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ENVIRONMENTAL SUSTAINABILITY OF ELECTRICITY GENERATION UNDER INSULAR CONTEXT: AN LCA-BASED SCENARIO FOR MADAGASCAR AND REUNION ISLAND BY 2050

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ABSTRACT

Considering environmental impact as constraint in energy planning and sustainable policy has gained in importance over the past two decades. Electricity is currently a key contributor to greenhouse gases emissions. These impacts are particularly significant in the case of remote islands due to the share of fossil fuel in electricity mix. This paper aims to first provide a clearer understanding of the electricity situation Madagascar and Reunion Island. Then a detailed evaluation of their environmental impacts through the Life Cycle Assessment (LCA) approach. The GWP of the electricity mix is respectively estimated for Madagascar and Reunion Island at 464 and 673 g CO2-eq/kWh. Scenario based on renewable energy sources development on these islands has been investigated to define a road map to 2050, for a greener and cleaner electricity generation. The analysis is conducted to help policymakers in defining a framework for gradually change the fossil fuel power plants from now to renewables in 2050

Keywords- LCA, Electricity, Energy scenario, Reunion Island, Madagascar

1. INTRODUCTION

Because of their geographical isolation, it is well known that islands have a high dependence to fossil fuel for their energy requirements. One of the main characteristic of these remote territories is an electricity production that still rely heavily on carbon-based sources. This electricity mix highlights an energy vulnerability to exogenous instabilities on the international market. This high share of fossil fuel lead to the electricity price volatility, [1] and is the main contributor to the global emissions of greenhouses gases, [2] [3] [4]. Nonetheless, these territories are generally endowed with high potential for renewable energy sources (RES). Madagascar has proposed during the COP21 conference an ambitious objective of 14% reduction of GHG by 2020. To achieve this, the government expects international assistance for development of RES for electricity generation. As Reunion island is a French overseas territory, is committed with Europe to reduce its emissions by 40% by 2030. Madagascar and Reunion, two islands located in Indian Ocean, were chosen because of their socio-economic differences and common issues:

- Demographic transition incomplete
- Different poverty rate
- High dependence to fossil fuels
- Ambition to increase RES share

In the last decades, ISO 14040 from Life Cycle Assessment (LCA) guidelines has been widely used to evaluate environmental impact of energy production. The objective of this paper is to provide an LCA-based approach to evaluate future plausible energy scenarios under insular context. This study first presents the electricity mix for the two islands.

2. ELECTIRCITY OVERWIEW

2.1. Case of Madagascar

According to the Ministry of Energy of Madagascar (MEM), the total energy demand through Madagascar is essentially provided by wood energy (92%), and fossil fuels (7%) [5]. Other renewable energies, besides the wood energy, composed only about 1% of this demand and are mainly constituted by hydropower. These values refer to electricity, transport and heat consumption. Referring to the Ordinance No. 74-002 of February 4th, 1974 on the

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International Journal of Engineering Researches and Management Studies

orientation of water and electricity policy, the government has the exclusive right to intervene on the electricity sector. Since 1975, this right has been conferred to the national so-city JIRAMA or Jiro sy Rano Malagasy (Electricity and Water provider of Madagascar), including the exploitation of production, transport and distribution electricity installations through the country. How-ever, activities reporting to electricity have been liberalized by the Act No.98-032 on January 20th, 1999 based on the electricity sector reform. It is based on the following principles: a vertical disintegration of the electricity activities and the implementation of a regulatory agency. The rural electrification will be carried out by private sector, with the support of an autonomous agency, the ADER or Rural Electrification Development Agency. Despite of the competitiveness insertion, JIRAMA remained to be the first electricity production provider almost in its entirety. For this study, the data considered is based only on JIRAMA's statistic, due to the lack of information on rural electrification.

Figure 1 represented the evolution of the electricity production in Madagascar between 2002 and 2012 [6][7], and shows an average annual increase of 5.61%, which means a growth of 71% in ten years, all technology considered.Madagascar's electricity mix depends essentially of hydroelectric production 56.56% and thermic production represented 43.43%. Electricity generation includes also photovoltaic (PV) system, but it represented below 1% and was integrated only since 2006 [6]. Electricity production based on fossil fuels has increased of an average annual growth rate of 9.79%. On another side, hydraulic production kept his growth on average of 3.69% per year.

Hydroelectric power plants are mainly located in the highlands; the interconnected network of Antananarivo records the maximum power on 112 MW, 87.8% of the total power in 2012 [6].

Thermal power plants operating in the national electricity network are divided between 41.6% of diesel steam turbine using heavy fuel oil and 58.4% of combustion turbine engine fueled with diesel [6]. Madagascar imports all the petroleum requirements, including heavy fuel oil and diesel necessary for electricity production. Refined oil products are usually delivered to the port of Toamasina, and are spread out the island by different conveyance system, by seaway or by land [5]. These products are mainly imported from South Africa. This study considers the port-to-port distance, which is equal to 3883 km.

The unique solar PV system in the JIRAMA production network is located in the southern region of Madagascar, a favorable region for the solar radiation concentration. However, the power granted by this system does not exceed 7 kW [6].

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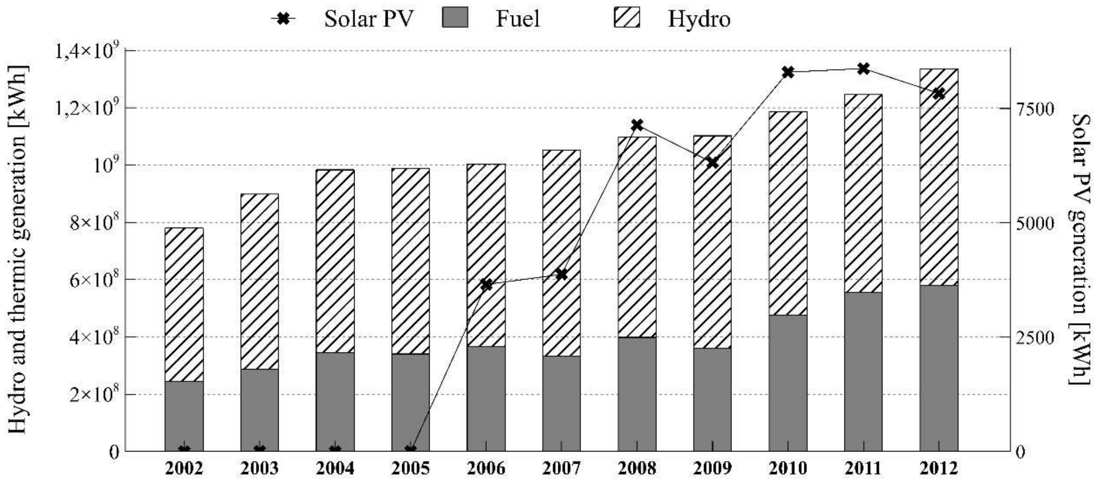

