Evaluation of the Energy Transition in the Process of Renewable Sources Expansion – A Case Study

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ABSTRACT

Considering the risks related to energy security and the challenges posed by climate change, this work presents a methodology to investigate energy alternatives to promote an adequate energy transition. Such methodology was applied to a case study, modelling the energy system of the Brazilian State of Minas Gerais to subsidize an energy transition with a view to expanding renewable energies and promoting energy efficiency at the state and municipal levels, as well as combating climate change. Projections, in the 2030-2050 horizon, were made using the tool Long-range Energy Alternatives Planning System (LEAP) to establish a model of energy transition policy for Minas Gerais State. The modelling considered key assumptions based on historical data of demographic and economic origin, which subsidized the elaboration of three scenarios, being a Reference Scenario (REF), a Moderate Energy Transition Scenario (ETM) that aims to contribute to the energy sector goals of the Brazilian Nationally-Determined Contributions – NDC, and an Advanced Energy Transition Scenario (ETA) that goes beyond of NDC's goals. The analysis has shown that current policies are not sufficient to promote the state transition to sustainable energy systems and that this process will depend on the energy policies initiated and implemented in the near future.

Highlights

- Energy transition in the Brazilian State of Minas Gerais has been considered;
- Three scenarios have been simulated using the tool LEAP;
- Projections in the 2030-2050 horizon were performed;
- The ETA (Advanced Energy Transition) scenario presented the best cost-benefit ratio.

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1. Introduction

The world has turned its attention to making efforts in the fight against climate change. The energy sector plays an important role as the main greenhouse gas (GHG) emitter in the world, around 34.6% of total global emissions [1]. Following this same line, in Brazil and in the Brazilian State of Minas Gerais, the sector contributed to the total balance of emissions in 2014 with the amount of 26% [2] and 37% [3], respectively. The role of energy as a driver of the development of the economy and modern life is undeniable. The effects of climate change can have catastrophic consequences for economic, social and environmental systems [4]. Thus, it is necessary to find a balance to ensure economic and social development and the energy supply for this, and at the same time, to act in the fight against climate change. The reduction in rainfall levels may increase in the coming years, resulting in a change of an energy matrix, as was investigated by the authors for the case of Minas Gerais [5].

Although there are undeniable benefits in relation to the use of fossil fuels for power generation, there are also several problems associated with these sources and their forms of production. Among these, we can mention, mainly, that they are non-renewable sources of energy, and consequently, they are limited resources. In addition, it is estimated that between the years 1970 and 2010, CO_2 emissions through the burning of fossil fuels and industrial processes accounted for around 78% of total GHG emissions worldwide [1]. This data allows us to infer that fossil fuels are one of the main responsible for the emission of GHG, and therefore contribute substantially to the intensification of global warming.

In view of the risks related to energy security and the challenges imposed by climate change, thinking about new energy alternatives, in view of promoting an energy transition, seems reasonable. In this context, Brazil has an ambitious Nationally-Determined Contributions (NDC) in order to achieve the Paris Agreement, signed at the 21st Conference of the Parties (COP-21), in Paris, in December 2015, which aims to limit the increase in global temperature to a maximum of 2ºC compared to pre-industrial levels through a substantial reduction in GHG emissions. Regarding efforts to reduce GHG in the energy sector, the Brazilian NDC expects to achieve an estimated 45% share of renewable energy in the composition of the energy matrix in 2030, including: "expanding the use of renewable sources, in addition to hydropower, in the total energy matrix for a participation from 28% to 33% by 2030" [6].

For the goals of the Brazilian NDC to be implemented effectively and within the agreed deadline, it is necessary to join efforts and share responsibilities between States, the private sector and civil society, in order to promote decentralization of the goals. In this sense, the NDC targets must be reflected at the subnational level and all Brazilian States must be committed to its achievements.

The case study performed in this work aims to present a study methodology, that the Brazilian States could use to meet their NDC share responsibility, by using the LEAP tool to carry out the modeling, contributing to energy transition researches. In this way, a modeling of scenarios of the energy system of Minas Gerais State in the medium and long term to subsidize an energy transition has been developed with a view to expanding renewable energies and promoting energy efficiency at the state and municipal level, as well as combating climate changes. Minas Gerais is a state in Southeastern Brazil. It is the second most populous, the third by gross domestic product (GDP), and with an area of 586,528 square kilometers, it is the fourth most extensive State in Brazil.

1.1. Energy transition in Brazil and Minas Gerais

Brazil, when compared to other countries that have energy matrices intensive in fossil fuels, has a very different energy profile. According to the latest energy balance in Brazil [7], in 2015, the country's energy matrix is composed of 57.9% of fossil fuels, and the remaining 42.1% are from renewable sources, mainly hydraulic, firewood and sugarcane products. Other renewable sources, such as wind and solar, have a very small share in total production.

A little different from the national scenario, the energy balance of the State of Minas Gerais [8], for the same period, reveals that of the total state energy demand, 52.7% referred to renewable energy sources and the rest non-renewable sources. Sugarcane derivatives represented 36.1% of the demand for renewable energy.

The current energy scenario is far from the future scenario envisaged by the Brazilian NDC, which foresees a total energy supply of 30% coming from renewable energy sources by 2030, except hydro, as well as expanding the use of wind, solar sources and biomass in the supply of electricity for a 23% share for the same period [6].

Like other countries that already engage in public policies to combat climate change and promote an energy transition to a "greener" matrix, in the Brazilian federal sphere, the absence of an effective plan to achieve the Paris Agreement goals is noted. The actions for the promotion of renewable energy sources are basically concentrated in programs such as the Incentive Program for Alternative Electric Energy Sources - PROINFA [9], the National Energy Efficiency Plan [10] and RENOVA BIO [11]. The first has actions to promote renewable energy sources, which include wind and solar; the second has premises and guidelines for increasing energy efficiency in the Brazilian energy matrix; the latter is a program that provides incentives for biofuels. In the State context, Minas Gerais has as a strategy the State Energy and Climate Change Plan - PEMC [12] and the Renewable Energy Minas Program [13] which address actions for the development of renewable energies and energy efficiency. In addition, Decree No. 47,231, of August 4, 2017, establishes an exemption from the ICMS (tax on transactions relating to the circulation of goods) for mini and microgeneration from renewable energy sources.

The Minas Gerais Renewable Energy Program is the main effort of the Minas Gerais government to promote the generation of electricity from renewable sources [13]. The program is limited in scope and does not serve the renewable energy sector as a whole, as it does not include all biofuels and thermal energy generation. Its greatest contribution was in the area of tax incentives with the consolidation of tax exemptions for the generation of electricity from renewable sources, except for large hydroelectric plants. The analysis of the effectiveness of this program points to sustained growth in the demand for electricity, consequently, emissions will also be increasing, especially in the reference scenario, in case renewable energy sources do not assume a more important role. This demonstrates that this policy, with regard to the responsibility of the State of Minas Gerais, is not sufficient to comply with the climate agreements signed by Brazil at the international level [13].

