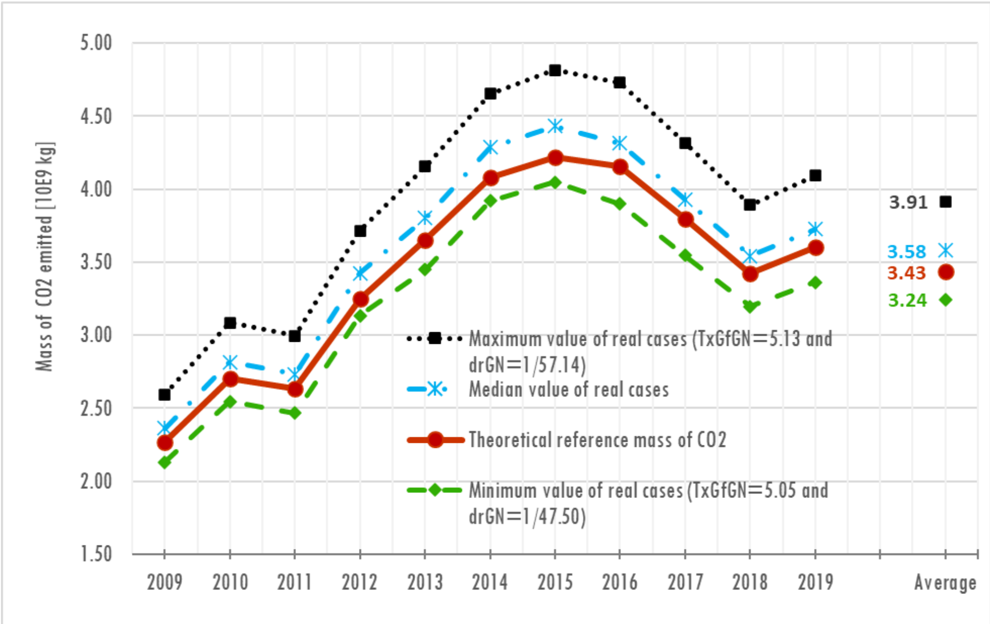

Figure 1 : *Actual CO_2 emissions, with the use of natural gas and HVO in the Ivorian IIPG, based on smoke analysis data and calculated theoretical emissions*

3-4. Emission factors of natural gas from IIPG and natural gas from IPCC (2006)

The theoretical natural gas emission factors per year of the IIPG, from 2009 to 2019 in ***Figure 2***, are all located within the confidence interval, at 95 % of the natural gas emission factor of the IPCC (2006) which is limited by a highest and lowest with a default emission factors.

