Energy-related carbon emission from electricity sector: past trends and futures for Madagascar

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ABSTRACT

To meet the increase in energy demand, many developing countries, such as Madagascar, have turned to fossil fuels for electricity generation. This dependence has a significant environmental impact. Moreover, in Madagascar, the current electricity mix does not allow for stable and serene economic development. Thus, in order to discuss an energy planning strategy of the territory, this paper intends to analyze the past trends of CO_2 emissions from electricity generation in Madagascar over the 1990-2015 period. In this study, the logarithmic mean Divisia index (LMDI) method is used to first quantify the driving forces of changes by examining past trends. Then, the combination of the LMDI with Kaya's identity through the concept of IPAT, allows us to link CO_2 emissions to anthropogenic activity.
This makes it possible to define Madagascar's future energy needs and the distribution of associated consumption by 2030. Starting from the classic business-as-usual trend scenario, two other scenarios have been implemented. The two cases selected come from Madagascar's new energy planning visions (NPE and IEM). The impact of political instability is discussed from the perspective of energy consumption and the economy.

KEYWORDS

Madagascar, Scenario, CO_2 emission, LCA, LMDI, KAYA, Clustering

INTRODUCTION

Since the COP21, many countries around the world have set ambitious new targets for reducing greenhouse gas (GHG) emissions. For developing countries, these objectives are all the more ambitious as they must both achieve the energy demand to develop the territory and mitigate the impact of economic and anthropogenic activity.
Reliable power generation is one of the main drivers of economic growth. Moreover, the electricity sector is among the most GHG emitting sectors. In 2016, electricity and heat generation accounting for 42% of the total global emissions, which corresponds to 13.41 Gt of

CO_2 [1]. As a significant contributor to CO_2 emissions, the power sector is particularly in energy planning scenario to achieve low carbon development [2][3][4]. The benefits of higher renewable energy sources (RES) penetration in electricity mix are commonly acknowledged. The fact that Africa contributes less than 4% of global GHG emissions while being the continent most vulnerable to climate change contrasts the need for an energy transition with regional policymakers' decisions. The challenges and opportunities are not the same whether these African states are developed, emerging or developing. Madagascar is currently in the third category and aims to become an emerging country through new political ambitions. Poor access to electricity remains a significant barrier to most businesses and economic growth in sub-Saharan Africa's regions [5][6]. Under this context, understanding the driver's forces in the power sector of Madagascar the sector appears to be essential in order to establish a diagnosis of the current situation of the country in order to be able to draw the outlines of possible future opportunities. Among the existing decomposition methods applied to energy, the LMDI approach is the one most used by the authors [7][8].

This paper aimed to first provide a general picture of Madagascar’s energy situation in the 1990-2015 period. It investigates the relationship between electricity consumption, economic growth, population, and CO_2 emissions. The remainder of this paper is arranged as follows. Section 2 summarizes an overview of Madagascar socio-economic and energy situation. Section 3 presents the methods used for the decomposition of CO_2 emissions and those used for the implementation of the scenarios. Section 4 describes the results of LMDI, factorial analysis, and the different scenarios and discusses the meaning of these results. Section 5 concludes this article and provide some policy recommendations for Madagascar.

MADAGASCAR AT A GLANCE

Located between the Mozambique channel and Indian Ocean, Madagascar is the fourth largest island in the world with total area of 586,295 km². Subjected to subtropical climate conditions, Madagascar spans 14 degrees of latitude. The territory thus offers a wide diversity of micro-climates between the highland areas and the 5600 km of coastline. From a global point of view, the climatic zoning of the island reveals three main areas: dry and arid (west), wet and rainy (east) and highlands characterized by low temperature and precipitation. Madagascar is heavily populated with an estimated population of 25.57 million people in 2017 [9]. In 2012, the poverty rate reached 70.7%. In rural areas where two-thirds of the population lives, this rate increases to 82%. The main consequence is a massive exodus of people to the six main urban areas of the territory. From an economic point of view, recurrent political instability has weakened the territory's growth and development over the past 30 years, see Figure 1. In order to put the economy back on a healthy and sustainable growth path at a level at least equal to 5%, the IMF[1] decided in 2016 to grant an extended credit facility of 305 million USD. This fund was backed by a three-year reform programme (2016-2019), whose energy is one of the cornerstones. The reliability of electricity supply is a strategic issue for the development of Madagascar's urban areas. Indeed, the chronic load shedding problems in large cities make it difficult for the country to emerge economically. The energy sector is characterized by the predominance of fuel wood and charcoal in final energy consumption (83% in 2017), which is the origin of the degradation of the natural forests (~ 36,000 ha/ year).

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[1] International Monetary Fund

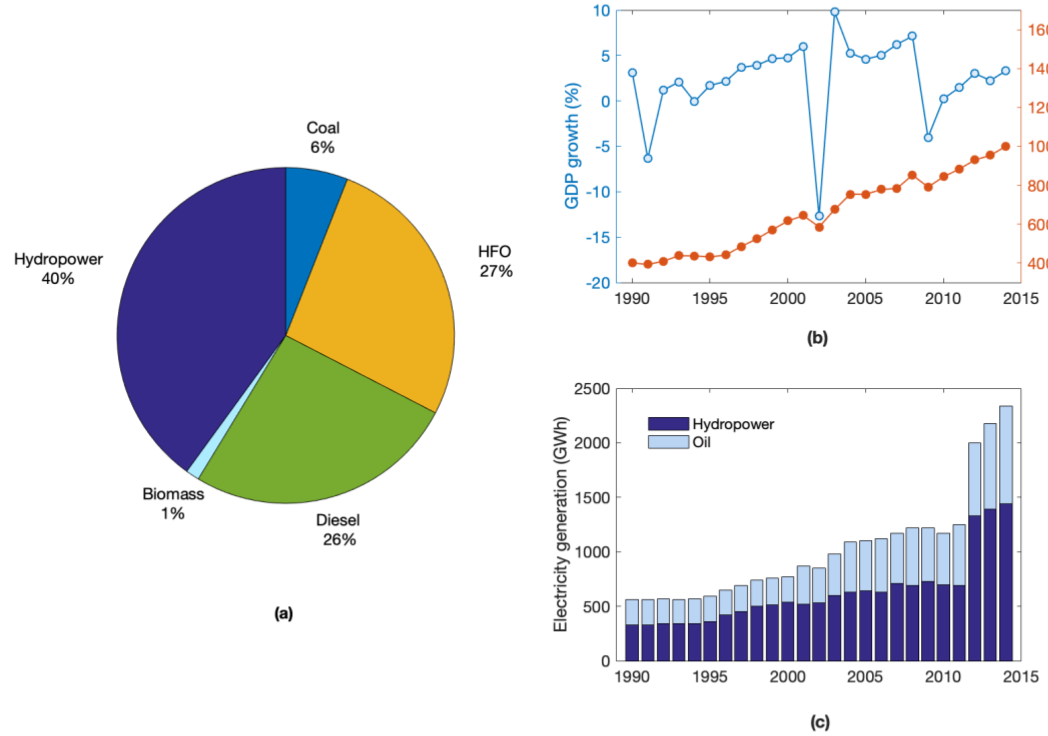

Figure 1. (a) - Electricity mix in 2017, (b) – Economic and electricity consumption evolution, (c) – Electricity generation

