Long-term electricity mix planning towards low GHG emission: The case of Reunion Island

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ABSTRACT

This study presents a linear programming model for an optimal long-term electricity mix planning of an insular territory. A prospective exercise on electricity generation is conducted over a period of 15-35 years. A general methodology is presented to determine an optimal generation mix that minimize greenhouse gas (GHG) emission by taking into account the environmental challenges of the territory. This methodology is applied to the case of Reunion Island. The main constraints considered here are the evolution of electricity emission factor and to meet the future electricity demand. Due to the long time-frame that we consider, a normative electricity mix scenario is presented, which aimed to reach the target by adjustments of the current electricity power system. The obtained results refer two scenarios: preserving and transforming structure. Referring to results, it is feasible to achieve environmental policy established by the energy transition act.

KEYWORDS

Linear programming, Normative scenario, Electricity mix, GHG emission, Reunion Island

INTRODUCTION

Energy planning models help to identify the best compromise between various constraints the energy demand increase, investment in technology production and climate change. There are different types of scenario that could be implemented, according to the objective of the study. Bradfield et al.[1] and Amer et al. [2] established a classification of scenario planning methods, there are three schools of major approaches for scenario development which are the intuitive logics, the probabilistic modified trends methodology and the French approach of La prospective. The latter approach is based on the principle that the future is not predetermined, thus it can be adjusted in accordance with national views. In order to reach the national policy objective, it is necessary to determine the type of scenario that will be implemented. Authors in [3] defined three typologies of scenarios: *predictive scenarios* which answer to the question "What will happen?", *explorative scenarios* respond to the question "What can happen?", and *normative scenarios* answer to the question "How can a specific target be reached?". Normative scenarios consist of two types, characterized by the system structures: preserving scenarios suggest solutions by adjustments to the current situation and transforming scenarios respond to the target by necessary changes in the current structure. In this work, the prospective normative scenario is considered, based on the goal of mitigation of greenhouse gas (GHG) emissions.

Saiah and Stambouli [4] presented a prospective analysis for a long-term energy mix planning in Algeria, where the scenarios are constructed from a forward-looking assumptions of economic (population, GDP) and energy variables (efficiency, capacity). They determined scenario trended and voluntarism scenarios for each variable, in order to highlight the benefits of the voluntarism scenario. Thangavelu et al. [5] propose a long-term optimal energy methodology, taking into account the risk associated in the energy planning due to the uncertainties in the projected variables. The optimal energy mix satisfied the renewable penetration and the fuel diversity constraints at each time periods for the input scenarios.

TIMES model is one of the most widely used in energy planning. Garcia-Gusano et al.[6] present a soft-linking of LCA an TIMES-Norway model, with a time-frame from 2010 to 2050. They showed that the life-cycle indicators evolve in accordance with the integration of new power generation technologies. Krakowski et al.[7] applied a long-term energy-planning model from TIMES family, by exploring different levels of renewable source penetration in the French power system. Drouineau et al. [8] analyze the capability of the Reunion Island's power system to reach electricity autonomy by 2030 through a TIMES-Reunion model, from a prospective analysis. They showed that this objective can be reached by integrating high levels of biomass and intermittent sources.

Given that small islands are heavily dependent on fossil fuels for energy, particularly for electricity generation. Energy planning will help the decision-makers in the right choice for the future electricity sector. In this work, we propose a linear programmation (LP) to find the best compromise electricity mix scenario, in which various parameters should be considered, as the emission costs, energy security, carbon emission limits targets, and renewable energy potential. A normative prospective scenario will be set out in this work. The structure of this document is as follows: first, a description of the adopted methodology. Then, we will introduce the case study of Reunion Island with an overview of the electricity sector and the assumptions considered. The different scenarios that will be compared with the corresponding results.