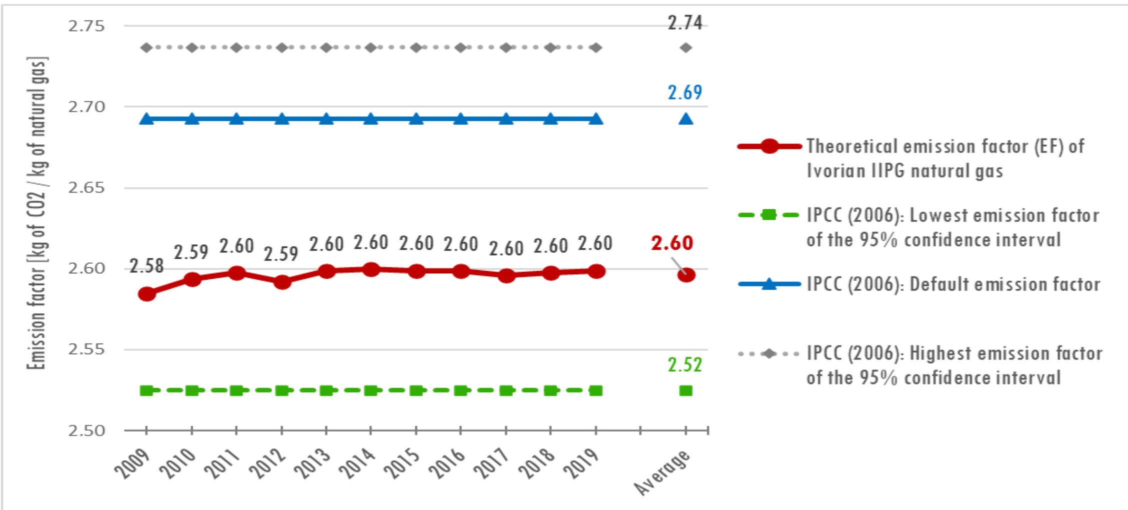

Figure 2 : *IPCC (2006) and IIPG natural gas annual CO_2 emission factors*

The relative deviation of the theoretical emission factor of IIPG natural gas compared to the emission factor of the IPCC (2006) natural gas, is between 3.45 % and 4.00 % with an average of 3.59 %. Which is less than the 5 % statistical tolerated error. The theoretical emission factor of the IIPG natural gas is therefore conformed with the data provided by the IPCC (2006) natural gases. But the average value from 2009 to 2019 is 2.60 kg of CO_2/kg of IIPG natural gas compared to 2.69 kg of CO_2/kg of IPCC (2006) natural gas used in different impact calculation of IIPG [4].

3-5. IIPG annual CO_2 emission factors for fossil fuel consumed

The IIPG annual average CO_2 emission factors is 2.62 kg of CO_2 / kg of fossil fuel consumed ***(Figure 3)***. Between 2016 to 2019, the IIPG annual CO_2 emission factors are closer of the annual CO_2 emission factors of natural gas ***(Figure 2)***. Between 2016 to 2019, the CO_2 emission factors of the IIPG are close to those of NG which is 2.60 kg of CO_2 /kg of NG. This is illustrated in ***Table 3*** with a mass percentage of NG of at least 99.71 % over this period. The same is true for the years 2009 to 2011.

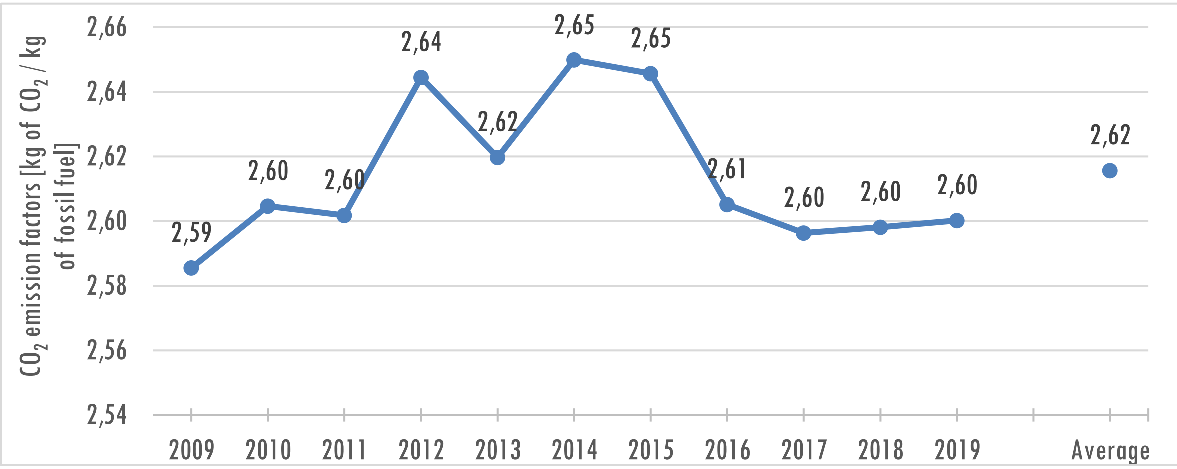

Figure 3 : *IIPG annual CO_2 emission factors*

3-6. Intensity of CO_2 emitted by power generation systems

Carbon comes from fossil fuels. The carbon intensity which represents the CO_2 emissions per kWh electricity production (gCO_2/kWh) of a power generation system is therefore linked to the amount of fossil energy consumed. ***Figure 4*** presents the carbon intensity by country or by groups of countries electrical power generation systems.