Figure 1 : Overview of the electricity production in Madagascar (2002-2012)

2.2. Case of Reunion Island

In Reunion Island, the energy supply for heat, transport and electricity dominated by fossil fuels 88.4%, and the rest is provided by renewable energies. The electricity generation in Reunion Island is mainly produced by the EDF or French Electricity Provider, besides the other partners as independent partners.

Figure 2 [8] shows the evolution of electricity mix of Reunion, since 2002 to 2015. In 2012, coal energy is leading the electric mix with 48%, renewable energies gathered represented 34.4% and the rest is occupied by heavy oil and gasoil. The contribution of coal energy increased from 32.54% to 48.04% within the ten years, and at the same time the hydraulic part decreased from 30.59% to 17.41%.

In general, power plants based on fossil fuels represent 65.6% of the total Reunion's energy mix. Thermal plants are composed by 54% of combustion turbine and 46% of diesel motor. It should be also noted the contribution of the power plants combining coal and bagasse that constitute more than 48% of the mix. In fact, these power plants are fueled with bagasse during the sugar season, between mid-July and mid-December. The rest of the time, they operate with fossil coal.

Production systems powered by green energy are divided in two groups: permanent productions including hydro, bagasse plants and those exploiting biogas. Alternative production gathered wind farms and photo-voltaic grid-connected systems.

As same as Madagascar's case, it is necessary to identify the imported raw materials for electricity production, particularly coal, heavy fuel oil and diesel. The fossil products are mainly imported from Singapore and Malta, whose distance from Reunion equals respectively 9500 km and 7000 km, but also from South Africa.

This study considers year 2012 as the base year of the comparison of the life cycle environmental impacts of electricity generation between Madagascar and Reunion Island.

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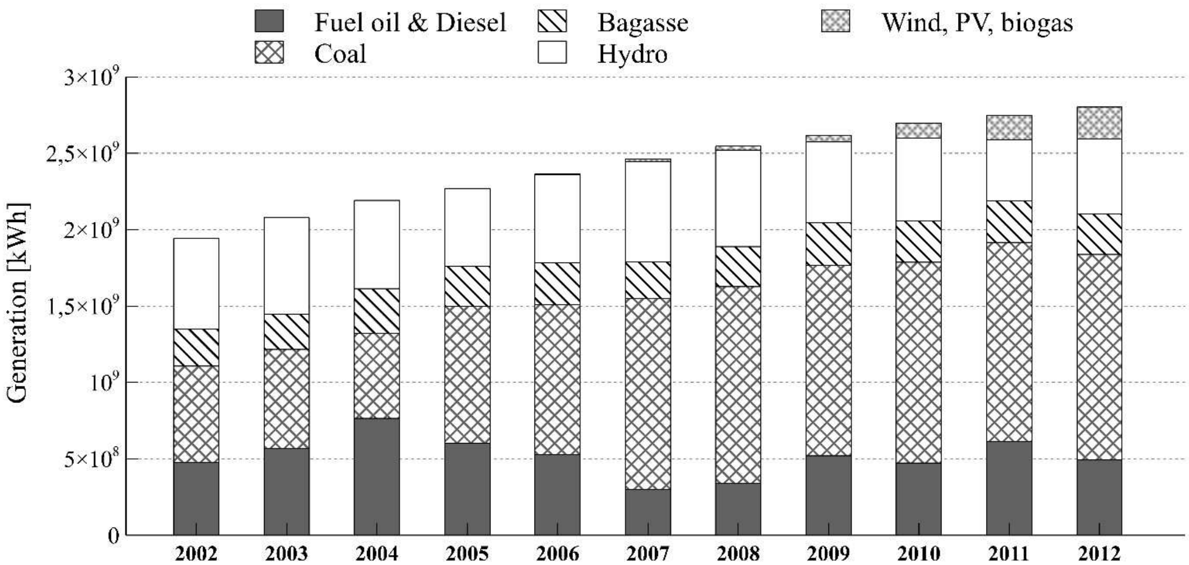

Figure 2: Overview of the electricity production in Reunion Island (2002-2012)

3. METHODOLOGY

This study follows the different guidelines described by the International Standard [9] [10]. The methodology intends to estimate the total amount of the greenhouse gases (GHG) emissions, through electricity generation in Madagascar and Reunion Island. The LCA software GEMIS [11] is used to estimate these emissions.

3.1. Goal and scope of the study

This study aims to compare and to identify the potential life cycle environmental impacts of the electricity generation mix of Madagascar and Reunion, in the public sector during the year 2012. The impacts of the annual electricity generated and per kilowatt-hour produced are both calculated, to compare the results with other countries in the next sections.

The system boundaries are from 'cradle to gate', which means that network losses are not taken into account. Based on the data collected, the different stages considered are the raw materials acquisition and their transformation into directly usable energy, the transport of these products to the islands, and the production operation for the electricity generation.

3.2. Database of LCA

3.2.1. Database of Madagascar

For Madagascar, the data are based only on the statistic collected by JIRAMA, due to the lack of information about the private partners' production and the rural electrification. It is essentially about the total production generated, production from fuels and from renewable resources as hydro and solar power, as outlined in Table 1.

3.2.2. Database of Reunion Island

In another hand, for Reunion Island, the data collected by ARER [8] is composed of the total electricity produced by renewable and fossil resources. Table 1 lists also the different technologies used in Reunion for electricity

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generation. Considering the power plant efficiency, type of fuel and technology, the GEMIS database has been used to estimate the direct emissions from operation power plant.