Regarding the regulation of the energy sector in Brazil, mainly the electric sector, the competencies are basically concentrated at the federal level, being the Ministry of Mines and Energy - MME, National Electric Energy Agency - ANEEL, National Petroleum, Natural Gas and Biofuels Agency - ANP, the Energy Research Company - EPE, the National Energy Policy Council and the National Electric System Operator - ONS, the main responsible for strategic planning and formulation of public policies in the energy sector. States and municipalities do not have the autonomy to legislate in terms of generation, distribution, transmission and commercialization of energy; these actions are an almost exclusive competence of ANEEL [14].

2. Development of the Analysis – General Methodology

To perform the case study, the model was developed using the LEAP (Long-range Energy Alternatives Planning System) modelling tool, which is widely used at the levels of international, national, subnational and local organizations to model energy systems and explore their implications for different policies energy for the future. LEAP has been applied to case studies in different places, for example, Greece [15], Korea [16], Nigeria [17] and China [18]. LEAP is a modeling tool under the energy and environmental aspects, which was developed by the Stockholm Environment Institute (SEI) to assess the effects - physical, environmental and economic - of alternative energy policies, technologies and other initiatives. The system has a technological and environmental database that offers extensive information on technical characteristics, costs and environmental impacts of several energy technologies, including existing technologies, current best practices and next-generation devices [19]. LEAP can also work in combination with WEAP (Water Evaluation And Planning), as it was applied to study the effects in the electric matrix of Minas Gerais considering scenarios of reduction in rainfall through the modeling of hydroelectric plants [20].

The structure of LEAP is shown in Figure **1** and it consists of four basic components: Demand - where the analysis of the system's energy demand is carried out, as well as the types of the end use of energy; Transformation - it evaluates the available energy resources as well as their conversion; Environment - it makes the estimates of emissions associated with the energy system; Evaluation - that allows the comparison of scenarios in terms of costs and physical impacts.
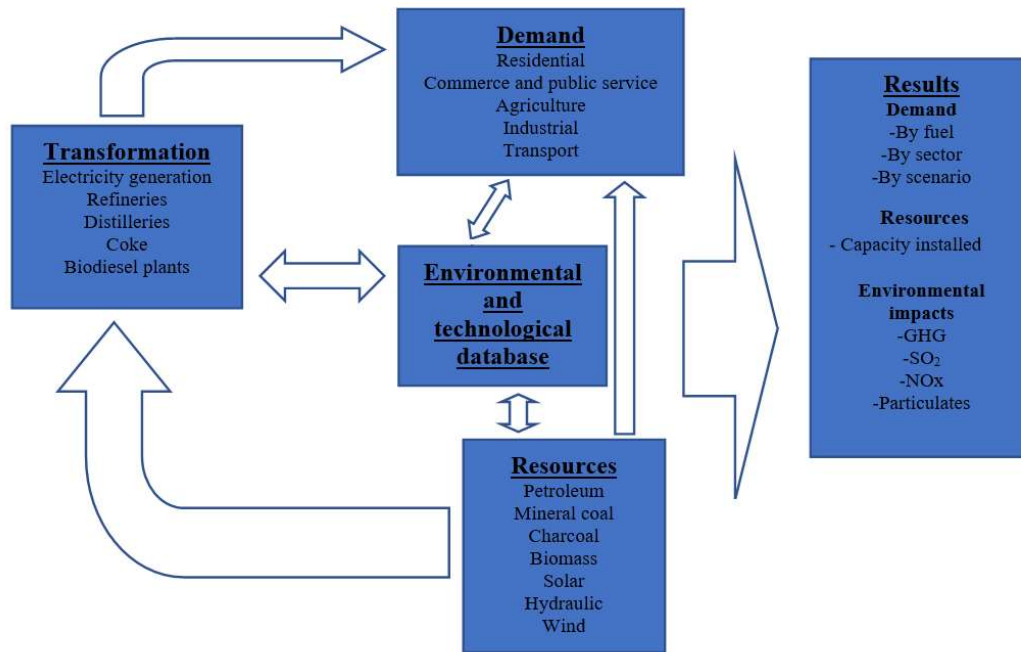
Figure 1: LEAP structure (Source: Adapted from [19]).

From the developed modeling it is possible to assess the impacts of energy demand and generation in the Minas Gerais energy system, over medium and long-term horizons. The data and premises to support the scenarios were obtained from available data from the literature.

2.1. Development of the Scenarios and Premises Adopted

In this work, three scenarios were elaborated, which have as a key objective to guide decision making for the elaboration of energy policies, within the scope of the State of Minas Gerais for the horizon 2030-2050. The first scenario, called the Reference (REF), was based on the plans of the government of Brazil, with a focus on the State of Minas Gerais, in relation to the expansion of electricity generation capacity, demand and final energy consumption, and energy services. Most of the REF scenario formulation was based on data from [21] and the National Energy Plan [22, 23], as well as the analysis of historical series of the State's energy system, which is available in the ANEEL database and in the energy balances of the State. This scenario makes projections based on what could happen if no additional efforts are made to create new energy policies that aim at more sustainable energy systems.

Based on the REF scenario, two alternative scenarios were elaborated, the first has the aim of contributing to the goals of the energy sector in the Brazilian NDC and is called the Moderate Energy Transition (ETM). The second one has the objective of going beyond the objectives of the NDC, being even more ambitious, which is the Advanced Energy Transition (ETA) scenario.

While the REF scenario represents projections based on what will happen if no additional intervention energy policy is created, alternative scenarios consider the gradual increase in strategic policies that seek to guarantee energy security while guaranteeing climate security. Therefore, the ETM scenario has moderate policies that aim to meet the climate agreements signed internationally by Brazil, with respect to the part corresponding to the State of Minas Gerais. The ETA scenario has bolder political strategies in order to build an energy system based mainly on renewable energies, as well as a gradual switch from fuels in the transport sector to biofuels and electricity.

The LEAP model for Minas Gerais is divided into four modules. In the first module are the General Premises, which is composed of demographic and economic data, used to project the growth in demand. The second one is the Demand module, composed of the residential, trade and services, agriculture, transportation and industry

sectors. The third one - the Transformation module - is branched into transmission and distribution, where electricity losses are computed at this stage of supply (electricity generation, oil refineries, coal plants, coke plants, distilleries, biodiesel production and biogas production). The last one, the Resources module, deals with the types of primary and secondary energy involved in the entire system.

The year 2010 was selected as the base year for the scenarios, primarily due to the availability of data, especially with regard to demographic data, since the last census, conducted by the Brazilian Institute of Geography and Statistics - IBGE, was carried out in that year. The choice was also made in line with the base year chosen by the Ministry of Science, Technology, Innovations and Communications - MCTIC to prepare the scenarios that subsidized the Brazil NDC.

All assumptions used to model the scenarios are in the Tables **4, 5** and **6**, in **Annex I**.

2.2. Elaboration of the State Energy Transition Policy - PETE

Once the scenarios are obtained, they will subsidize the elaboration of the State Energy Transition Policy - PETE.

The modeling of energy systems allows an integrated assessment that considers the security of supply, access to the system at a fair price, dimensioning of environmental impacts and financing strategies [24]. Thus, the PETE is based on modeling medium and long-term scenarios developed for the state's energy system, using the LEAP tool.