The electricity access does not exceed 16% and this value falls to less than 5% in rural areas. In 2017, gross electricity production amounted to 1,970.5 GWh. JIRAMA's[2] gross production is 1,701.6 GWh. The year 2017 is marked by a particular episode which is the inversion of the majority source type. Indeed, for the first time in its history, electricity is generated mainly from fossil fuels (53%) and hydroelectricity (40%), see Figure 1. The situation of energy production remains alarming due to the aging of the installations (30 years for some hydroelectric power plants), but also the obsolescence of the distribution network.
In contrast to this high dependence on imported fossil fuels, Madagascar has considerable potential for the development of renewable energies. Previous studies have highlighted the technically high potential of the territory in the development of hydroelectric power plants (180,000 GWh), [1]. Wind and solar energy are the other most interesting resources. The total horizontal solar radiation is about 2000 kWh/m². The island's coastal regions have a potential wind speed of 7 - 8 m/s. This value decreases to 6 m/s for the highlands,[10][11]. Other resources such as biomass and waste valorization are currently being studied to identify the production potential and the processes to be adapted.
The definition of an energy policy is relatively recent in Madagascar. The first step was to define the New Energy Policy (NPE) 2015-2030. The NPE is part of the implementation of the National Development Plan (NDP) 2015-2019. It aims to "respond to the country's urgent economic, social and environmental challenges." The three energy sub-sectors concerned are biomass, electricity, and hydrocarbons. Aiming both at preserving its environment and developing RES, this policy aims to guarantee the country's energy security and independence through the diversification of the energy mix and the reduction of hydrocarbon imports. Adaptation and strengthening of the regulatory and institutional framework and business

[2] Jiro sy rano malagasy

environment to achieve the NPE vision by ensuring effective coordination between the various entities involved, including ministries involved in boosting the energy sector, as well as public and private partners [12].
The Emergence for Madagascar initiative of the very recent Malagasy President is an ambitious vision of the territory by 2023. We focused on the aspirations on the energy issue. This new policy aims to commit the country by 2023 to a resilient territory. Emerging countries such as China inspire IEM's development model. This plan is first and foremost a new one aimed at contributing to development and prosperity for all in a generation. This vision of emergence is based on the in-depth economic reforms needed to move from a counter-economy to an economy that exports finished products with high added value. This re-foundation is the subject, in all African countries, and all Asian countries in the emergence phase or having successfully emerged, of skills and performance in terms of reforms. Regarding the question of the energy situation, no precise planning has yet been established. The only quantified targets are on the one hand to increase the electrification rate from 16% to 50% by 2023. In addition, at the beginning of 2019, several hydroelectric power plant construction projects are aimed at contributing to the penetration of renewable energies into the electricity mix. In addition to the development of RES, the project also intends to control the cost of electricity production, which is one of the highest in the Indian Ocean region. The last point is the production guarantee in order to limit the risks of power outages in Madagascar's major cities.

MATERIALS AND METHOD

Environmental assessment

LCA Methodology. Although Madagascar is a non-issuing country with a low contribution of 0.2% of world emissions in 2000, Madagascar’s Intended Nationally Determined Contribution (INDC) was established as the outcome of the COP21 in Paris in 2015. The INDC aims to reduce GHG emissions by 14% compared to the Business-as-usual (BAU) scenario, projections based on the 2000 emissions inventory [13].
In the context of the recent energy policies, the first part of this study involves in defining the level of emissions from electricity sector. This approach is to determine the basis of the energy scenarios. The Life cycle assessment (LCA) method used in this study is a standard approach which allows to identify environmental burdens of a product through its life cycle [14]. It comprises four steps: (1) goal and scope definition phase, (2) inventory analysis phase, (3) impact assessment phase and (4) interpretation phase. The goal is to determine the environmental impacts of electricity sector at the territorial level.
The functional unit (FU) is defined by the amount of annual electricity produced by this sector. The impacts per 1 kWh are also calculated to measure the change in the electricity mix. The study’s boundaries are from cradle-to-gate, including raw material acquisition, transport, infrastructure construction and electricity production.
A number of methods and tools are available to assess environmental impacts and can assist in decision-making. Software databases of current LCA tools, as seen in [15], [16] where Simapro is used or in [17] [18] with GaBi, do not generally integrate systems used in insular territories or developing countries. An evaluation tool that can be adapted to each territory, was developed, [19], to assess electricity production, based on the LCA methodology and the adaptation of the GEMIS database [20]. At first, the methodology consists in describing the production facilities with the specific characteristics related to the study area: the installed capacity for each technology, the supply distance of raw materials for petroleum products, the

output generated by each plant. Then, the collected data are treated on the basis of the corresponding emission factors, at each life cycle stage, according to Equation (1):

$$C_i = \sum_{k=1}^{n} \quad EF_k \times q_{p,k} \qquad (1)$$

where C represents the emission value of each technology i, k the life cycle stage, EF the corresponding emission factor for 1 FU of the life-cycle stage and q_p the quantity of the product expressed in the FU.
The obtained results will allow to determine the environmental indicators of both total electricity production and ratio values. This methodology was applied to non-interconnected French territories, demonstrating the assessed environmental impacts of the system and the comparison of territories on a global scale [21].

KAYA- LMDI methods

Madagascar's electricity-related carbon dioxide (CO_2) emissions are analysed using an approach which results from the combination of KAYA's identity and the LMDI [22] The objective is to be able to identify and quantify the links between CO_2 emissions and human activities.
KAYA identity: The concept of the IPAT, which is becoming increasingly popular, consists in dividing environmental impacts (I) into three factors: population (P), affluence (A) and technology (T). By establishing links between the environmental and socio-economic dimensions [23], it allows to measure the environmental impacts of human activities [23]–[25], as summarized in the following equation:

$$Impact\ (I) = Population\ (P) \times Affluence\ (A) \times Technology\ (T) \qquad (2)$$

Based on the IPAT equation, Kaya's identity applies this principle to GHG emissions, promoting the assessment of energy-related CO_2 emission factors [24], [26], according to :

$$CO_2\ emissions = Population \times \frac{GDP}{Pop} \times \frac{Energy}{GDP} \times \frac{CO_2}{Energy} \qquad (3)$$

From Equation (3), the effects of the different variables and their evolution over time can be studied regardless of the geographical scale chosen (city, region, country, world). In addition, many researchers have extended or modified the basic Kaya equation to include other explanatory variables depending on the nature and scope of their research [26] [27][28][29]. In the current case, regarding electricity consumption, Madagascar is a country characterized by a low electricity rate and a dependence on fossil fuels. As a result, the vision of the country's energy policy is mainly focused on increasing access to electricity and promoting renewable energy [12]. Thus, in order to integrate the specificities of the Malagasy electricity sector into the analysis, the Kaya equation has been modified as follows:

$$C = \sum \quad C_i = \sum_i \quad (\frac{C_i}{FF_i} \times \frac{FF_i}{FF} \times \frac{FF}{E} \times \frac{E}{GDP} \times \frac{GDP}{Pelec} \times \frac{Pelec}{P} \times P) \qquad (4)$$

where C_i represents the carbon emission for the energy source type i, FF_i the electricity generated by the energy source type i, FF the total electricity production, E the total electricity consumption, P the number of inhabitants and P_{elec} the number of inhabitants with access to electricity.