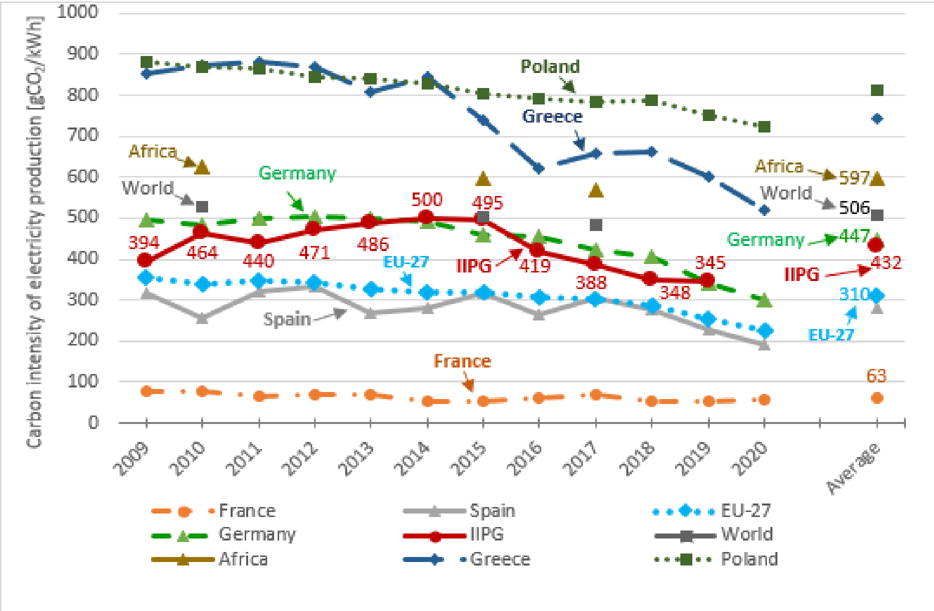

Figure 4 : *Carbon intensity of electricity generation from power systems in different countries* [6, 12]

The carbon intensity of the IIPG varies between 500.27 gCO_2/kWh in 2014 to 345.11 gCO_2/kWh in 2019 with an average of 431.82 gCO_2/kWh from 2009 to 2019. This trend is similar to Germany carbon intensity which is 447.00 gCO_2/kWh at the same period of time. The carbon intensity of the IIPG is higher than the average for the Europe of 27 (EU-27) which is 317.64 gCO_2/kWh, but better than the world average (506 gCO_2/kWh) and the African average (597 gCO_2/kWh). The global trend is downward, a sign of an increasingly significant reduction in the quantities of fossil energy in power generation throughout the world and the optimization of power generation systems. This is certainly due to the transformation of simple cycle gas thermal power plants (gas cycle) into combined cycle thermal power plants (gas and steam cycle) and the commissioning of other renewable energy source power plants. In the case of Côte d'Ivoire, this downward is due to the gas-fired power plants of Azito Energie and CIPREL have moved from the simple cycle to the combined cycle, since 2015 and the commissioning of the Soubré hydropower plant in 2017.

3-7. Intensity of CO_2 emitted for IIPG for MV and LV customer's consumption

The carbon intensity average for a customer's consumption of MV (medium voltage) and LV (lower voltage) of the IIPG, over the period 2009 and 2019 is 555.62 g CO_2/kWh at the national level, as illustrated in ***Figure 5***.