The PETE is also based on the measures described in the document [25], in which it is suggested that effective strategies should be based on ambitious goals, supported by research and development mechanisms, financing, training, exemplary projects, awareness and regulation.

3. Case Study – Results and Discussion

In this section, the results obtained from the modeling performed in LEAP are presented and discussed. It is important to highlight that the assumptions used in this work are the same used to build the Brazilian NDC, so a comparison and sharing basis could be established. Through the interpretation of these data, at the end of the session, an energy transition strategy for the State of Minas Gerais is proposed. The scenarios obtained in this research show trends and alternatives in the medium and long term, based on a collection of historical and statistical data, which aim to guide decision making regarding the planning of energy systems in order to achieve the goals of the Brazilian NDC.

3.1. Modeling the Minas Gerais Energy System in the 2030-2050 Horizon

In this section, the results obtained from the modeling carried out in LEAP for the period 2030-2050 are presented.

3.1.1. Energy Demand

Based on general assumptions, which practically involve economic and demographic criteria, the time evolution of final energy consumption, in the 2030-2050 horizon, by economic sectors is shown in Fig. **2**. The values reflect how consumption will evolve in the REF[1] scenario.

In general, final energy consumption increases considerably over a 40-year period, from 35 million toe in 2010 to 95.7 million toe in 2050, almost tripling in its base value. The sectors of industry (65.4%) and transportation (24%) together accounted for more than 89% of the total energy consumed in 2010. In 2030 and 2050, it is expected, with population growth and an outlook for economic growth more conservative, that the transport

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[1]Since the objective of this research is to provide alternatives and diversity of energy supply in order to achieve the Brazilian NDC, the ETM and ETA scenarios have the same final energy consumption in terms of toe.

sector should have greater participation, 28.5% and 31.3%, respectively. Thus, the industry would represent, 61.2%, in 2030, and 59.4% in 2050. The high participation of these two sectors is mainly due to performing high energy intensity activities.
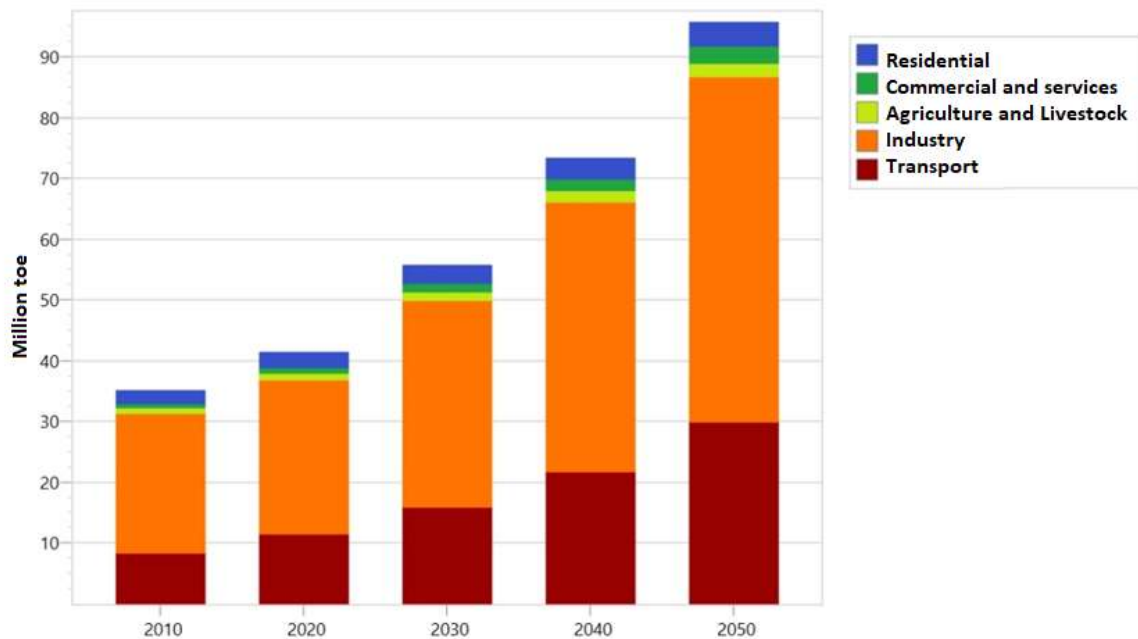

Figure 2: Final energy consumption by sectors – REF scenario (Source: Own elaboration).

3.1.2. End-Use of Energy by Fuels

The structure of the end-use of energy in the REF scenario is shown in Fig. **3**; as it can be seen, fossil fuels represent more than 50% of final energy demand in 2010. This share tends to increase to 54% in 2030 and to 55% in 2050.

In alternative scenarios, policies have been proposed that aim at a gradual transition from oil products in the transport sector to electric vehicles and biofuels. Thus, the ETM scenario (Fig. **4**), has a slight decrease in the share of fossils to 50% in 2030, and 47% in 2050. The ETA scenario (Fig. **5**), foresees a more audacious policy, with great penetration of electric vehicles in the matrix, reducing the demand for fossil fuels to 43% in 2030, and to 36% in 2050. In this scenario, in 2050, electricity will represent 32% of final energy demand, an increase of 100% when compared to the same period in the REF scenario.

The electricity demand for all scenarios is shown in Fig. **6**. As expected, the ETA is the scenario that demands more energy, with a need for 148 thousand GWh in 2030, and more than doubling in 2050, with 359 thousand GWh. This high difference is mainly due to the transition from fossil fuels to electricity in the transport sector, thus indicating that an intensive penetration of electric vehicles will significantly impact the demand for electricity.

In relation to the ETM and REF scenarios, when compared to each other, there is no difference as significant as the ETA, since the ETM has an increase of around 20% of the share of electricity in its final energy demand in relation to the REF.

3.1.3. Transformation

The transformation modules are programmed to produce electricity and resources from renewable sources as demand for them. However, when it comes to fossil-based resources, the system is completely limited to the capacities already existing in the base year, and it remains so in the projected period, since there are no plans to expand oil refineries or coke plants in the planning government, and it is not an objective of this study to promote these energy sources. In Fig. **7** is shown that in the REF scenario, the modules with the highest production capacity