The "Technology" group refers to the technology of the electricity production system: the CO_2 emission factor by energy source (C_i/FF_i), the electricity mix (FF_i/FF) and the energy losses during distribution (FF/E). The "Affluence" group expresses the country's richness in relation to its electricity consumption through electricity consumption per GDP (E/GDP) and the ratio of GDP per capita to the electrification rate (GDP/P_{elec}). The "Population" group denotes the characteristics related to the social dimension: the electrification rate (P_{elec}/P) and the number of inhabitants (P).
The modified Kaya equation then passes through a decomposition method that quantifies the effect of the parameters considered on the evolution of the CO_2 emission. The most commonly applied method for this is the LMDI [30] [31].

LMDI: The LMDI (Logarithmic Mean Divisia Index) was preferred to other decomposition methods due to its advantages [22], which range from perfect decomposition (no residual terms) to the ability to deal with zero values (replacement with small positive values). In addition, as it is easy to formulate, LMDI I was the most recommended methodology [7], [22]. Therefore, in accordance with Equation 3, the decomposition by the LMDI I is performed through seven effects that are categorized into three groups: technology, affluence, population. Each effect is defined in Table 1. The decomposition formulas, presented in Table 2, will be performed for each pair of years during the period considered. Thus, as can be seen in Table 2, the analysis will be carried out using both additive and multiplicative decomposition to obtain both quantities and change ratios.

Table 1. Definition of LMDI effects

Group	Effect	Notation	Variable	Significance
Technology	Emission-factor effect	C_{ef}	$Fi = \frac{Ci}{FFi}$	Effect of the CO_2 emission factor for each type of energy source
	Energy-mix effect	C_{em}	$Si = \frac{FFi}{FF}$	Effect of the share of each energy source in electricity production
	Energy-loss effect	C_{el}	$L = \frac{FF}{E}$	Effect of energy losses in electricity distribution
Affluence	Energy-intensity effect	C_{ei}	$I_1=\frac{E}{GDP}$	Effect of electricity consumption per GDP
	Economic-related electrification rate effect	C_e	$I_2=\frac{GDP}{Pelec}$	Effect of economic growth in relation to the electrification rate
Population	Electrification rate effect	C_{er}	$I_3=\frac{Pelec}{P}$	Effect of changes in the electrification rate
	Population effect	C_{pop}	P	Effect due to the population growth

Table 2. LMDI decomposition formulas

Additive decomposition	Multiplicative decomposition
Change scheme	

$$\Delta C_{tot} = C^T - C^0 = \Delta C_{ef} + \Delta C_{em} + \Delta C_{el} + \Delta C_{ei} + \Delta C_e + \Delta C_{er} + \Delta C_{pop}$$

$$DC_{tot} = \frac{C^T}{C^0} = DC_{ef}.DC_{em}.DC_{el}.DC_{ei}.DC_e.DC_{er}.DC_{pop}$$

Decomposition formulas

$\Delta C_{ef} = \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \ln(\frac{F_i^{\,t}}{F_i^{\,0}})$	$DC_{ef} = \exp(\sum_i \frac{(C_i^T - C_i^0)/(\ln C_i^T - \ln C_i^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)} \ln(\frac{F_i^{\,t}}{F_i^{\,0}}))$
$\Delta C_{em} = \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \ln(\frac{S_i^{\,t}}{S_i^{\,0}})$	$DC_{em} = \exp(\sum_i \frac{(C_i^T - C_i^0)/(\ln C_i^T - \ln C_i^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)} \ln(\frac{S_i^{\,t}}{S_i^{\,0}}))$
$\Delta C_{el} = \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \ln(\frac{L^t}{L^0})$	$DC_{el} = \exp(\sum_i \frac{(C_i^T - C_i^0)/(\ln C_i^T - \ln C_i^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)} \ln(\frac{L^t}{L^0}))$
$\Delta C_{ei} = \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \ln(\frac{I_1^{\,t}}{I_1^{\,0}})$	$DC_{ei} = \exp(\sum_i \frac{(C_i^T - C_i^0)/(\ln C_i^T - \ln C_i^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)} \ln(\frac{I_1^{\,t}}{I_1^{\,0}}))$
$\Delta C_e = \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \ln(\frac{I_2^{\,t}}{I_2^{\,0}})$	$DC_e = \exp(\sum_i \frac{(C_i^T - C_i^0)/(\ln C_i^T - \ln C_i^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)} \ln(\frac{I_2^{\,t}}{I_2^{\,0}}))$
$\Delta C_{er} = \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \ln(\frac{I_3^{\,t}}{I_3^{\,0}})$	$DC_{er} = \exp(\sum_i \frac{(C_i^T - C_i^0)/(\ln C_i^T - \ln C_i^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)} \ln(\frac{I_3^{\,t}}{I_3^{\,0}}))$
$\Delta C_{pop} = \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \ln(\frac{P^t}{P^0})$	$DC_{pop} = \exp(\sum_i \frac{(C_i^T - C_i^0)/(\ln C_i^T - \ln C_i^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)} \ln(\frac{P^t}{P^0}))$
$\Delta C_{technology} = \Delta C_{ef} + \Delta C_{em} + \Delta C_{el}$	$DC_{technology} = DC_{ef}.DC_{em}.DC_{el}$
$\Delta C_{affluence} = \Delta C_{ei} + \Delta C_e$	$DC_{affluence} = DC_{ei}.DC_e$
$\Delta C_{population} = \Delta C_{er} + \Delta C_{pop}$	$DC_{population} = DC_{er}.DC_{pop}$

PCA-based Clustering

Principal component analysis (PCA): PCA and HCA (Hierarchical Clustering Analysis) are usually used concomitantly in many studies in the field of biology. PCA is part of the group of multidimensional descriptive methods called factorial methods widely used in the literature for the analysis of quantitative data [32]. This approach makes it possible to better identify the data on which we are working, and to detect possible outliers, [33]. The PCA makes it possible to define new factors (the principal components) by synthesizing a certain percentage of the total variance contained in the initial set of data. The criterion of an eigenvalue $\lambda > 1$ was used to select the number of relevant components on which to conduct the analysis, [34]. This first step allows us to define the variables considered significant to our analysis but also to define the projection plan of the individuals. In our case this corresponds to the countries. Thus, the first plan consisting of two first components will be retained for the next step.