Table 1 : Overview of the power plant technologies used in Madagascar and Reunion Island for electricity generation in 2012 [6] [8] [12]

Power plant technology	Generation (GWh)	Total capacity (MW)
Madagascar		
Hydropower	755	127.7
Fuel oil ST	241	201.9
Diesel CE	339	143.6
PV system	0.008	0.007
Total	1335	473.2
Reunion Island		
Hydropower	488	133.4
Wind	18.2	16.5
Biogas	0.96	2.9
PV system	190.4	152
Bagasse ST	267.1	210
Coal ST	1346.3	210
Fuel oil ST	491.4	120
Diesel CE		177.2
Total	2802.36	210

3.3. Assumptions

Regarding to the life cycle of the electricity generation in Madagascar as shown in Figure 3, the processes selected into the GEMIS database reflected the Malagasy conditions in operation power plant, from cradle to gate. Using the LCA software GEMIS, some parameters have been considered in the estimation of the potential impacts:

- power plant infrastructures, which have been included directly by GEMIS
- transport,
- residues have not been considered in the estimation,
- calculation referred to the low heat value.

Reflecting Malagasy conditions and their efficiencies, the different power plants have been classified as the following suggestions in order to compare with GEMIS processes:

- the oil power plants have been divided between fuel oil steam turbine and diesel combustible engine, of which technology have been divided as 18.1% of dieselmotor-small-generic, 18.9% of dieselmotor-medium-generic, 21.4% of dieselmotor-big-generic and 41.6% of oil-heavy-ST-small-generic;

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- hydroelectric power combined 54.56% of hydro-dam-mini-generic and 45.44% of hydro-dam-medium-generic;
- the solar photovoltaic system has been considered as solar process used in Algeria, because both countries presented the same solar radiation per square meter.
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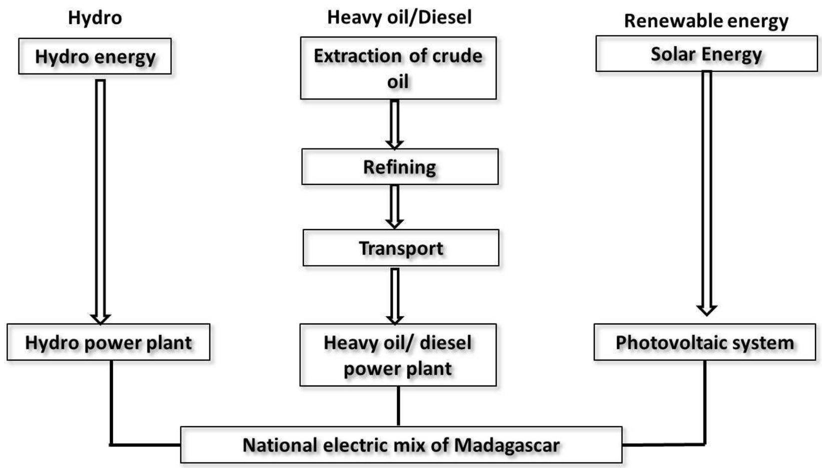

Figure 3: Life cycle of electricity mix generation in Madagascar

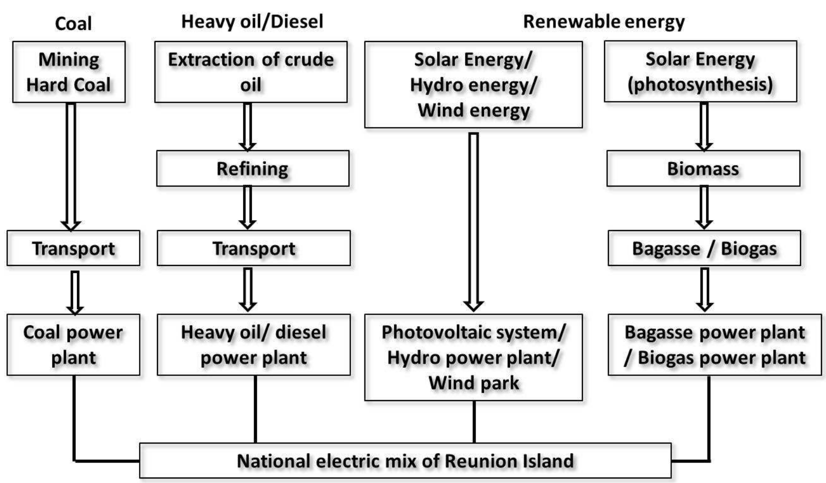

Figure 4: Life cycle of electricity mix generation in Reunion Island

On another hand, Figure 4 represents life cycle of the fossil fuel technologies in the electric mix of Reunion Island. Renewable sources, as hydraulic, wind and solar energy are gathered together because their process shaft are similar. Proceeding in the same way as Madagascar's case and considering that Reunion Island operates power plants of the same type as the developed countries, Reunion's processes will be assimilated to French facilities in GEMIS, in most of case:

– Hydropower plants in Reunion are the type of "run of river", considered as 60% of hydro-ROR-big-FR-2000 and 40% of hydro-ROR-small-DE-2000.

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- Heavy oil and diesel power plant have been divided into two parts: 54% of dieselmotor-big-generic and 46% of oil-heavy-ST-FR-2000.
- Coal-ST-FR-import-2010 is the corresponding process for coal power plant that had been considered.
- Bagasse-ST-BR-2010 is the only process including the raw material bagasse.
- According to their efficiencies, here are the corresponding processes for the rest of the power plants: windpark-big-DE-2010 biogas-dieselmotor-generic-small-2000, and solar-PV-multi-framed-with-rack-DE-2010.

To note that power plant processes that do not have their corresponding in French facilities are replaced by other processes in GEMIS, generic or from other developed countries.

The following results involve the products transport, as mentioned before. The metadata of the processes including coal, heavy oil and petrol in the electricity production have been revised and data on Table 2 have been integrated in the green house gases (GHG) estimation of electricity production.

Table 2: Amount of the fuels used for electricity generation in 2012 for Madagascar and Reunion Island

	Quantity (t)		Distance (km)	
	Madagascar	Reunion	Madagascar	Reunion
Heavy oil	72 570	77 176	3 883	9500
Diesel	58 083	399 192	3 883	7000
Coal	-	659 100	-	10471

4. LCA RESULTS AND DISCUSSION

4.1. Environmental burdens

According to the GEMIS software, different types of results can be highlighted as GHG emissions, air emissions, solid wastes, water emissions, operating resources. Table 3 fixes the different gases included in GHG emissions and the gases contributing to acidification in the GEMIS results that will be considered and discussed in the next paragraphs. Figure e and Figure f shows the results of the different emissions generated by electric production in Madagascar and Reunion Island, respectively for the GHG and air emissions.