are electricity generation and coal, with 23 and 12 million toes, respectively, until 2050. The scenario predicts an increase in transmission and distribution losses of 17 % to 18.5% by 2030, according to data from [22].
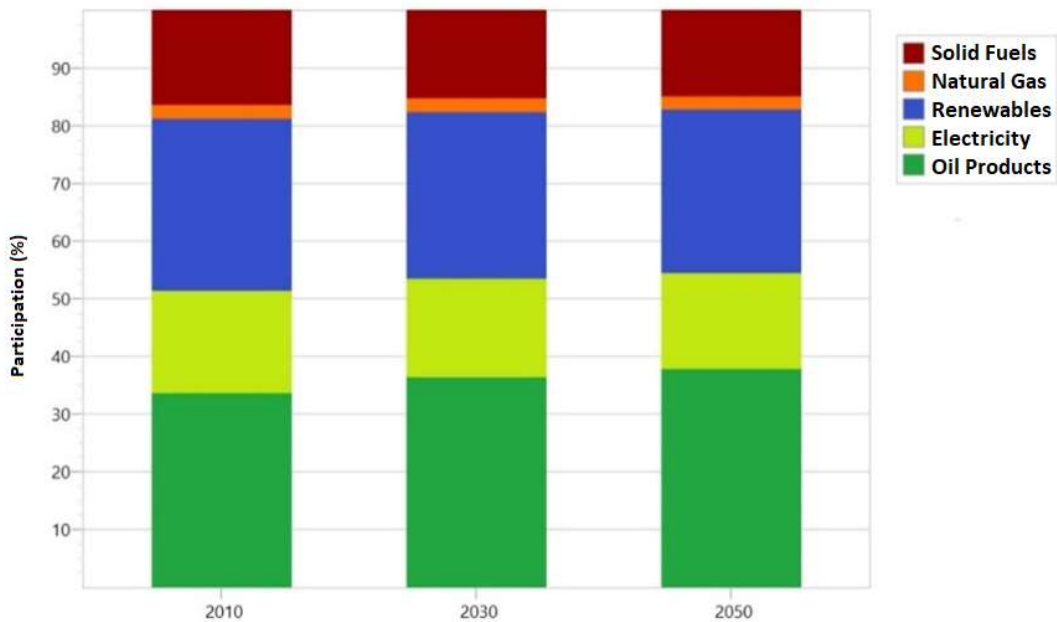

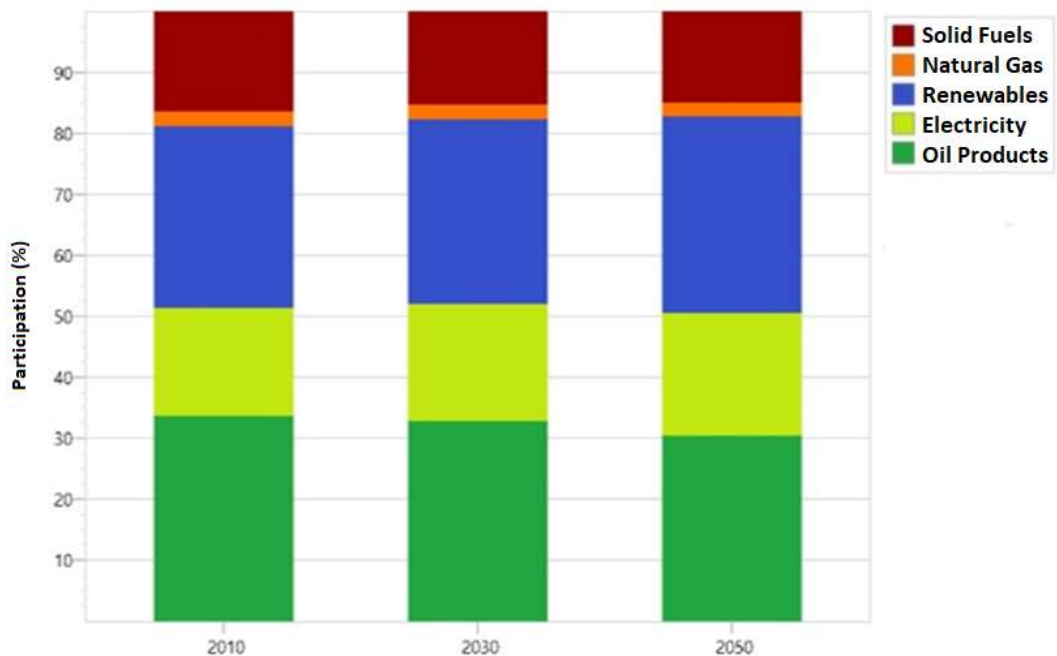**Figure 3:** Final use of energy by fuels – REF (Source: Own elaboration).

Figure 4: Final use of energy by fuels – ETM (Source: Own elaboration).

The alternative scenarios ETM and ETA, in addition to remaining with significant production of electricity and charcoal, also start to produce biofuels (biogas, biodiesel and ethanol) in a considerable way, in order to supply raw material for electricity production and meet the demand of the transport sector. Accordingly, it will be necessary that 12.9 million toes of liquid biofuels be produced in 2050 to meet the demand of the energy system of the ETM scenario, and 14.1 million toes of the ETA scenario.
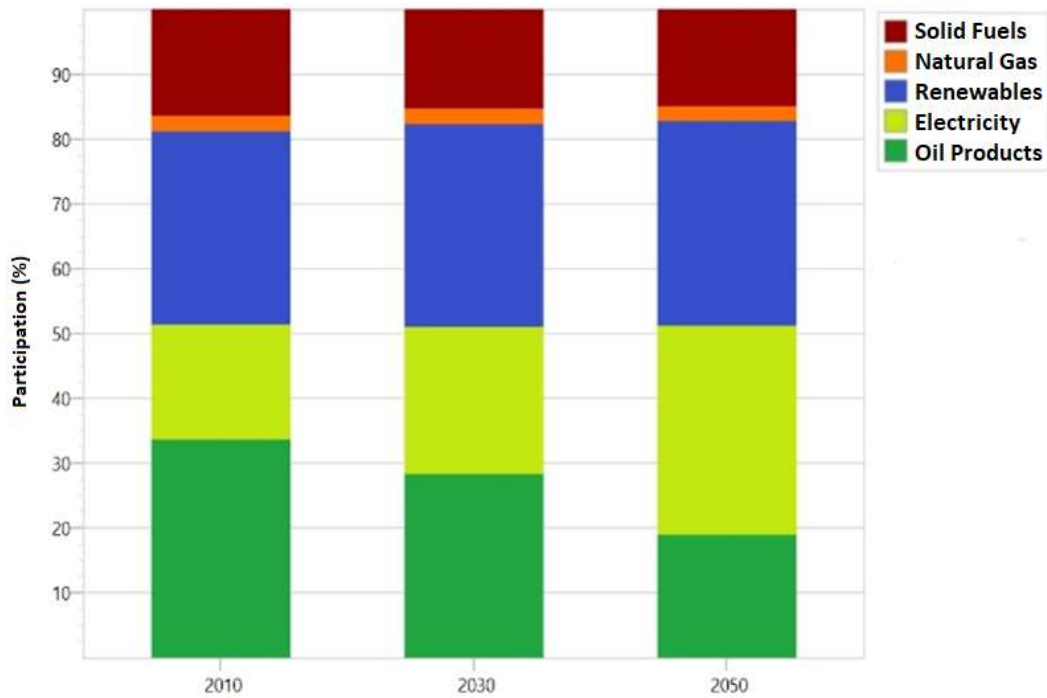
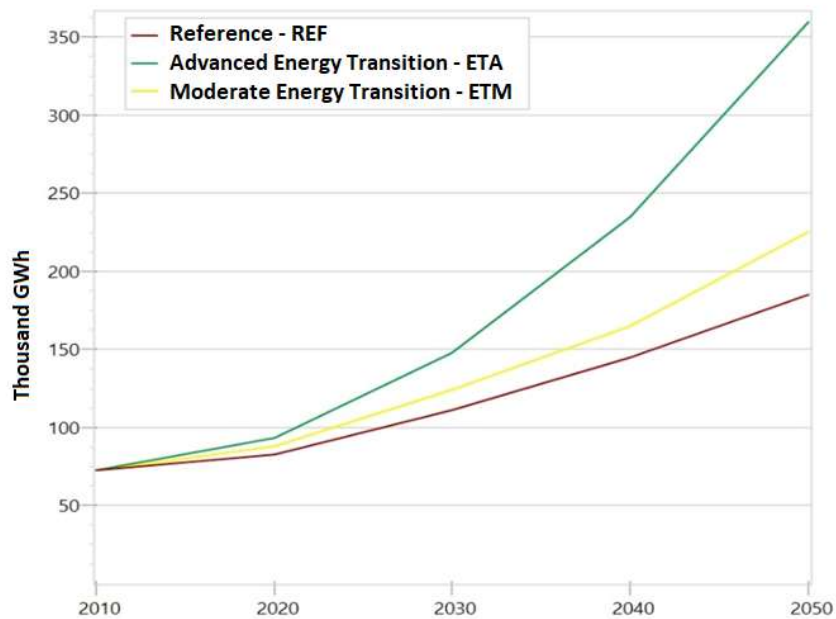**Figure 5:** Final use of energy by fuels – ETA (Source: Own elaboration).