Hierarchical Clustering on Principal Components (HCPC): The second step of the consists in the implementation of clustering based on the K-means partitioning method, which is one of the most commonly used clustering algorithms. Clustering is an unsupervised learning process, often used for data analytics. The method is intended to identify homogeneous groups called clusters from a set of parameters. In other words, data clustering aims to minimize the total within-cluster variation. The objective of this clustering is to study the socio-economic characteristics of different developing or emerging countries. Understanding the current situation of Madagascar is useful to implement policy scenario proposed the government and thus see which trajectory the country could take in the coming years.
All statistical analyses investigated in this study are performed using the FactoMineR package developed by [35].

Data collection

Impact assessment and decomposition analysis: To establish a diagnostic of the electricity sector, the data over a period of 25 years from [36], [37], shown in Figure 2, have been used. These data describe the evolution of the Malagasy electricity mix, in Figure 2.a. The installed capacity for each technology is illustrated in Figure 2.b. They are used to determine the emission value for each type of technology. To note that only JIRAMA's data have been used in this study, not including off-grid rural electrification.

All these data concerning the power generation system are injected into the equations of the decomposition method. Thus, as required by the combined Kaya-LMDI method, they are enhanced by socio-economic data from 1990 to 2015: GDP, electrification rate and number of inhabitants obtained from [38]–[40] and the electrified population calculated on the basis of the electrification rate and the number of inhabitants.

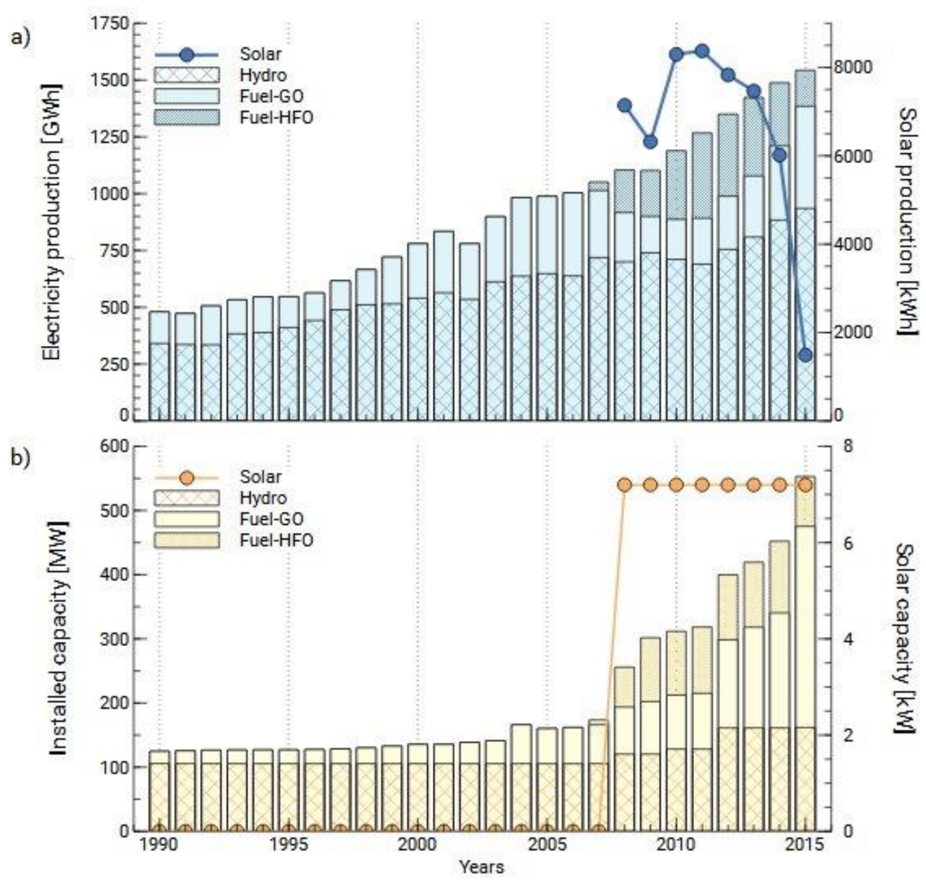

Figure 2. (a) Electricity production by fuel source (b) Installed capacity for each technology from 1990 to 2015 (Data from [36], [37]).

RESULTS AND DISCUSSION

CO_2 emission drivers

Environmental burdens: The main environmental indicators obtained from this evaluation are related to the Global Warming Potential (GWP), the acidification potential, the tropospheric ozone precursor potential, the eutrophication potential, the cumulative energy used and the

material expenditures. In fact, these are the most recurrent indicators in LCA studies [41], [42]. However, this study will focus on results based on climate change, expressed by GWP in CO_2 equivalent (CO_2-eq).
As can be seen on Figure 3, total emissions show an increasing trend, which is explained by the increase in production, but also by the increase in the use of fossil fuels in the Malagasy electricity mix. Indeed, the environmental loads of renewable energies are mainly attributed to the infrastructure construction. To note that construction phase represents only 7% of the total emissions. It can be observed that the emission rate varies over the last 25 years in quasi-sine wave manner. This is due to the continue slight increase of hydroelectric production that contributes at an average of 67% of the electric mix, and also due to the variation of fossil fuel production, even the installed capacity has increased.

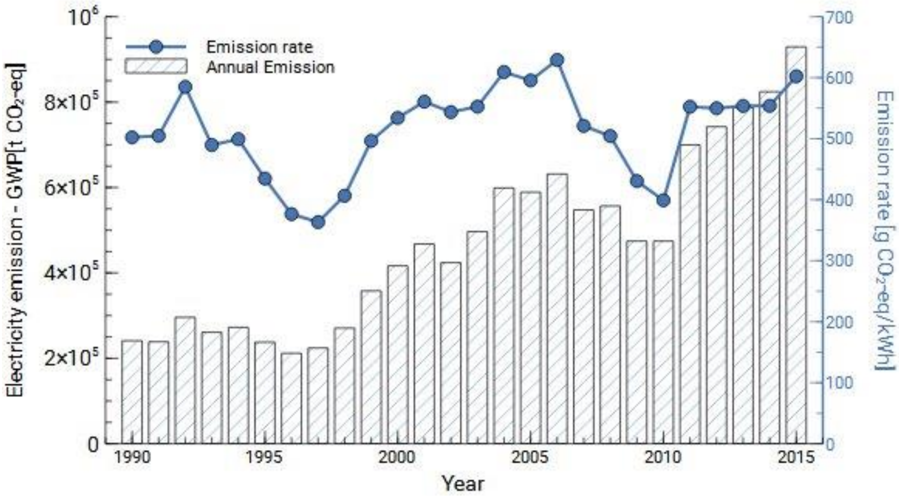

Figure 3. Evolution of total CO_2-eq emissions and emission rate per kilowatt-hour due to electricity sector between 1990-2015

The electrical emission rate value in 2015 equals 602 g CO_2-eq/kWh, which represents a 20% increase over 25 years. This assessment categorizes Madagascar, in 2015, at the lower bound of the countries with a high GHG emission rate, as classified by [43].
Regarding the total emission, according to the production growth, it can be observed that value in 2015 is equal to nearly 4 times of value in 1990 due to the high installed capacity in gasoil infrastructure. However, other parameters related to CO_2 emission are identified by Kaya's identity coupled with the LMDI presented in the following paragraph.