Figure 5 and Figure 6 show the results of the different emissions generated by electric production in Madagascar and Reunion Island, respectively for the GHG and air emissions. Values on Table 8 (see on Appendix A) summarized the emissions values from the different life cycle power plants, per kWh electric. They were all, on the whole, in range of the emissions order found in literature [4], especially for the SO_2 and NO_x emissions.

Table 3: Life cycle impact categories defined by GEMIS

Emissions type	Emissions included by GEMIS	Potential impact	Unit
GHG emission	CO_2, CH_4, N_2O, CF_4, perfluorinated ethane	Global warming potential	g CO_2-eq
Air emission	NO_2, SO_2, HCl, HF, NH_2, H_2S	Acidification potential	g SO_2-eq

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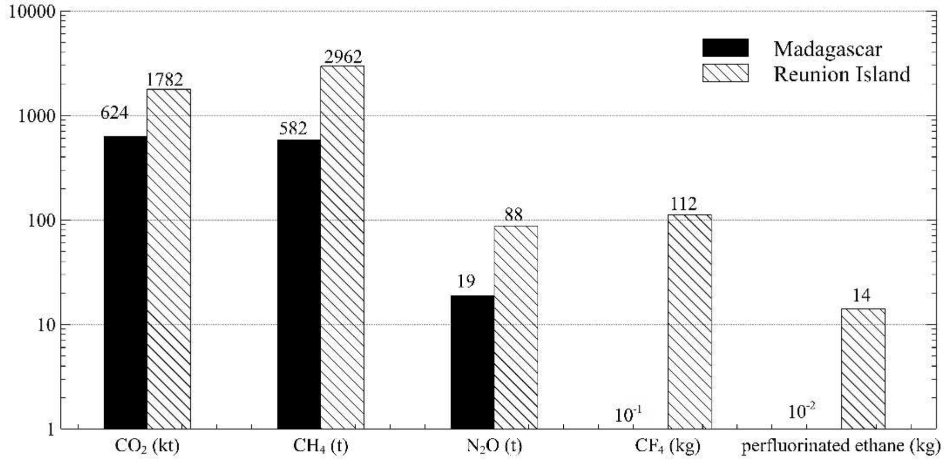

Figure 5 : Comparison of the GHG emissions from life cycle of electricity mix generation in 2012

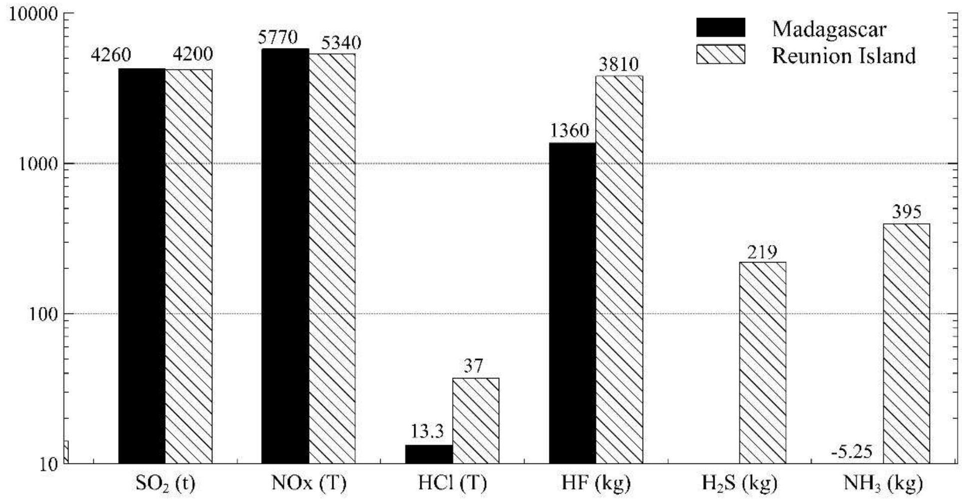

Figure 6 Comparison of the air emissions from life cycle of electricity generation in 2012

As can be seen on figure 5 and figure 6, among the GHG emissions, CO_2, CH_4 and N_2O produce the highest emissions quantity, and SO_2 and NO_x for the air emission. Those results will be discussed in the following. Based on Table 4 are due to the fossil energy production, as 59.9% to the diesel production, 36.8% to the heavy oil production and only 3.3% to the renewable energies in Madagascar. Diesel motor engine has the highest results on CO_2, CH_4, NO_2 and NO_x emissions (respectively 360 kt, 343 t, 9.85 t and 4332 t), followed by heavy oil results (221 kt of CO_2, 194 t of CH_4, 7.90 t of N_2O and 664 t of NO_x). Heavy oil steam turbine has the highest SO_2 rate with 11.08 g/kWh, so the total emission of SO_2 amount to 2 672 t and represented about 64% of the total emission. In another hand, renewable energies production represented only 0.2% of the SO_2 emissions. For the NO_x emissions, 86% of the total emissions are due to diesel motor production.

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For Reunion, 64% of the total emissions are attributed to coal steam turbine production: 74% of CO_2 (1321 kt), 89% of CH_4 (2646 t), 78% of N_2O (68 t), 40% of SO_2 (1752 t) and 49% of NO_x (4006 t). The second main contributor is heavy oil combined to Diesel motor production, and renewable energies occupied only less than 1% of the total emission of GHG. Emissions from renewable energies are mainly imputed to the construction of the power plant.