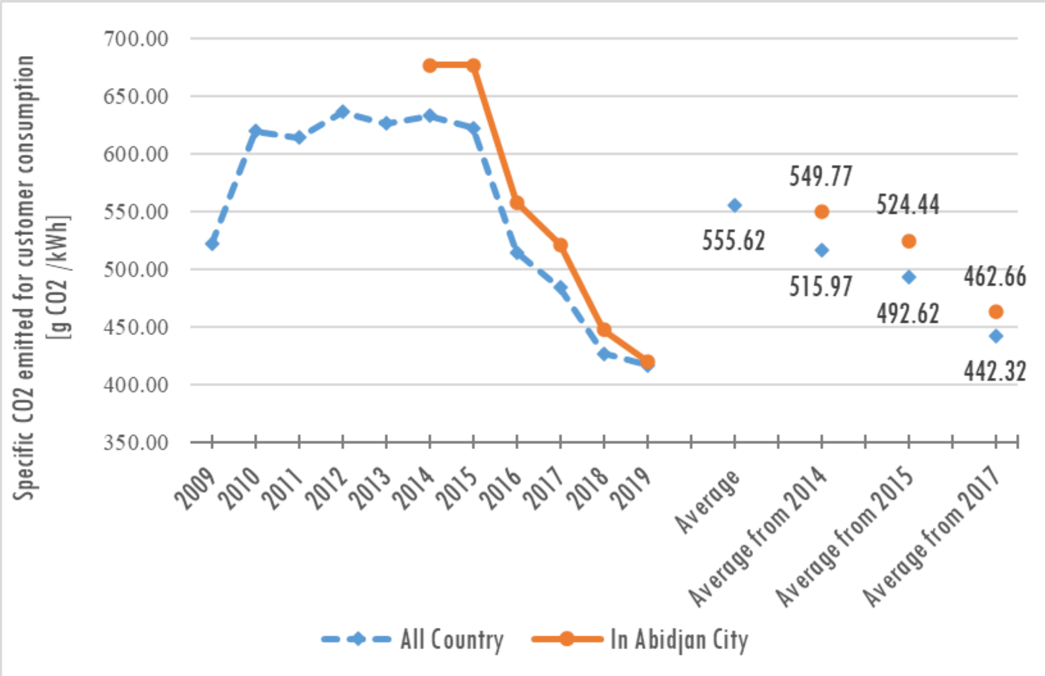

Figure 5 : *Carbon intensity of electrical energy consumption of the IIPG by customers in MV and LV*

While the carbon intensity of net electricity production is 431.82 gCO_2/kWh ***(Figure 3)***. Thus, over the period from 2009 to 2019, the environmental impact of the energy losses on the electricity transmission and distribution system of the IIPG in MV and LV voltage at the national level, are 123.20 gCO_2/kWh of electrical energy consumed by a customer, which represent 22.17 % of the direct CO_2 emissions of IIPG customer's consumption. Between 2015 and 2019, this average is 492.62 gCO_2/kWh at the national level and 524.44 gCO_2/kWh at the level of the Abidjan city, i.e. an increase in CO_2 emissions impact of the Abidjan city consumer by 6.46 % compared to the country level. This gap is shrinking over the years over the study period to be only 3.24 gCO_2/kWh in 2019. This is the consequence of the policy implemented to reduce technical losses of the IIPG since 2014 [13] in the distribution network of the Abidjan city which has concentrated at least 54.54 % of Ivorian consumption since 2009 [14].

4. Conclusion

This study carried out on the Ivorian interconnected power grid (IIPG) electricity production highlighted the real direct impact of fossil energy consumption and CO_2 emissions in terms of electricity production and the medium (MA) or lower (LV) voltage consumption. From 2009 to 2019, the electrical energy production system of the IIPG provided 99.9 % of the average net production, of which 24.86 % is provided by its hydropower plants and 75.14 % by its thermal power plants. In thermal power plants, natural gas accounts for 96.90 % of all fossil energy consumption, i.e. 96.28 % of the average annual mass of fuel consumed. The mass of CO_2 emitted using natural gas (NG) is estimated at 95.58 % of the average annual mass of CO_2 emissions by the IIPG. For all the average annual CO_2 emissions of the IIPG only 4.40 % and 0.02 % are due to HVO and DDO respectively. Over the same period, the carbon intensity of net electrical energy production fluctuates between a maximum value of 500.27 gCO_2/kWh in 2014 and a minimum value of 345.11 gCO_2/kWh in 2019 with an average of 431.82 gCO_2/kWh. On the same period, the average CO_2 emission factor for natural gas of the IIPG is 2.60 kg of CO_2/kg of NG, different from the default emission factor of the IPCC (2006) which is 2.69 kg of CO_2/kg of NG, used for environmental impact calculations. The IIPG average CO_2 emission factor is 2.62 kg of CO_2/kg of fossil fuel consumed. Over the period from 2015 to 2019, with the IIPG MV and LV consumer's, in the country, the average fossil energy intensity is 8.81 MJ/kWh with a carbon intensity average of 492.62 gCO_2/kWh which are less than Abidjan city consumers with an average of 9.38 MJ/kWh and 524.44 gCO_2/kWh respectively. This represents an increase in the energy and CO_2 emission impacts of the Abidjan consumer by 6.46 % compared to the country level due to the electrical technical loss. These results show the energy and CO_2 emission impacts of electrical loss in the one hand. For any determination of energy and environmental impacts in Côte d'Ivoire or in the city of Abidjan, the using of these real results of direct impact from the IIPG will provide an image closer to the reality in the other hand.

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