<u>*Decomposition analysis:*</u> Decomposition was performed using both additive and multiplicative decomposition. However, the analysis focuses mainly on the interpretation of variations in CO2 emission in terms of quantities. For this reason, only the results of additive decomposition are presented.
As outlined in the materials and method section, the decomposition analysis highlights the relation between electricity production, CO_2 emissions and the socio-economic situation in Madagascar. The results obtained are summarized in Figure 4.
Whether for annual or aggregate variations, the evolution of CO_2 emission follows the trend of variations generated by the technology of the electricity generation system. Indeed, regarding the LCA, by its formula (Equation 1) the CO_2 emission of the electricity sector is linked to the electricity mix.

However, the analysis by the combined Kaya-LMDI method shows the importance of exogenous factors on the environmental impact of the electricity sector.
On one hand, the results reveal that the increase in CO_2 emissions is mainly due to changes in the country's demographic situation, represented by the Population group. As shown in Figure 4, the trend of the population group effect and the total effect are of the same slope. On the other hand, Madagascar's economic situation in relation to its electrification rate, expressed by the Affluence group, contributes to the reduction of CO_2 emitted by the electricity sector. From 1990 to 2015, CO_2 emissions increased by +688 kt with an impact of +649 kt for the Population, -222 kt for the Affluence and +261 kt for the Technology.

In addition, as illustrated in Figure 4, the GWP variation from 1990 to 2015 can be subdivided into five periods of alternating increases and decreases (1990-1992; 1992-1997; 1997-2006; 2006-2010; 2010-2015).
The first period considered, 1990-1992, shows an increase in CO_2 emissions. This is mainly due to the Technology group, which generated an increase of 48,486 tonnes, essentially caused by an energy-mix effect of 40,059 tonnes. In addition, the positive population growth effect (+14,890 tonnes) is followed by a negative electrification rate effect (-11,743 tonnes). The population is increasing but the electrification rate is decreasing: the growth of the electrified population is therefore slight. For the impact of the Affluence group, the increase in electricity consumption followed by a decrease in GDP led to a positive energy-intensity effect. Thus, as GDP and electrification rates decline, the economic-related electrification rate effect is also declining. Nevertheless, this energy-intensity effect (ΔC_e) passes through two remarkable phases between 1990-1992: a drop of -22,684 t CO_2-eq from 1990 to 1991 followed by an increase of 25,979 t CO_2-eq between 1991 and 1992. In addition to its impacts on the country's social situation, the political crisis of 1991 strongly affected Madagascar's economic development [44]: the ΔC_e involved is -53,751 t CO_2-eq; at the end of the crisis, an economic recovery is observed, the ΔC_e rises to 49,584 t CO_2-eq.

From 1992 to 1997, the environmental impact of the electricity sector was reduced of -71,862 t CO_2-eq. Although the Population group makes a positive contribution of 88,753 t CO_2-eq, Affluence and Technology respectively had a negative effect of -48,568 t CO_2-eq and -112,047 t CO_2-eq. During this period, the population and electrification rate increased, so the number of electrified people increased, leading to a rise in the demand for electricity. However, to meet this demand, it was decided to increase hydropower generation rather than thermal generation.

For the 1997-2006, the growing trend of CO_2 emissions from the electricity sector is resuming again, reaching a total change of 407,424 t CO_2-eq with a Technology effect of 210,303 t CO_2-eq, an Affluence group effect of -21,010 t CO_2-eq and a Population group effect of 407,424 t CO_2-eq. As the population is constantly changing, the variation in CO_2 emissions follows the instability of the electricity mix and the economic situation. The same pattern applies for the 2006-2010 and 2010-2015 periods. A total decrease of -157,134 t CO_2-eq can be observed between 2006-2010 which is due to a Technology effect of -198,279 t CO_2-eq, an Affluence group effect of -67,052 t CO_2-eq and a Population group effect of 108,198 t CO_2-eq. This is followed by an upward trend for 2010-2015 with an observable peak of increase for 2011. The total variation in CO_2 emissions for 2010-2015 amounts to 454,800 t CO_2-eq with a contribution of 312,629 t CO_2-eq for the Technology, -88,354 t CO_2-eq for the Affluence and 230,525 t CO_2-eq for the Population.

In conclusion, fossil fuels are playing an increasingly important role in Madagascar's electricity mix from 1990 to 2015. As a result, CO_2 emissions increase. However, the country's socio-economic situation prevents CO_2 emissions from rising further: Madagascar is a developing country with a low GDP growth rate. As electricity consumption is correlated to GDP [45], this situation limits the country's electricity consumption and production and therefore the environmental impact of the electricity sector. Furthermore, since the electrification rate is low for the 25 years studied, population growth is not accompanied by an extension of the electricity distribution network. The interpretation of the results also revealed that the evolution of GDP in relation to the electrified population is mainly correlated with the evolution of GDP per capita. The evolution of the electrification rate did not have a significant influence on the evolution of Madagascar's level of development during the period studied.

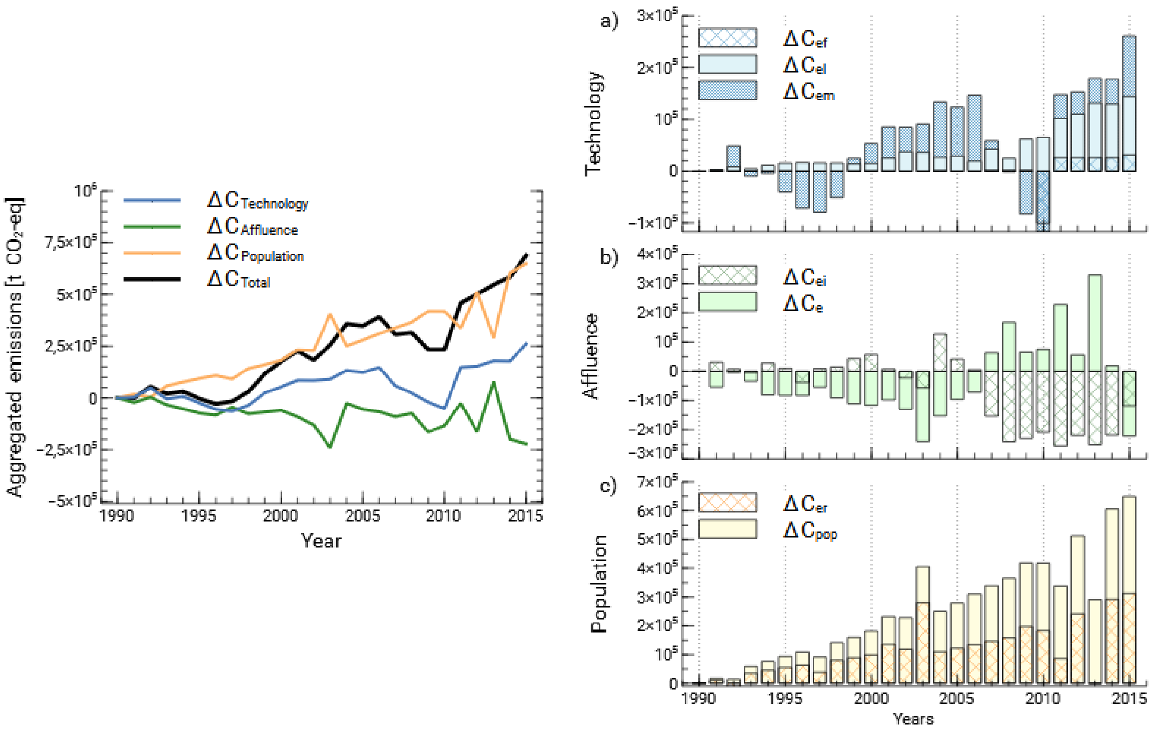

Figure 4. Additive decomposition results of the electricity-related CO_2 emissions of Madagascar, based on the reference year 1990