METHODS

Problem statement

The work addresses a long-term electricity planning of a country, taking into account the GHG emissions associated with the energy scenario. This long-term electricity planning is identifying the optimal combination of electricity generation, to satisfy the objective of GHG reduction by kilowatt-hour electricity produced. This method is based on the MARKAL principle [9] and [5]. Linear programming models are subject to bounds, linear equality and inequality constraints. The objective function is to define the best electricity mix repartition which minimizes the total emission cost of the proposed electricity mix, and allows to reach the GHG reduction targets, over a time period horizon.

$$\min : EmissionCost = \sum_{i=1}^{n} E_{g,i} x_i ef_i C^{ctax} \qquad , \forall t \tag{1}$$

Eq(1) quantifies the expected cost of GHG emission for t time, where i represents each generation technology that enters into the electricity mix, x_i represents the share of the

generation technology, E_g the electricity generation, *ef* the GWP emission from power generation technology and C^{ctax} represents the carbon tax emission.
This problem is subject to various constraints relative to energy security, carbon emission limits, potential capacity and renewable contribution in the electricity mix. These parameters will be converted into appropriate constraints of equalities or inequalities in Eq (2-4).

Energy security

Energy security considered in this study, quantifies the ability of the electricity mix to meet the future energy demand. Eq(2) forces the electricity generation E_g to meet the electricity demand *d* at time *t.*

$$\sum_i E_g x_i = d_t \tag{2}$$

Carbon emission limits

According to the environmental policy of the studied area, emissions through electricity generation should not exceed the targets established by the government. As carbon emission relies on the power technology type, Eq (3) will force the integration of renewable sources and limit the fossil fuels contribution. The carbon target *CT* represents the emission factor from one kilowatt-hour electricity produced.

$$\sum_i x_i ef_i = CT_t \tag{3}$$

Potential capacity

According to their availability or capacity *Cap*, renewable energy sources have to face clear limitations of electricity generation. Eq (4) illustrates this limitation, which can be the potentiality, or the limit integration of intermittent sources of energy.

$$E_g x_{i,r} \le Cap_{i,t} \quad ,\forall t \tag{4}$$

Values of *Cap* can change over time, based on the adopted scenario. In line with the territory objectives, renewable share in electricity mix can be imposed over the time period.

ASSUMPTIONS

Case study: Reunion Island

Reunion Island, a territory of 2520 km², is a French overseas department and an ultraperipheral European region located in the Indian Ocean, among the Mascarenes islands with Mauritius and Rodrigues islands. Reunion Island is characterized by a diversified electricity mix, thanks to local resources as biomass, hydropower, wind, sea and solar energy. Despite these resources, primary energy consumption is 86.1% dependent on fossil fuels and current electricity generation is 35% self-sufficient [10]. Within the framework of the energy transition for green growth, decision-makers have to consider how Reunion can achieve the energy, or electricity autonomy since 2030. Due to its geographical location, numerous environmental policy can be applied to this territory, and consequently, various energy scenarios.

In the base year of 2015, the electricity mix of Reunion Island is composed by coal (40%), heavy fuel oil and gas oil (24%), hydropower (17%), bagasse (9%) and the remainder is provided by other renewable sources as solar, biogas and wind energy (10%).
An overview of the potential of renewable energy sources in Reunion is well described in [11]; Reunion has huge potential in promising renewable such as geothermal and ocean energy. However, these technologies can be exploited only after 2030.

On the basis of the foregoing and the history of the electricity consumption, Reunion's future energy demand is expected to increase at least in one of four possible ways that the French electricity provider (EDF) established: low (0.2%), high (3.02%), baseline scenario energy-side management (ESM) (1.4%) and an enhanced ESM (0.7%) on average per year. EDF takes into account various parameters in the implementation of the energy demand of the population, as the demography, the economic growth through the gross domestic product (GDP), or the household equipment rate [12]. In this study, we will consider the ESM enhanced scenario.

The environmental burdens of each power technology for a 1 kWh electric produced are defined by its lifecycle assessment (LCA). These values have been assessed with the LCA methodology, regarding the 'cradle-to-gate' boundary. The GHG emissions reduction targets are defined by different complementary policies. Within the framework of the energy transition for green growth, the national energy policy aims to reduce the GHG emission by 40% below 1990 levels by 2030, and to a quarter of those in 1990 for 2050. Emissions targets implying a major slope for the first 15 years of the scenario. Here, we consider the medium-term objective on 2030, as shown in Figure 1.