Table 4: Total amount of emissions by power plant categories for Madagascar and Reunion Island

Technology		Emissions				
		CO_2 (kt)	CH_4 (t)	N_2O (t)	SO_2 (t)	NO_x (t)
Renewable energy	MDG	19.63	21.86	0.43	6.83	42.32
	RUN	27.49	68.17	5.48	366.35	1 484.24
Diesel	MDG	360.27	343.39	9.85	1500.57	4332.22
	RUN	240.67	228.61	6.56	1018.63	2308.45
Heavy oil	MDG	221.39	194.17	7.90	2672.52	663.73
	RUN	194.30	44.80	7.31	1202.94	417.12
Coal	RUN	1321.24	2646.14	68.09	1752.97	4006.57
Total	MDG	601.29	559.42	18.18	4179.92	5038.27
	RUN	1783.71	2987.72	87.43	4340.89	8216.38

4.2. Interpretation of impact assessment

The life cycle impact assessment is an important phase of the LCA methodology; it aims to classify the potential environmental impacts. The results summarized in Table 5 and in the Figure 7 will be discussed in the next paragraphs.

Table5 : Total environmental impacts per country in 2012

Technology	GWP (kt CO_2-eq)		AP (t SO_2-eq)	
	MDG	RUN	MDG	RUN
Renewable energy	20.30	31.80	36.41	1401.55
Dieselmotor engine	371.79	248.34	4525.23	2631.44
Heavy oil ST	228.60	197.60	3139.47	1493.72
Coal ST	-	1407.72	-	4564.84
Total	620.70	1885.45	7701.11	10091.55

GWP: Global warming potential; AP: Acidification potential

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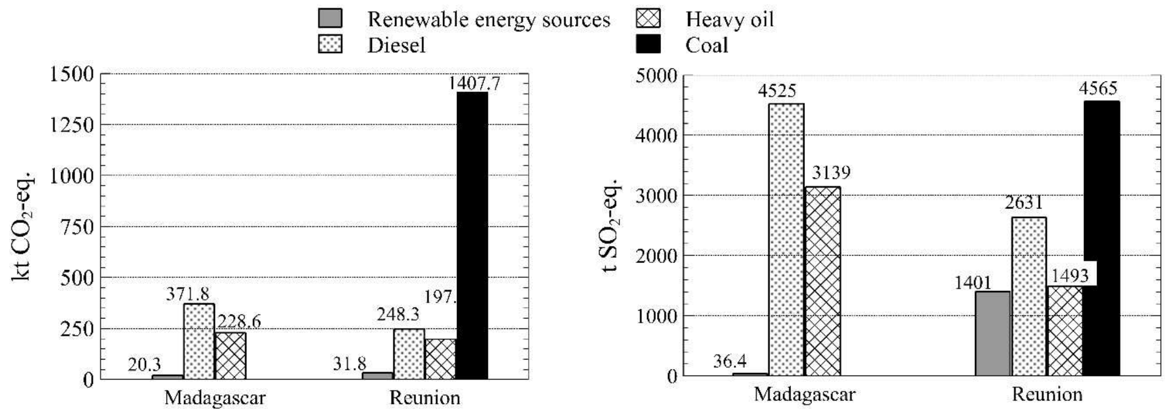

Figure 7: Impacts expressed on GWP and AP, generated by electric mix in Madagascar and Reunion Island in 2012

4.2.1. Global warming potential (GWP)

The GWP includes the main GHG emissions as CO_2, CH_4 or N_2O. For this study, the GEMIS software has also calculated this GWP generated by electricity production. The GWP reported values in GEMIS database are in the range of the emissions order in the literature [4]. During the year 2012, Madagascar recorded 621 kt CO_2-eq all technologies combined, 97% are imputed to thermal power plants. According to these results, Madagascar has an emission factor of 464.8 g CO_2-eq/kWh (by dividing the total of GWP by the amount of electricity production in 2012).

On the other part, Reunion Island has an emission factor of 673 g CO_2-eq/kWh, result that is not far of the value of the ARER report [8]. The results of this study indicate a total emission of 1885 kt CO_2-eq in 2012, results that differs by 7% compared to the ARER's results which calculated a total emission based on electricity production of 2033 kt CO2-eq [8].

Comparing the values, 60% of the total emissions of CO_2-eq for Madagascar are imputed to electricity generation from fossil fuels (dieselmotor production) against 13% for Reunion Island, whose coal generation is responsible of 75% of the total emissions.

The total GWP from electricity generation in Madagascar is estimated at about 33% of the Reunion's emissions (Table 5). Regardless coal generation, Madagascar and Reunion Island's emissions are quite similar, even if emissions based on dieselmotor and heavy oil production of Madagascar is higher of 39% than Reunion's results.

4.2.2. Acidification potential (AP)

It can be observed in Table 5 that 59% of the total amount of SO_2-eq emissions in Madagascar is imputed to power plants based on diesel generation and the rest is allocated to heavy fuel oil production. The NOx emissions contributed mainly to this high rate.

In Reunion Island, renewable energies occupied 14% of the emissions, which implies a majority part of the fossil energies with 45% by coal generation, 26.1% diesel production and 14.8% by heavy oil production. As can be seen on the GWP results, Madagascar records approximately the three quarters quantity of the total SO_2-eq emissions of Reunion Island (7701 t SO_2-eq and 10091 t SO_2-eq). Reunion's emission from the heavy fuel oil production represents the half of Madagascar's (1494 t SO_2-eq and 3 139 t SO_2-eq, respectively), and the diesel production presents the same proportion as heavy fuel oil (2631 t SO_2-eq against 4525 t SO_2-eq).

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4.3. Comparison with other countries

In this section, the electric mix of Madagascar and Reunion will be compared to other countries having a close composition. The main characteristic that will be compared is the GWP generated through the electricity production. To note that the operation process considered does not integer the transport of raw materials, due to the lack of information about the other countries.

4.4. Choice and composition mix of the countries

Concerning the repartition mix, Mali and Tanzania on the year 2010 present approximately the same composition mix as Madagascar, about 42-44% of fossil fuels energies against 56-58% of renewable energies; Reunion Island's case will be compared to Japan and Mexico's mix. Mali, Tanzania and Japan are based on the GEMIS database [11], and the results for Mexico in 2006 is based on the study of E. Santoyo-Castelazo et al [13].

To note that the technologies included in the repartition mix are not exactly the same but the study has focused on these countries due to the global repartition between fossil energies and renewable energies, as can be seen on Table 6.