Energy Scenarios

<u>*Hypothesis:*</u> Based on these results and taking into account the current energy policies in Madagascar, prospective scenarios can be modelled on the basis of the qualitative and quantitative targets of energy policies. Three scenarios are therefore depicted: the BAU scenario, the NPE scenario and the IEM scenario.

The BAU scenario, also known as the reference scenario, is based on a projection of the different effects obtained by the decomposition method according to their past trend. In other words, it is a scenario without any particular intervention. The forecast is performed by extrapolating the average trend of each effect that characterizes the evolution of the CO_2 emission.

The NPE Scenario is defined by the quantitative and qualitative objectives of the new energy policy established in 2015, for the 2015-2030 period [12]. The targets set are focused on the following parameters: increasing the electricity generation, with an ambition to produce 7900 GWh by 2030, raising the country's electrification rate by up to 70% in 2030, increasing the contribution of renewable energies in 2030 (75% hydropower, 5% solar energy, 5% wind power, 15% of fossil fuels). At a middle level, in 2023, additional criteria are considered, through the performance contract presented by the Ministry of Energy and Hydrocarbons: a twofold production of electricity compared to the reference year, which we have taken as 2015 and an electrification rate of 50% [46]. The remaining parameters are based on the BAU scenario.

The IEM scenario allowed us to translate the ambitions of the Malagasy government into a scenario. The initial difficulty is that this program is currently being developed in the form of a national vision. No quantified targets have so far been proposed. Our prospective exercise focused on translating this ambition into quantitative constraints or objectives. However, it is important to note that the President Andry Rajoelina's initial objective have been adjusted from five to ten years. This choice is a direct result of the exploratory analysis of data from developing and emerging countries. This hypothesis will be discussed in the results section.

We have thus selected some parameters that make it possible to characterize the current socio-economic situation of a country. We have then selected a list of developing and emerging countries. Our methodology, therefore, consists in classifying these countries first, identifying the group to which Madagascar belongs, then seeing to which cluster the country would be most likely to migrate over time. Thus, it is the characteristics of the paragon of the cluster that will be attributed to Madagascar by 2030.

The technique proposed in this paper is the one initially used by Lebart et al. [47]. This exploratory data analysis approach will combine on the one hand the principal component analysis that allows us to synthesize the information contained in a data set. Then, besides, an ascending hierarchical classification is performed, the partition of which is optimized by the K-means algorithm. The assumptions of the IEM scenario take into account the increase in three main elements: population, electrification rate, and energy intensity. Regarding the electrification rate, the evolution is similar to that of the NPE from 2019 to 2023. However, this rate will not exceed 60% by 2030. The analysis of clusters defines the evolution of energy intensity.

Scenarios discussion: The driving factors in the three scenarios, including electricity consumption, are calculated based on the previous assumptions. As seen in Figure 5, the BAU scenario estimates electricity consumption at 1372 GWh by 2030, taking into account the trend observed over the period 1990-2015. These results confirm that the consideration of a BAU scenario over the long term cannot reflect the evolution of electricity demand. Indeed, according to the data observed in 2017 by JIRAMA, electricity consumption already reaches 1.146 TWh [48] compared to 1.027 TWh for the BAU projection. So, noteworthy, the importance of the BAU scenario is that it serves as a basis for comparing and interpreting scenarios established in terms of political ambitions.

The NPE scenario projects an electricity consumption of 6193 GWh by 2030. The NPE electricity consumption projection focuses on the importance given to the exponential increase in the number of subscribers due to the electrification improvement objectives. As population and economic growth are at the same level as those of the BAU, the increasing electrification rate to 70% raises electricity demand to 4.5 times higher than that of the BAU scenario.

For the IEM Scenario, the initial dataset of 75 countries and 9 variables (one of which is qualitative) was reduced to 72. Indeed, the particular cases of India, China and Russia were removed because their situation and projection did not allow a good observation of the rest of the data sample. Details of the variables used in this analysis are provided in Table 3. Three categories are also added as a qualitative parameter: UM, LM, L respectively for Upper medium, Lower medium, low country.

Table 3. Summary of variables used for PCA based clustering

Variables	Unity	Designation
Country		72 countries designed by iso-code alpha 3
HDI	[-]	Human Development Index
POP	[-]	Population, in the base year of 2016
GDP.CAP	[$/capita]	Gross domestic product per capita, 2016
ELEC.Sh	[%]	Electrification rate, 2016
ELEC.CONS	[kWh/capita]	Electricity consumption per capita, 2014
CO2.ELEC	[kt CO_2]	CO_2 emissions due to electricity production, 2014
H.FI	[-]	Human Freedom Index, 2016
Eco.FI	[-]	Economic Freedom Index, 2016
Perso.FI	[-]	Personal Freedom Index, 2016
Category	[-]	Classification of countries by income , 2016: L : Low income/ LM : Lower middle income/ UM : Upper middle income

As shown, in Figure 5, the classification made on individuals reveals 3 clusters. Each country is represented on the graph by its ISO alpha-3 code. Madagascar belongs according to the 2016 indicators to Cluster 1 in green (MDG at the bottom left of the figure), given the position of the barycenters of each cluster, a migration to Cluster 3 seems to be the most likely. The cluster 1 is made of individuals such as ETH, HTI, MMR, NER and YEM. This group is mainly characterized by low value for all the freedom index. Low values characterize the cluster for a large number of variables. Electricity consumption per capita is around 250 kWh in the category compared to an overall mean of all countries of around 1517 kWh. The observation is the same for the electrification rate, which does not exceed 52% compared to 81% of the overall mean. Also, it can be noted that Madagascar is still far from the mean trend of Cluster 1: the country barely reaches 42 kWh of electricity per capita for an electrification rate not exceeding 16%. This clearly indicates that Madagascar's fundamental transformations in this scenario, even if ambitious, will not change its cluster in the first place. Instead, it will be a matter of getting closer to the average trends of Cluster 1. The cluster 3 made of individuals such as BGR, CRI, HRV, MUS, MNE and ROM. This group is characterized by:

- high values for the variables H.FI, Eco.FI, HDI, Perso.FI, ELEC.Sh, GDP.CAP and ELEC.CONS (variables are sorted from the strongest).
- low values for the variables CO2.ELEC and POP (variables are sorted from the weakest).