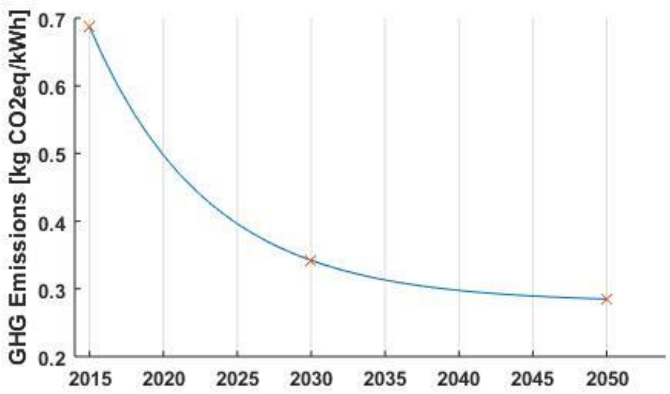

Figure 1. Evolution of the GHG emissions targets

ENERGY SCENARIO

In order to reach the GHG emission targets explained in the previous section, a normative scenario has to be implemented for each scenario case in order to reach a specific target. Based on the previous assumptions, two scenarios are distinguished:

- Scenario A: This scenario reflects a normative preserving scenario, where the current energy structure is not modified, meaning that any other technology can be added to the existing one, but their capacity can be extended in order to meet energy demand.
- Scenario B: This scenario will assume both preserving and transforming scenario. Indeed, according to the potential of renewable, the effective use of geothermal and OTEC technology will be possible from 2030.

For both scenarios, the following assumptions will be implemented in the methodology described previously:

- Hydropower capacity cannot be extended. As hydropower generation is closely tied to the rainfall, we assume that the maximum $Eg_{,hydro}$ equals the maximum value observed for the capacity installed [10].

$$E_g x_{hydro} \leq \max(E_{g,hydro}[2010:2015]) \quad ,\forall t \tag{5}$$

- Electricity from bagasse depends essentially on the sugar campaign. For an agricultural area of 22,664 ha, the current variety of sugar cane produces about 569 kt of bagasse. Authors in [13] presented the increase of electricity generated from bagasse by using a higher fiber cane, which allows to produce the same amount of sugar with a higher amount of bagasse. Assuming that this new variety is integrated progressively in the cultivation of sugar cane, the electricity production from bagasse will increase proportionally until 2050.

$$E_g x_{bagasse} = E_{g,bag,norm} + E_{g,bag.highfiber} \quad ,\forall t \tag{6}$$

- Reunion Island is a volcanic island whose geothermal potential is not clearly defined. However, an expected potential of 30 MW capacity is anticipated for 2030. Assuming that this process is exploited, we have determined the potential electricity production based on the process in Guadeloupe. Among the overseas department, only Guadeloupe exploits the geothermal energy, and there are two geothermal facilities with a total capacity of 15 MW. Based on the effective efficiency of those of Guadeloupe, we have determined the maximum electricity production expected [14].
- Ocean thermal energy conversion (OTEC) is one of the most promising technology of sea energy in Reunion. Studies are currently carried out in the south of the island, but others sites can be exploited [15]. However, a potential capacity of 130 MW is expected to be installed in 2030.
- To ensure the network stability, electricity from intermittent resources cannot exceed the limit of 30%.

$$E_g x_{ren,\text{intermittent}} \leq 0.30 E_g \quad ,\forall t \tag{7}$$

- All renewable production is equal or greater to the baseline year 2015,

$$E_g x_{ren} \geq E_{g,ren,2015} \quad ,\forall t \tag{8}$$

- Section 1 of the law of the energy transition for green growth defines the increase of the C^{ctax} from 2020 to 2030 (56 EUR to 100EUR per carbon ton) [16]. We will consider the 2030 C^{ctax} value until the end of the energy programming.

RESULTS AND DISCUSSIONS

The development of the methodology in order to find the best electricity mix and to minimize the emission cost is the main result obtained. The case study of Reunion Island has been considered. The linear programming result is presented in this section, which has been calculated by the Eq (1, 5-8). In this context, two main parameters have to be discussed: the renewable contribution and the final electricity produced from each technology. The optimal electricity mix of both scenario satisfies the emission target and renewable integration at each time period for the given assumptions.