Table 6 : Comparison of environmental impacts [5] [8] [11] [13]

Energy source	Electricity mix (%)					
	Madagascar (2012)	Reunion (2012)	Mali (2010)	Tanzania (2010)	Japan (2010)	Mexico (2006)
Fossil fuels	43.43	65.58	42	42.5	63.44	78.7
RES	56.57	34.42	58	57.5	36.56	21.3
Hydro	56.56	17.41	58	57.5	7.02	13.50
Biomass	-	-	-	-	1.98	-
Bagasse	-	9.53	-	-	-	-
Wind	-	0.65	-	-	-	0.02
Biogas	-	0.03	-	-	-	-
PV system	0.01	6.80	-	-	0.25	-
Geothermal	-	-	-	-	0.31	3
Nuclear	-	-	-	-	27	4.80
Heavy oil	18.07	9.47	12	-	10.09	21.60
Diesel	25.36	8.07	10	1	-	0.50
Coal	-	48.04	-	2.5	27.99	14
Gas	-	-	20	39	25.35	42.60
Total	100	100	100	100	100	100
GWP (g CO_2-eq/kWh)	464	673	441	309	511	571
AP (g SO_2-eq/kWh)	5.77	3.60	3.45	1.11	1.52	6.59

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4.3.1. Comparison of the GWP

With a comparable proportion of fossil energies production, Mali's CO2-eq emissions (441 g CO2-eq/kWh) are lower by 5% than Madagascar's results (464 g CO2-eq/kWh). This di□erence can be explained by the fact that the diesel production of Madagascar equals 2.5 times of Mali's production. 48% of the fossil energies of Mali's mix is based on gas production, that can also explain the di□erence between Madagascar and Mali.

About the case of Tanzania, gas-based production dominates 91% of the fossil fuels production, which is remarked on the results on CO2-eq emissions. In fact, the emission factor of Tanzania is reduced by 33% compared to those in Madagascar (309 against 464 g CO2-eq/kWh, seen on Table 6).

According to the values on Table 6, the electric mix of Japan is closest to the energy mix of Reunion Island, in overall distribution. However, it generates 24% less emission than Reunion's composition. With gas production at about 40% of the fossil generation and a coal proportion that equals the half Reunion's proportion, the CO2-eq emission generated by electric mix of Japan totals 76% compared to Reunion's result, 511.28 g CO2-eq/kWh against 673 g CO2-eq/kWh.

Compared to the Reunion's energy mix, Mexico includes 20% more on fossil energies production but the results do not reflect this di□erence. On the contrary, the GWP emissions of Mexico are lower by 15% than those of Reunion, as can be seen on Table 6 (571 g CO_2-eq/kWh against 673 g CO_2-eq/kWh). The dominance of coal in the Reunion mix can be the main cause of this high emission rate, with 48% for Reunion against 14% for Mexico, however, it is necessary to note that the heavy fuel part of Mexico equals more than twice of Reunion's production (respectively 21.6% and 9.47%). According to the values on Table 6, the thermic production based on diesel combustion in Mexico equals the sixteenth part of the Reunion's total (0.50% and 8.07% respectively).

From these results, can be deduced that the coal part in electricity production has a high influence on the GWP emission, as showed in the Reunion's results.

4.3.2. Comparison of the AP

About the AP, Mexico has the highest rate with 6.59 g SO_2-eq/kWh, followed by Madagascar (5.77 g SO_2-eq/kWh). Reunion equals the half of Mexico's rate (3.60 g SO_2-eq/kWh), Japan and Tanzania have a rate 4 to 6 times lower than Mexico's value, with results values ranging from 1.52 to 1.11 g SO_2-eq/kWh, respectively.

5. PROPOSITION OF SCENARIOS

The following section proposes some evolution scenarios for the electricity production of both countries, depending on the electrification rate, the population growth and the number of subscribers. The horizon set for this projection is the year 2050. This paragraph aims to evaluate the potential quantity of kWh required per year, including the renewable energy potential for each country. From this evaluation, will be estimated the GHG emission, especially the GWP emissions in CO_2-eq, valued by the LCA methodology.

5.1. Assumptions

5.1.1. Case of Madagascar

According to the report National Institute of statistics (INSTAT) [14], the electrification rate of Madagascar is about 12.3% of the total household identified for a total population of 22,359,659 in 2010. To note that a Malagasy household is composed by 4.8 persons in average. Identifying a household to a low voltage subscriber (LV) and small and medium industries to high/medium voltage subscriber (MV/HV), the total number of subscribers amounted to 456422 in 2012, of which 99% is dedicated to LV (455,409) for a consumption equals to 584 GWh and 1% to MV/HV (1,013) for a consumption of 345 GWh, as shown in JIRAMA's report [6].Through the ten current years, between 2002 and 2012, there was an average increase of production of 6% per year, and 3% for the number

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of subscribers to electricity consumption, so an average consumption of 1.282 MWh/LV sub and 341 MWH/HV sub.

In the following, the population growth is defined by the United Nations report, in the World Population Prospects [15], it will show three degrees of evolution: low, medium and high scenario.Referring to the International Energy Agency's value [16], this study will take as assumption an electrification rate of 14% with a decennial increase of 3%. The electricity consumption is estimated based on the number of subscribers and the electrification ratio on the year 2012. The consumption is considered as the minimal electricity production quantity, required for each year.

Concerning the renewable energies potential of Madagascar, the hydropower has the highest potential through the country. Referring to the sites identified by the "O□ce de Régulation de l'Electricité" (ORE) [17], Madagascar has numerous sites with potential power superior to 60 MW. On the other hand, the Japan New JEC Inc study [18] has identified a potential up to 3500 GWh of annual production, if all the sites are operating.

In the framework of this study, it is more coherent to fix a gradual increase until 2050, assuming a regular introduction of new hydropower plants. The solar energy has also an interesting potential, with a solar radiation about 2000 kWh/m^2/year throughout the island [19].

The potential environmental impacts generated by the electricity production will be estimated from the assumptions above. The hydropower will reach from 56% to 70% in 2050, so an average annual growth of 0.35%; solar energy will attain 5% of the energy mix. This situation will imply a progressive decrease in production based on fossil energies. Figure 8 shows the evolution of the contribution of each power plant in the electricity mix.

5.1.2. Case of Reunion Island

Proceeding as for the case of Madagascar, here are the key values for the electricity production of Reunion Island until the horizon set 2050.