Figure 6: Electricity Demand (Source: Own elaboration).

3.1.4. Electricity Generation

To meet the growing demand for electricity, the REF scenario foresees an expansion in the electric generation capacity that will allow the generation of 136 TWh by 2030, and 227 TWh by 2050, as is shown in Fig. **8**. The alternative scenarios ETM and ETA have an increased capacity for generation of electricity, being able to generate up to 149 TWh and 177.5 TWh by 2030, and 267 TWh and 426 TWh by 2050, respectively. This high amount is due to the penetration of electric vehicles and intermittent source generation technologies (solar and wind), mainly in the ETM scenario, which has a more considerable insertion of these technologies.
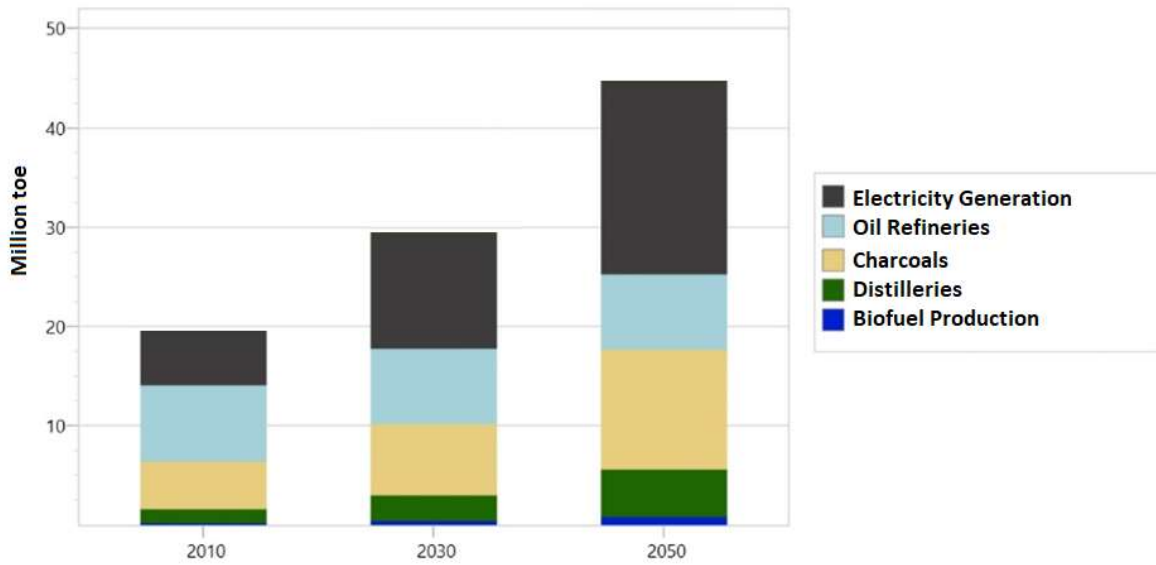
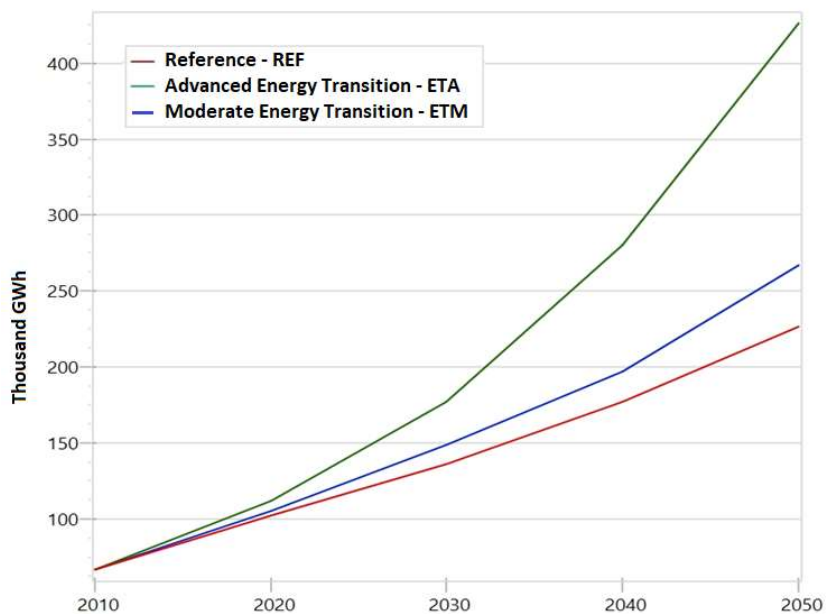**Figure 7:** Energy production – REF (Source: Own elaboration).

Figure 8: Projection of electricity generation (Source: Own elaboration).

The results of the modeling of the electricity generation system can be seen in Table **1**, as well as in Figs. **9** and **10** for 2030 and 2050, respectively. In the base year 2010, more than 80% of the electric matrix of the State of Minas Gerais was composed of hydroelectric plants. In the projections designed for the 2030 period, the REF scenario has an installed capacity of 42.2 GW, being mainly composed of Hydroelectric and Small Hydroelectric Plants (32.3%), followed by natural gas (24.5%), fuel oil (22.8%) and mineral coal (13.5%). The ETM scenario has an installed capacity of 49.6 GW, and its composition differs significantly from the REF scenario, being composed mainly of renewable energy sources. In this scenario, combined cycle UTEs powered by natural gas are the main base of the matrix, with 34.4%, followed by hydroelectric plants, with 27.9%, and thermal plants powered by biomass, which add up to 24.6%. In this scenario, photovoltaic technology has more expressive participation, accounting for 10.1% of the matrix composition. The ETA scenario has the largest installed capacity when compared to the others, with 64.8 GW, in which combined cycle thermal plants account for 27.8%, and biomass thermal plants have a more expressive role than hydro plants, with 24.3% and 21.5%, respectively. The

photovoltaic share also grows to 15.4% and, in this scenario, the wind farms that represent 7.7% of the matrix are inserted.