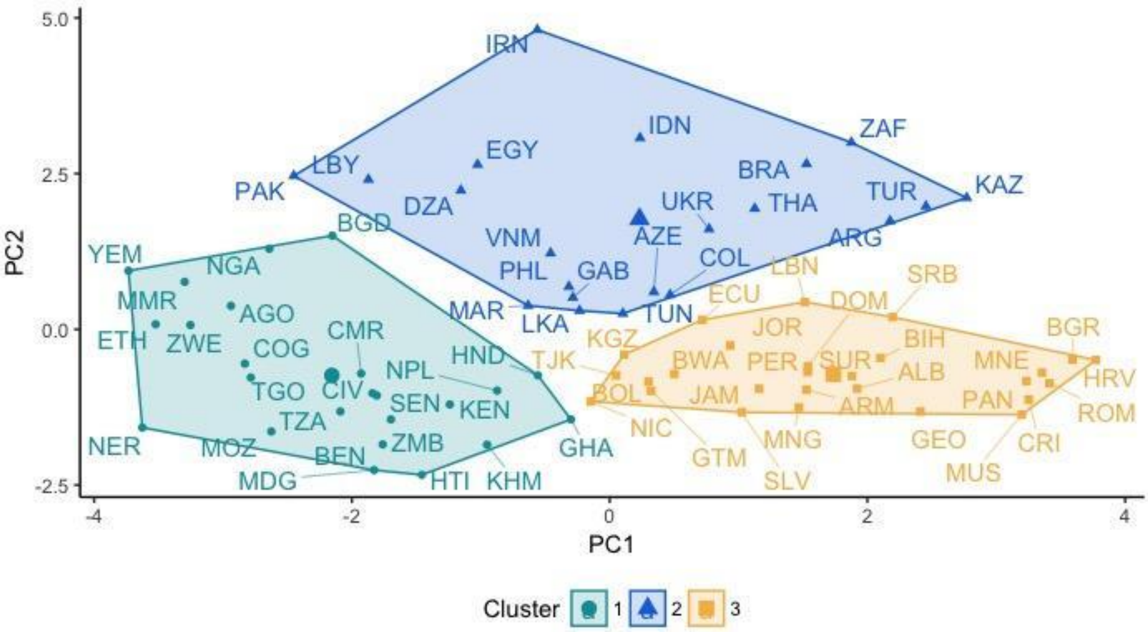

Figure 5. Hierarchical clustering projected on first two components.

The paragon of cluster 3 is Dominica. That means that if Madagascar's evolution tends towards group 3, the country's common characteristics would be closer to those of Dominica. Thus, the characteristics of the latter in terms of electrification and energy intensity have been taken as an objective for 2030. The cluster 2 is not considered for the scenario as it is mainly defined by high values for energy and economic development. And it has low value for all the freedom index. The choice to limit the increase in the electrification rate to 10% over the period 2023-2030 is enlightened by the analysis of the data from the cluster 3 countries. Indeed, most of the countries in this group have experienced an improvement in the electrification of their territory over the past twenty years. However, this rate never exceeds 10% per 10-year period. As shown in Figure 6, the ambitions of the IEM scenario are reflected in an increase in the logarithmic trajectory of electricity demand that differs significantly from the other two scenarios (NPE and BAU). Indeed, we can see that the consumption in this case if it amounts to nearly 54.7 TWh which is almost thirty-three times higher than the consumption obtained in the NPE scenario. Although the needs obtained seem exorbitant given current values, the territory has a hydroelectric power generation capacity of around 180,000 GWh according to recent prospecting studies. The question is, therefore, about proposing a financial engineering plan which aims at establishing a closer link-up between public and private financing to encourage the development of renewables power plant on the territory. According to the country's observations over the last twenty years, this issue of financing and securing electricity production is the major challenge for Madagascar's economic development for the next years.

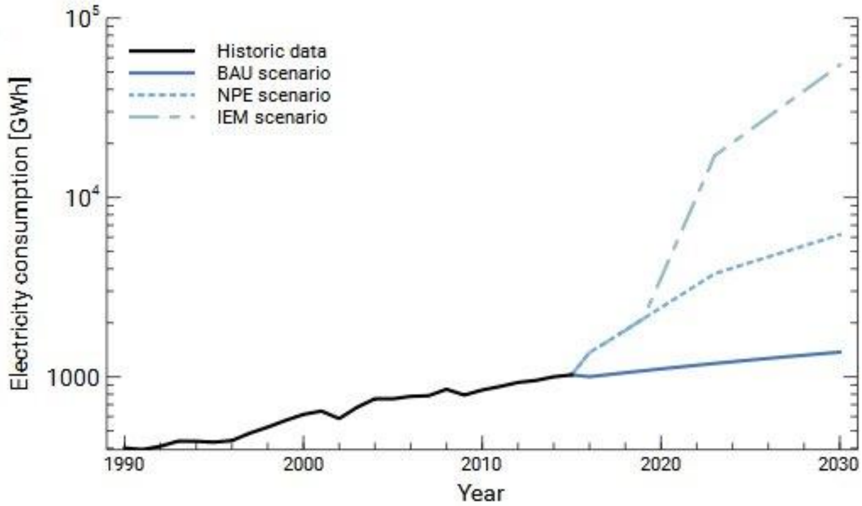

Figure 6. Electricity consumption results from the BAU, NPE and IEM scenarios

The evaluation of the CO_2 emission from the Malagasy electricity sector for the period 2015-2030 is then carried out by the combined Kaya-LMDI method (Table 2). Figure 7 shows the CO_2 emissions of electricity production in Madagascar under the BAU and NPE scenarios. In the BAU scenario, the aggregated CO_2 emissions predicted to be 899,243 t CO_2-eq, based at the year 1990, representing a 54% increase over 2014 and a 31% over 2015. The electrical emission rate value in 2030 equals 440 g CO_2-eq/kWh, representing a 27% decrease compared to 2015. This reduction is a consequence of considering the average trend of the last 25 years: the year 2015 shows a peak in CO_2 emission which, according to the BAU scenario, reaches the average trend from 2016 onwards, which leads to a reduction in CO_2 emission. The Population group and the Technology group effects increase by 834,842 t CO_2-eq and 257,584 t CO_2-eq respectively, whereas, the Affluence group effect decreases CO_2 emissions by -193,174 t CO_2-eq. This is an extension of the past situation: population growth and the electricity mix favour an increase in CO_2 emissions while the effect of the electrification rate and the level of development reduce it.

The CO_2 emissions in the NPE scenario are considerably higher than that in the BAU scenario. The total aggregated emissions value reaches 1,677 kt CO_2-eq, based at the year 1990. This is mainly due to a positive Population group effect of 2,900 kt CO_2-eq and a negative Technology effect of -1,134 kt CO_2-eq. However, the NPE scenario estimates the electrical emission rate value at 242 g CO_2-eq/kWh by 2030. These results support those resulting from the breakdown of the NPE scenario for 2015-2030: the Malagasy government's energy policy, which promotes the use of renewable energies, has reduced the CO_2 emission factor to 45% less than the BAU scenario. The NPE is therefore achieving the emission factor reduction targets set at COP21 [13].