The assessment of the consumption evolution will depend on the population growth. With a high electrification rate and a total population of 837 870, Reunion records an electric rate of 3.344 MWh/habitant [8]. For this study, the projection has been calculated through the ANN's methodology, taken account of the production between the years 1980 and 2011. The results follow three evolution curves: low, medium and high value.

This section intends to reduce at most the electricity production dependence to fossil energies, by including the renewable energies potentiality. Indeed, the energy mix of reunion is composed by 34% of renewable energies in 2012. However, it has been identified other green energy resources that can provide the electricity demand, as ocean thermal energy conversion (OTEC), wave energy, geothermal or energy pumping transfer station (EPTs). The repartition of energy mix of Reunion Island until 2050 is illustrated on Figure 8. The GEMIS database will be used for the assessment of the environmental impacts [11] but for the new technologies, some values have been taken from ADEME [20] and study report about ocean energies [21].

5.2. Scenarios results and discussion

Referring to these assumptions and the use of the LCA method, the following section discusses about the results generated from the electricity production until the horizon 2050. To compare the results for both islands, Table 7 summarizes the production scenarios according to the high-medium-low assumptions with the corresponding results of GWP.

Based on values on Table 7, the minimal production demand in Madagascar in 2050 equals 8-7 and 6 times the electric consumption of 2012, respectively for high, medium and low scenarios. Considering the GWP, the assumptions taken above engender a significant decrease of the emission factor: a reduction of 39% compared to the

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value on 2012, 283 g CO_2-eq/kWh in 2050 against 464 g CO_2-eq/kWh in 2012. Generally, the electrification rate presents an improvement, with a climb of 193% between 2012 and 2050. But this result does not reflect the real electricity access through the country, because urban zones are electrified at about 39% and 4.8% for rural areas in 2011. The electric consumption per capita jumped of 41 kWh/person to 121 kWh/capita in 2050.

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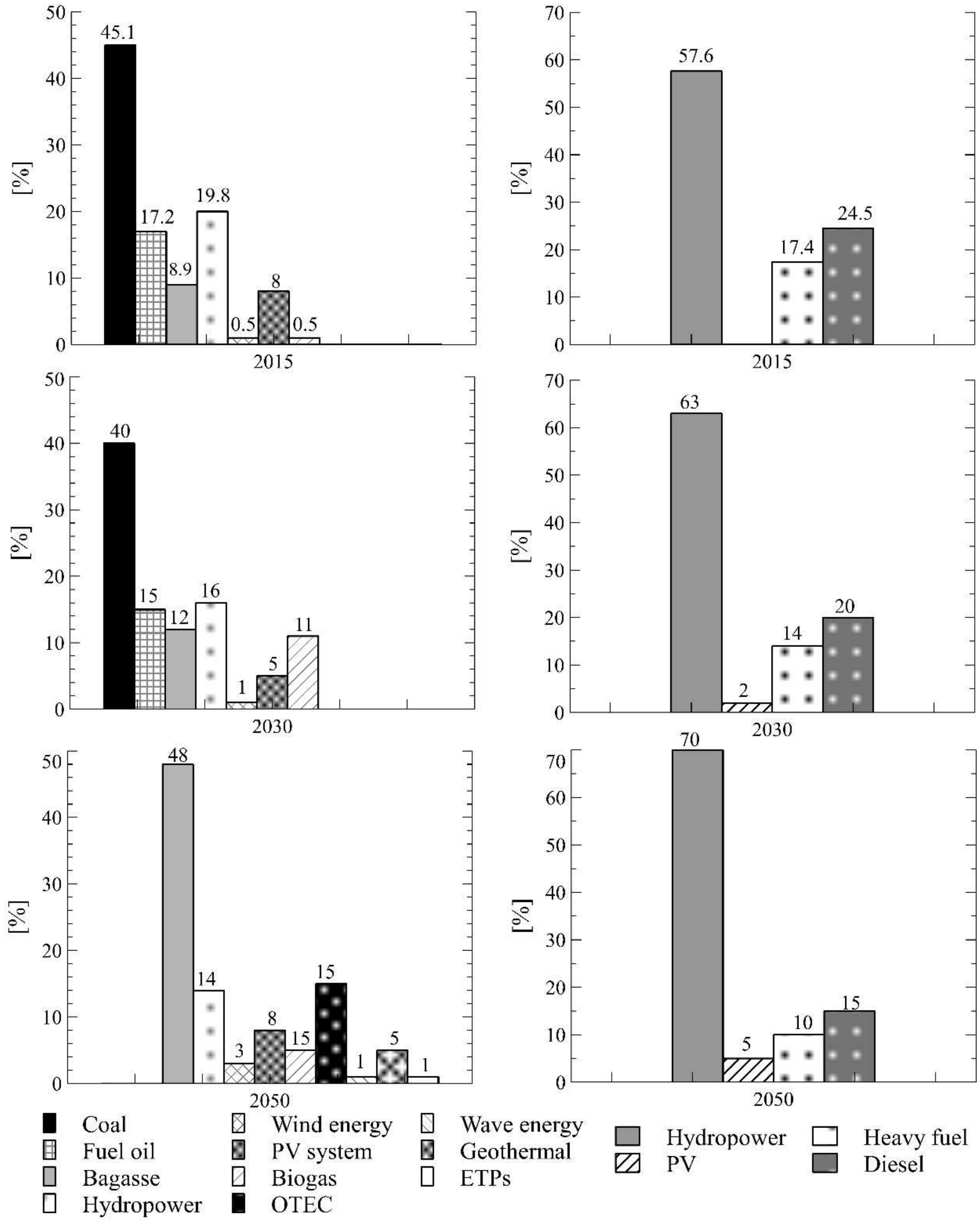

Figure 8 : Repartition of the electric mix of Reunion Island (left part) and Madagascar (right part) 2015-2050

The emission factor in CO_2-eq per capita, 19.17 kg in 2012, rose of 78% on 2050 and attains a result of 34.05 kg.

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Although the total quantity of emission recorded in 2050 equals 5 times the emissions of the year 2012, the gradual increase of the part of renewable energies in the electric mix will allow reducing the emission factor per kWh. About the results of Reunion, the integration of the wave energy and those of geothermal, the electricity production will not depend on fossil energies anymore, and so to reduce considerably the GWP emissions.