Table 1:   Installed Capacity (GW) by scenario

Scenario	2030	2050
Reference – REF	42.2	69.8
Moderate Transition - ETM	49.6	90.9
Advanced Transition - ETA	64.8	155.0

Source: Own elaboration.
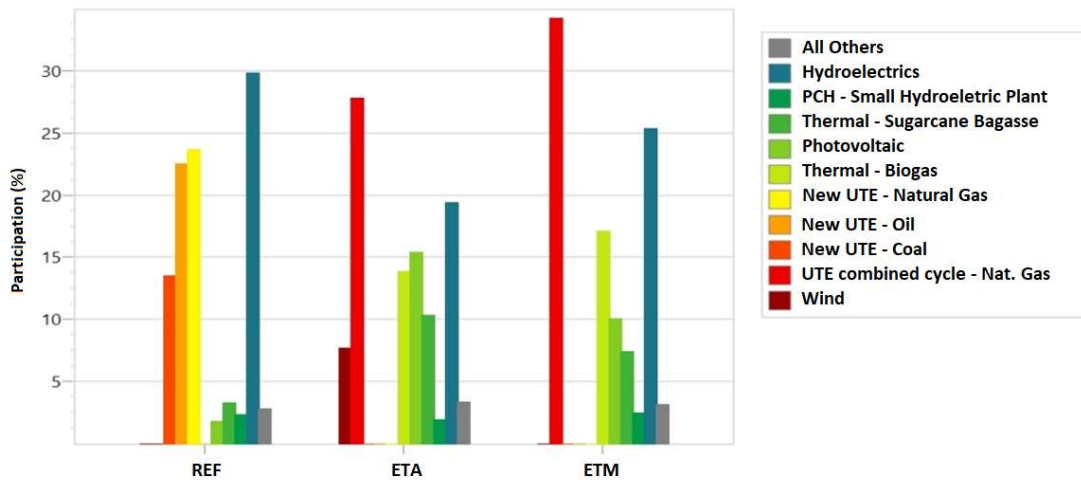
Figure 9: Electric matrix in 2030 by scenario (Source: Own elaboration).

The electrical matrix of the REF scenario in 2050 has a significant increase in the share of technologies powered by fossil fuels (75.7%), becoming the main basis of the system. The ETM and ETA scenarios manage to maintain themselves by a majority generation of renewable energy sources, however, there is a significant reduction in the water source, 15.8% and 9.4%, respectively. In these scenarios, the biomass thermal plants and photovoltaic plants correspond to a large part of the system, in the ETM scenario, 25.8% and 14.3%, and in the ETA scenario, 26.4% and 16.8%, respectively.

Figure 10: Electric matrix in 2050 by scenario (Source: Own elaboration).

3.1.5. Resources

As expected, in the 2050 horizon, the ETA scenario is the one that most needs energy resources to supply its energy system,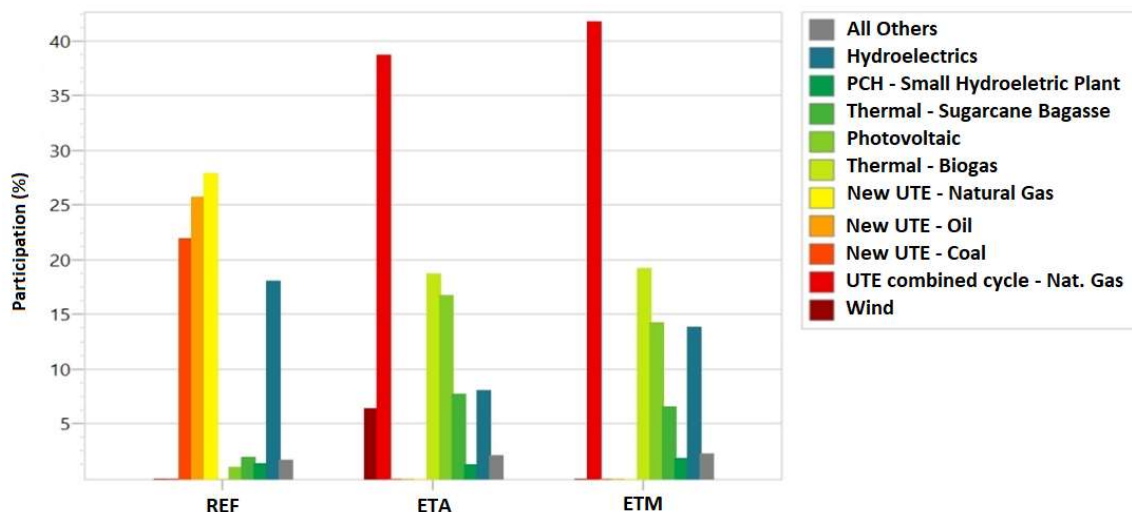 with demand in the order of 160 million toe. However, until 2030 both REF and ETM scenarios had their respective demands for resources practically equal, with an order of 85 million toe. The scenario with the lowest resource intensity over the entire projected period is the ETM scenario, with 79 million toe in 2030, and 141 toe in 2050. This represents a difference of approximately 20 million toe between the ETM and ETA scenarios.

Although the ETA scenario is the most intensive in energy resources, it is the least dependent on the import of resources, since its system is predominantly dependent on renewable resources, which are produced within the scope of the mining territory. On the other hand, the REF scenario, which is intensive in non-renewable energy sources, is highly dependent on their import, since Minas Gerais does not have significant reserves of oil, mineral coal or natural gas. As it is shown in Fig. **11**, the ETM and ETA scenarios have similar import needs over the analyzed period. However, the REF scenario has a difference of nearly 40 million toe, in the year 2050, when compared to the other two scenarios.
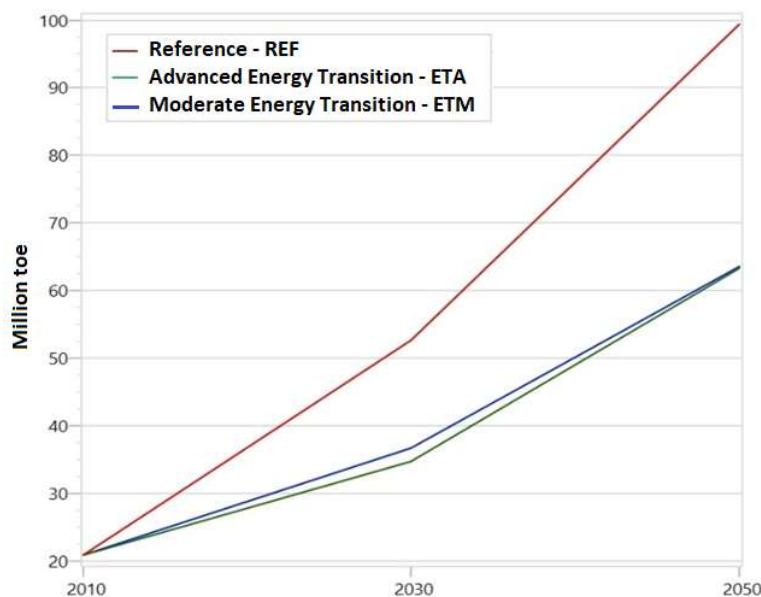

Figure 11: Import of energy resources by scenario (Source: Own elaboration).