Figure 2 illustrates the electricity production from 2015 to 2050 under the scenario A and B. The electricity production from each technology was calculated over a 5-year period within the given constraints. Bagasse production is the same in the two scenarios, which is defined in Eq(6). Given that OTEC and geothermal energy production can be exploited only from 2030, the obtained electricity mix in both scenarios remains the same between 2020 and 2030, as the emission target is the same. However, owing to their limited potential, these two energies contribute at about 180 GWh in 2050. We observed that electricity from fossil fuel-based technologies decreases gradually until 2050. Biomass production increases significantly between the first-time period, and helps to meet energy demand since the fossil fuels contribution have to decrease in order to reduce GHG emission. This implies a high investment in biomass facilities.

Solar and wind energy have also shown significant growth between the baseline scenario and the given horizon 2050. Scenario A shows that reducing GHG emission is feasible if the electrical structure is maintained in its current form. The potential of geothermal and OTEC electricity generation can be improved, according to future researches. Indeed, the potential value used in the implementation of this energy scenario at this stage remains in expectation. However, investment in biomass, solar and wind energy facilities is essential to that goal, whether for Scenario A or Scenario B.

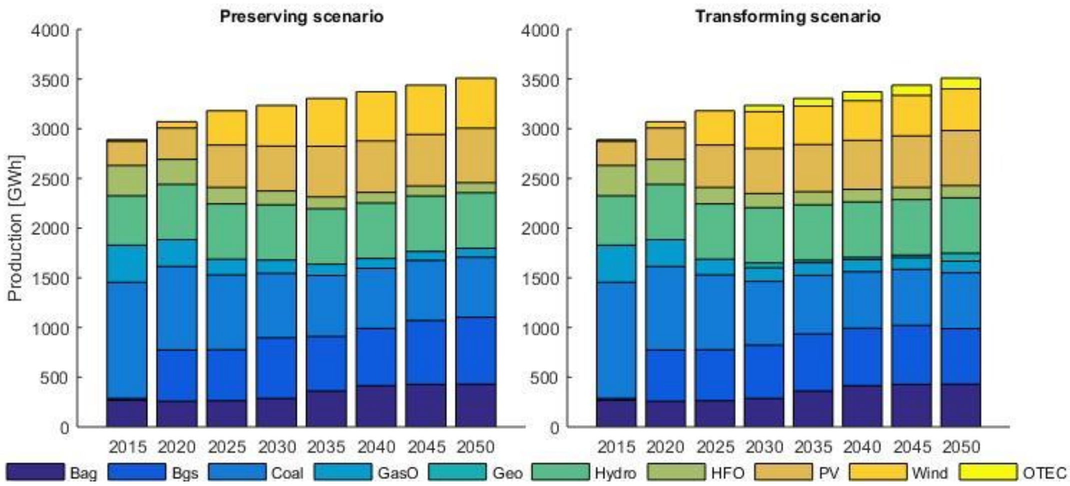

Figure 2. Evolution electricity production of scenarios A and B [GWh]