Referring to the results of the high scenario, the total emissions in 2050 (178 kt) represent only 10% of the 2012 emissions (1709 kt). These results exceeded the targets of the environmental policy concerning the reduction GHG emissions, fixed by the POPE law [22]. This program has set up a goal to reduce to a quarter the GHG emissions generated by the energy mix in 2050.

Tableau 7: Results of production and GWP emissions from scenarios for Madagascar and Reunion Island 2012-2050

		High scenario (%)		Medium scenario (%)		Low scenario (%)	
		Production	GWP	Production	GWP	Production	GWP
Year	Country	GWh	kt CO_2-eq	GWh	kt CO_2-eq	GWh	kt CO_2-eq
2012	Madagascar	926	430	926	430	926	430
	Reunion	2540	1709	2540	1709	2540	1709
2015	Madagascar	1738	782	1723	775	1708	769
	Reunion	3160	2023	3100	1985	3039	1946
2030	Madagascar	3507	1327	3333	1261	3159	1195
	Reunion	4475	2565	4053	2324	3632	2082
2050	Madagascar	7616	2156	6727	1904	5900	1670
	Reunion	6010	178	4836	143	3760	111

Comparing the results of Madagascar and Reunion Island, based on Table 7 and Table 9 (see on Appendix B), Madagascar's production in 2012 represent 36% of those of Reunion, and concerning the GWP emissions, 28%. This difference can be explained by the low electricity rate of Madagascar, whereas in Reunion, practically all of their people have access to electricity network.

It can be seen on these values that the total emission quantity of Madagascar kept on rising up over the years, due to the contribution of fossil energies in the electric mix, even if their part has gradually decreased. On the other side, the Reunion emissions increased until 2030, but the removal of the fossil energies in the energy mix has allowed reducing the GWP emissions.

If in 2012, GWP emissions of Madagascar represent only 25% of those of Reunion as said before, the trend reversed and Reunion Island records only 8% of the Madagascar's results in 2050.

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Table 10 (see Appendix B) shows the evolution of the emission factors of both islands, in parallel. These values reflect the contrast of the consumption per person in each country, and the environmental impacts generated until 2050, based on the assumptions. The consumption evolution for each country, between 2012 and 2050, is respectively 193% and 55% for Madagascar and Reunion. Although Madagascar has improved its electricity consumption ratio, it represents only 2% of the average consumption per year of one person in Reunion in 2050.

6. CONCLUSION

The objective of this study deals with evaluating the environmental burden of electricity generation in the case of two remote islands in Indian Ocean: Madagascar and Reunion Island. The paper has first presented an overview of the electricity mix situation under insular context. Then a detailed life cycle inventories has been investigated and assessed to define emission factors and finally the current global warming potential of electricity production in the two cases. Due to their heavy dependence to fossil fuel Madagascar and Reunion has a high GWP (respectively 464 and 673 g CO2-eq/kWh). The results particularly highlight the impact of the diesel motor in thermal power plant for both GWP and AP.

This paper also involved three scenarios for electricity production. The scenarios are essentially based on electrification rate and population growth to estimate the demand. This prospective analysis proposed to defined electricity mix in 2030, 2050. The new mix reduce the use of coal for Reunion and Diesel for Madagascar. And in the same time, the scenario increase the share renewables such as hydropower, biomass or PV in the mix. Thus, this study shows the possibility to reduce the environmental impact of electricity, by the introduction of RES. The main difficulty is to define the roadmap to meet intermediate objective in 2030 and the final in 2050 for the electricity mix. The paper clearly show the significant role of LCA for policymakers in energy planning strategies. Further investigation will be done to identify the potential of renewable resources for electricity generation.

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Appendix A. Lists of emissions in GEMIS

Table 8: Life cycle emissions per kWh of different power plants, according to GEMIS values

Technology		Emissions (g/kWh)				
		CO_2	CH_4	N_2O	SO_2	NO_x
Hydro dam	mini	30.84	0.04	0.00	0.01	0.07
	medium	20.15	0.02	0.00	0.01	0.04
Hydro-ROR	small	1.30	0.00	0.00	0.00	0.00
	Big	31.92	0.03	0.00	0.01	0.07
Bagasse ST		0.38	0.04	0.02	1.27	5.31
Wind turbine	big	23.65	0.03	0.00	0.01	0.05
Biogas engine	small	70.80	0.25	0.03	3.51	18.02
PV system	(a)	109.77	0.27	0.00	0.12	0.16
	(b)	90.82	0.25	0.00	0.11	0.14
Heavy oil ST	(a)	917.59	0.80	0.03	11.08	2.75

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Dieselmotor	small	1265.49	1.21	0.03	5.27	18.62
	medium	1052.70	1.00	0.03	4.39	11.90
	big (a)	902.57	0.86	0.02	3.76	8.65
	big(b)	906.96	0.86	0.02	3.84	8.70
Coal ST	medium	981.38	1.97	0.05	1.30	2.96

(a) refers to Madagascar's power plants; (b) refers to Reunion's power plants ROR: run-of-river

Appendix B. Scenario results

Tableau 9: Electricity mix of Madagascar and Reunion Island 2012-2050 (%)

	2015		2030		2050	
	Madagascar	Reunion	Madagascar	Reunion	Madagascar	Reunion
Heavy fuel/Diesel	41.98	17.00	34.70	16.53	25.00	-
Coal	-	45.06	-	49.59	-	-
Bagasse	-	8.94	-	11.51	-	48.11
Hydropower	57.62	19.80	62.93	15.74	70.00	13.92
Wind energy	-	0.54	-	1.08	-	3.19
Photovoltaic	0.01	7.97	2.37	4.52	5	7.97
Biogas	-	0.53	-	1.03	-	3.83
OTEC	-	-	-	-	-	15.33
Wave energy	-	-	-	-	-	1.49
Geothermal	-	-	-	-	-	5.1
EPTs	-	-	-	-	-	1.06

Tableau 10 : Emission factors from scenario results

	kWh/capita		g CO_2-eq/kWh		kg CO_2-eq/capita	
	MDG	RUN	MDG	RUN	MDG	RUN
2012	41	3031	464	673	19	2040
2015	71	3498	450	640	32	2240
2030	93	4154	378	573	35	2381
2050	121	4692	283	30	34	139
Evolution 2012/2050	193%	55%	-39%	-96%	78%	-93%

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