3.1.6. Greenhouse Gas Emissions

The evolution of GHG emissions, in the period 2030-2050, referring to the energy sector in the State of Minas Gerais, for the three scenarios modeled in this study, are shown in Fig. **12**. In the REF scenario, emissions are expected to increase around 36 million tCO_{2e} by 2030, when compared to the base year, and in 2050 that value more than triples, reaching the amount of 109 million tCO_{2e}. In alternative scenarios, emissions are lower when compared to the REF scenario, with the ETA scenario being the least carbon-intensive, with an increase of 23 tCO_{2e} in 2030, and 54 tCO_{2e} in 2050, this last presenting a reduction of approximately 50% when compared to REF. The ETM is expected to increase by 31 million tCO_{2e} by 2030, and 87 million tCO_{2e} by 2050, a reduction of around 30% compared to the REF scenario.

3.1.7. Cost-Benefit Analysis

A cost-benefit analysis of the projected scenarios was performed, and the results are shown in Table **2**. The results are based on the costs of electricity production and the costs of importing energy resources, as well as the Net Present Value - NPV of the scenarios alternatives compared to the baseline scenario. The NPV represents all discounted costs, at a rate of 8% in 2010 and accumulated benefits in one scenario minus the other. Thus, we can observe that in the period from 2010 to 2050 the ETM scenario will cost around 18.1 billion dollars more than the REF scenario in terms of electricity generation costs, while this value for the ETA scenario will be around 34.8

billion dollars. This difference was expected since the alternative scenarios, in addition to having a higher installed capacity, also have generation technologies with higher associated costs when compared to the REF scenario.
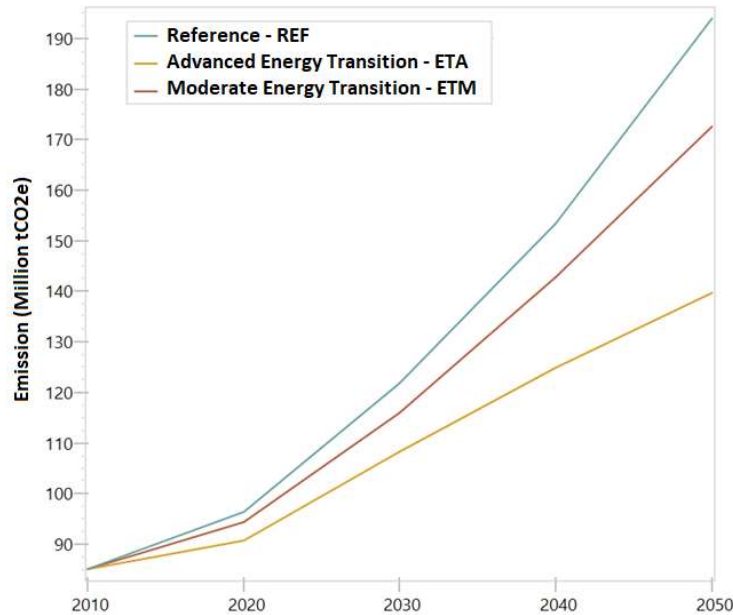

Figure 12: Evolution of GHG Emissions in the 2030-2050 horizon by scenario (Source: Own elaboration).

However, when the analysis is made for energy resources, the REF scenario, as it is more dependent on imports, is more expensive when compared to alternative scenarios, with the ETM scenario being 159.2 billion dollars cheaper, and the ETA scenario 182 billion dollars. Since the cost of importing energy resources exceeds the costs of producing electricity, the NPV for the ETM and ETA scenarios is negative. This means that the REF scenario is more expensive than the alternative scenarios; in other words, the negative sign denotes how much cheaper these are compared to the REF scenario. For this study, the ETM scenario is 141.1 billion dollars cheaper than the REF; for the ETA scenario this amount is equivalent to 147.2 billion dollars. The ETA scenario, in addition to presenting the best cost-benefit relation, it is also the least emitter, avoiding the emission of 746 million tCO_{2e} in relation to the REF scenario.

Table 2:   Cost-benefit analysis of alternative scenarios compared to the REF scenario

Cumulative costs and benefits: 2010-2050. Relative Scenario: Reference. Discount rate 8% for the year 2010. Unit: Billions U. S. Dollar		
Scenario	**Moderate Energy Transition**	**Advanced Energy Transition**
Transformation	18.1	34.8
Electricity Generation	18.1	34.8
Resources	-159.2	-182.0
Production	-	-
Import	-159.2	-182.0
Export	-	-
Net Present Value - NPV	-135.1	-147.2
Avoided Emissions (Millions of tCO_{2e})	286.6	746.2

Source: Own elaboration

3.2. Energy Systems in the Future

As shown in the REF scenario, it is expected that with population growth and economic development, energy consumption will increase significantly over the 2030-2050 horizon. The results show that the ETA scenario is the most promising in terms of meeting the growing demand for energy, with the least dependence on the import of energy resources in the studied horizon, and that it is still the most effective in terms of reducing GHG emissions in the energy sector. The ETA scenario is also cheaper compared to the REF scenario, according to the electricity generation associated with the import of energy resources. In this way, the ETA scenario was chosen as a basis to support the decision-making process related to the construction of the energy transition policy guidelines for the State of Minas Gerais.

Figures **13** and **14** are shown the energy matrix of the State of Minas Gerais, under the ETA scenario, for the years 2030 and 2050, respectively. In the first period, it is clear that renewable sources, in addition to hydraulic sources, represent the main basis of the system, and that fossil fuels, although they have expressive participation, are used basically to serve the transport sector and industry. In 2050, renewable sources are expected to expand further, mainly in electricity generation to meet the expressive demand of the transport sector, which will have undergone a significant transition to biofuels and electric vehicles. To ensure the reliability of the electrical system, natural gas is the main fossil fuel used in the system, since the thermal plants of the combined cycle are more efficient, and natural gas is more environmentally sustainable, when compared to the other sources.
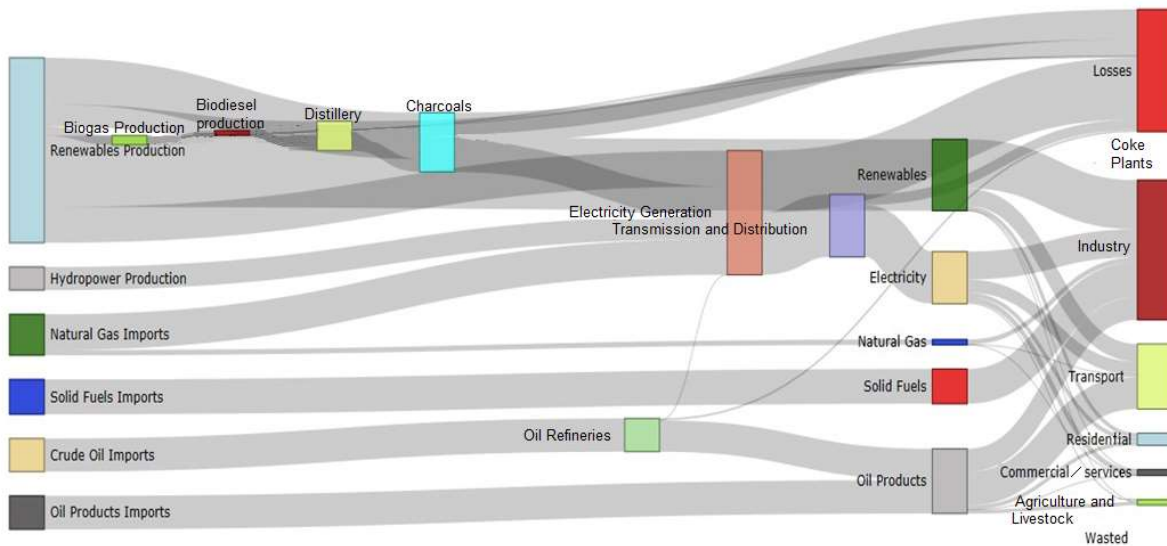