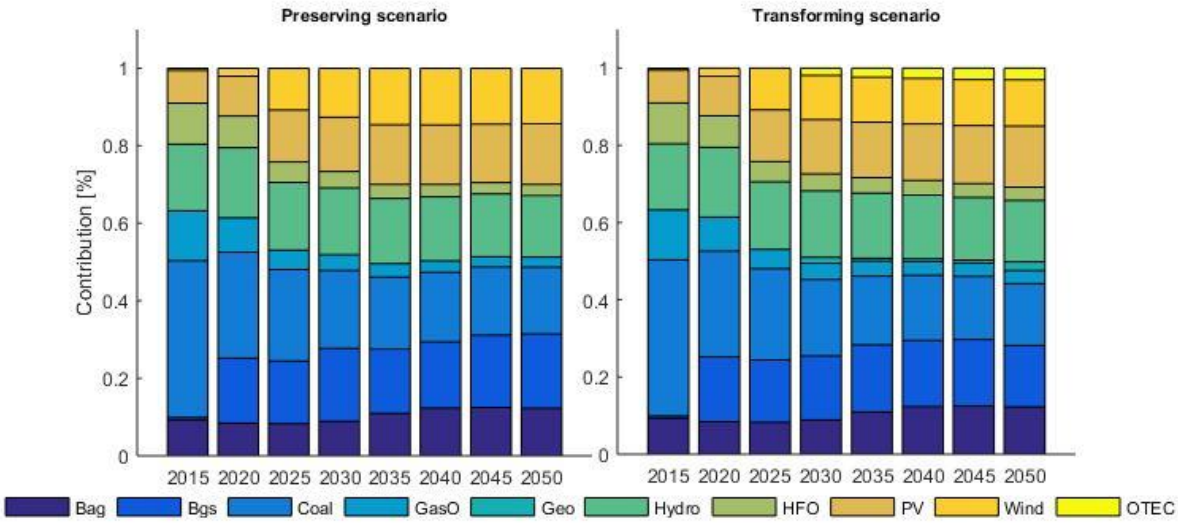

Figure 3. Evolution electricity mix contribution of scenarios A and B [%]

Figure 3 shows the contribution of all power technologies in the future electricity generation. Renewable energies attain about 77% of the electricity production in 2050, thanks to fuel diversity. Future renewable electricity generation will be ensured by bagasse 8-12%, hydro 15.8-18.1%, biomass 0.5%-19%, geothermal 0-2.3%, OTEC 0-3%, solar 8.4-15.8% and wind 0.5 – 14.7%. According to these results, investment in renewable facilities is necessary to reach these goals. These scenarios allow to reverse the current situation, and reduce the fossil fuel contribution. Coal contribution has to decrease by more than half in 35 years (40% to 16%). Thermal production based on oil derivatives also presents a gap in their contribution (23.5% to 6.8%). The total emissions cost during the planning horizon will amount to about 582 million EUR.

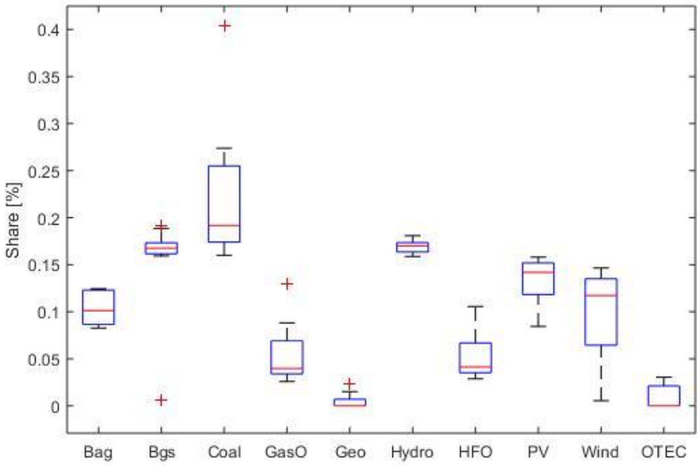

Figure 4. Variations of power technologies contribution in future electricity

Figure 4 shows the variation contribution of each technology at the end of the planning period. As can be observed, renewable contribution as biogas, hydro and geothermal energy is not significant over time. The coal contribution faced high variability, followed by wind and solar. The allowable contribution of each technology has been capped at 40% of the energy demand during the optimization.

CONCLUSION

A multi-period electricity planning linear model has been developed to find the optimal electricity combination for any region and at any horizon time. The optimal electricity mix of each scenario satisfies all the technological and environmental constraints, and minimizes cost associated with GHG emission. In this case study, we have considered the enhanced ESM scenario for the future energy demand, which implies that population has to consume less energy in the future. The main constraint considered in this study was to reach the different targets in reducing GHG emissions. The electricity mix planning shows that the current technologies allow to reach these goals, subject to the condition of increasing of the solar, biomass and wind capacity. In this study, energy planning has been implemented for 35 years with a 5-year interval. The obtained results can be used directly to assess more accurately the life cycle environmental burdens of each scenario. To complete the developed model, future works have to include economic aspects regarding to investment, operation and maintenance cost.

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