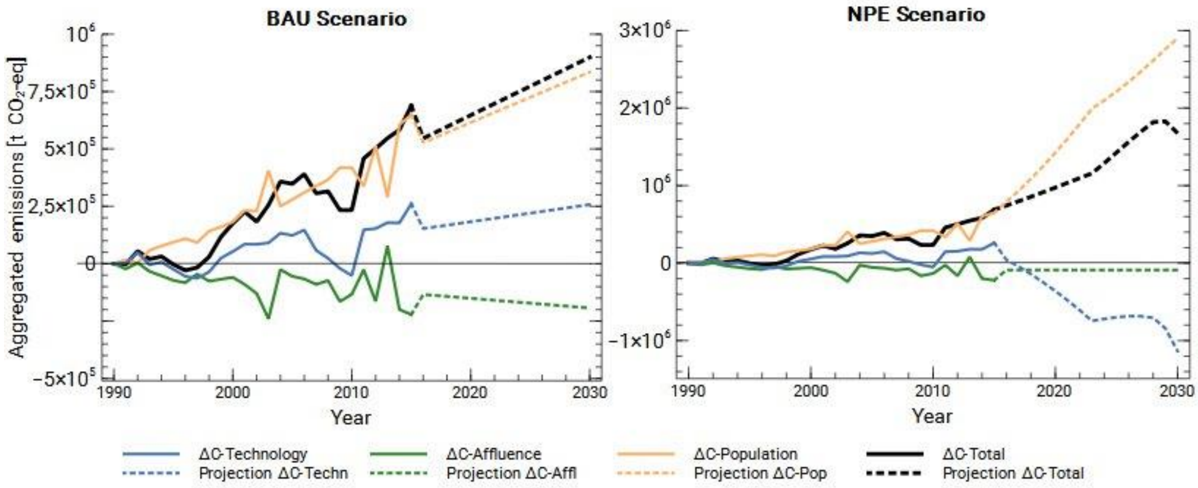

Figure 7. Decomposition of BAU and NPE scenarios

Exploring Political disruption

Based on the hypothesis and results of the NPE and IEM scenario, Madagascar's economy should improve and reach the status of emerging countries within the middle term scenario.
As stated before, energy consumption and GDP nexus in Madagascar has been established in literature [45]. However, several researches have reported the relevance of political stability on economic growth. [49] studied a panel of Middle East and North African region, in order to analyze the parameters that influence economic growth. It has been shown that tourism and energy consumption have positive influence in economic growth, whereas political instability impedes the economic and development growth. Authors in [50] have used ARCH and GARCH model to examine the political uncertainty on the economic growth with parameters as election, regime and strikes. They conclude that the short-term change in the political targets of a territory demonstrates political instability. Authors in [51] studied the transition period of 10 CEE countries, and have stated that the causal dependence between economic growth and political instability is unidirectional, from political instability to growth rate. Effects of political instability has been examined by [52], in order to identify the key drivers from political instability to economic growth. The variables included amongst others trade, the economic freedom index, GDP per capita, and polity scale. As known, Madagascar has also witnessed some political instability in 1992, 2002 and 2009. The outcomes in this study provide the basis for studying the impacts of political instability on economic growth. However, it can already be observed that the periods of strikes mentioned above in the country have an impact on electricity consumption, which is marked by shifts in consumption Figure 1.b. Over the past 30 years, Madagascar has been the scene of three "coups d'état" in 1992, 2002 and 2009. These instabilities have a substantial impact on the economy. As shown in Figure 1-b, for the three years concerned, the impact on GDP growth is well illustrated. This effect is also sharply observed in electricity consumption. The decrease in consumption is very pronounced. This change is particularly significant for small and medium-sized enterprises.

CONCLUSION

The economic growth of developing countries must meet a dual challenge of transforming and implementing change while securing the transition. These changes concern an increase in electricity demand and, at the same time, the control of CO_2 emissions. Embarking on the path of the energy transition is today an essential step in the emergence of Madagascar's territory. The present work used a combined Kaya – LMDI method to decompose Madagascar's electricity consumption from 1990 to 2015. It is well known that electricity generation is a significant component of GHG emissions. At the end of this first stage, this enabled us to define three energy scenarios, two of which are directly inspired by national strategies.

The LCA approach allows identifying the CO_2 emissions level through the studied period. This study focused on GWP but over indicators can be decomposed. The decomposition of electricity consumption highlights that the increase in CO_2 emissions is mainly due to the increase of the share of fossil fuels in the electricity mix and population growth. Madagascar's socio-economic situation, characterized by a low electrification rate and a low level of development, prevents CO_2 emissions from increasing further. Between 1990 and 2015, GDP did not increase at a constant rate. This period is systematically marked by declines in growth due to political crises. The decomposition shows the impact of the percentage of the population electrified on these emissions. This result is particularly crucial given national ambitions to increase access to electricity from 16 to 50% by 2030. The constancy of the population's energy intensity means that the increase in CO_2 emissions can be explained more by an increasingly carbon-intensive electricity mix. In 2017, for the first time in its history, electricity production depended more on fossil fuels than on renewable resources. The prospective approach allowed us to define three scenarios.

The NPE scenario estimates a CO_2 emissions variation of 1,677 kt CO_2-eq by 2030, which is about twice the BAU scenario. Increasing the electrification rate to 70% has considerably increased the total CO_2 emission. However, the NPE scenario estimates the electrical emission rate value at 242 g CO_2-eq/kWh by 2030, 45% less than the BAU scenario, which is the result of an electricity mix dominated by renewable energies. The results of the IEM scenario, which corresponds to the most ambitious vision, highlight an energy requirement that takes on very high values until it reaches more than 54 TWh. This highlights the difficulty of achieving the target over a period as long as 2019-2023. To sum up, the Malagasy economy must initiate its transition to a better energy-efficiency status and reduce its import of fossil fuels for electricity generation. At the same time, increasing access to electricity requires that we consider controlling household energy intensity in order to mitigate the increase in total electricity production.

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NOMENCLATURE

BAU	Business-As-Usual
C	Emission value from
C_e	Economic-related electrification rate effect
C_{ef}	Emission factor effect
C_{ei}	Energy-intensity effect
C_{el}	Energy-loss effect
C_{em}	Energy-mix effect
C_{er}	Electrification rate effect
CO2.ELEC	CO2 emissions due to electricity production
C_{pop}	Population effect
Eco.FI,	Economic Freedom Index
EF	Emission factor of each technology
ELEC.CONS	Electricity consumption
ELEC.Sh,	Electrification rate
FF	Electricity production
GDP.CAP	Gross domestic product per capita
H.FI	Human Freedom Index
HDI,	Human Development Index
i	Production technology
IEM	Initiative Emergence Madagascar
k	Life cycle stage
LCA	Life cycle assessment
NPE	*Nouvelle politique énergétique* New energy policy
Perso.FI,	Personal Freedom Index
POP	Population

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