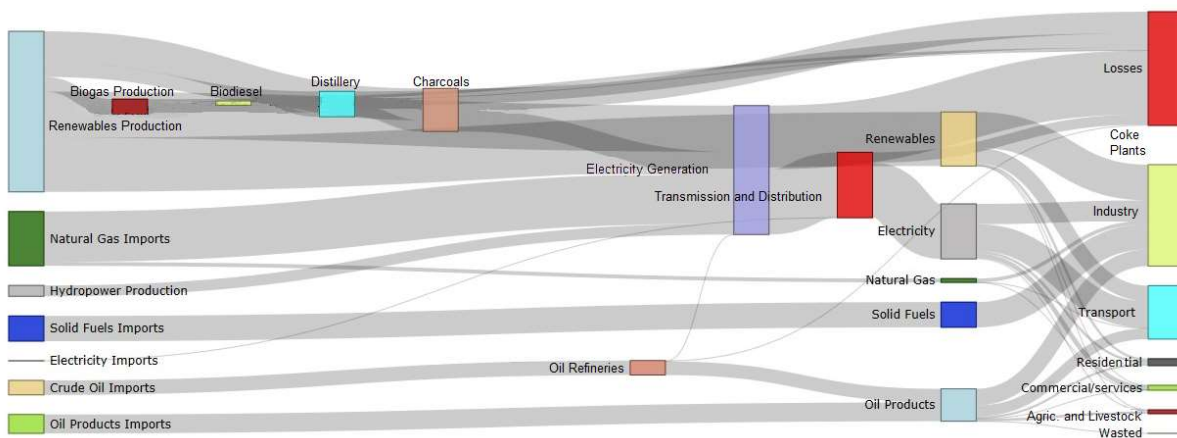**Figure 13:** Energy matrix in 2030 - ETA scenario (Source: Own elaboration).

Figure 14: Energy matrix in 2050 - ETA scenario (Source: Own elaboration).

3.3. Transition Energy Policy Proposal - PETE

The proposal for a PETE for Minas Gerais aims to promote the integrated and improved adoption of the modeling of energy scenarios in the medium and long term, to develop and accelerate the energy transition in the State of Minas Gerais. In this sense, the ETA scenario, which demonstrates greater viability in view of the parameters evaluated in this research, should be integrated into the decision-making process, in order to provide the goals and guidelines for the planning of the energy system of the State of Minas Gerais in the horizon 2030-2050.

3.3.1. Energy Transition Goals for the Horizon 2030-2050

The goals that will guide PETE correspond to the composition of the ETA scenario and they are listed in Table **3**.

Table 3: Energy Transition Goals for the 2030-2050 horizon.

	2030	2050
Renewable Energies	50% excluding large hydroelectric plants	60% excluding large hydroelectric plants
Energy efficiency in the electricity sector	10% gain in the electricity sector	15% gain in the electricity sector
Reduction of GHG Emissions	12% compared to the REF scenario	28% compared to the REF scenario

Source: Own elaboration

3.3.2. PETE Guidelines

PETE establishes the following guidelines:

- Identify and solve challenges that hinder the achievement of renewable energy and energy efficiency goals;
- Reduce dependence on fossil fuels as a primary energy source to meet the state's energy demands;
- Promote widely the achievement of renewable energy and energy efficiency targets;
- Provide tax, financial and credit instruments that increase the economic viability of renewable energy projects and energy efficiency actions in the state;
- Invest in research and development in renewable energy and energy efficiency to contribute to the state's socio-economic development.

3.3.3. PETE Axes

The PETE aims to make efficient and diversify the energy matrix of Minas Gerais by, mainly, the following axes of efficiency and renewable energy:

- Energy efficiency in the electricity sector;
- Energy efficiency in final energy consumption;
- Low carbon technologies;
- Solar energy, mainly technologies;
- Wind energy;
- Biomass.

3.3.4. PETE - State Political Action Lines

The energy transition strategy of Minas Gerais is designed in order to implement public policies that guarantee the favorable milestones so that the actions of the government and the private sector, which aim at the fulfilment of the goals proposed here, are supported by a base of regulations and mechanisms of sustainable development.

In this perspective, the energy transition policy is divided into six categories:

- Regulation;
- Awareness;
- Research & Development & Innovation;
- Demonstration of Projects;
- Training of Human Resources;
- Markets and financing;
- International cooperation.

3.3.5. Regulation

It will provide the legal framework that aims to provide the rules that regulate the economic and social activities involved in the energy transition process. Initially, it is suggested that the regulatory framework be composed of at least three legal instruments, namely:

- A law establishing the Minas Gerais State Energy Transition Policy - PETE, regulated by two decrees:
- the State Renewable Energy Expansion Program;
- the State Program for Low Carbon Technologies and Energy Efficiency;

3.3.6. Awareness

Sensitize all the actors involved by campaigns that clearly demonstrate the objectives and importance of the energy transition, as well as the need for the whole society to commit to this process. It is also necessary to involve governmental and non-governmental institutions in order to coordinate the design, implementation, operation, and evaluation of policies, programs and projects for the state energy transition.

3.3.7 Research & Development & Innovation (R&D&I)

It aims to increase and disseminate knowledge about energy transitions, as well as to promote innovation by providing direct incentives for specific projects, and thus provide both the technical and economic improvement of existing technologies, as well as the creation of new technologies.

3.3.8. Demonstration of Projects

The state should use the principle of exemplarity, and promote renewable energy and energy efficiency projects within its competence, in order to demonstrate sustainable technologies, as well as their social, environmental and economic impacts.

3.3.9. Human Resources Training

The energy transition process consists of massive adoption of technology and best practices that constantly evolve and modify in order to generate new opportunities and needs. Thus, it is essential to have sufficient and trained human resources to guarantee the implementation of the energy transition not only in technological terms but also in terms of coordinating the policies, programs and projects associated with it.

3.3.10. Markets and Financing

Promote financing mechanisms, as well as tax incentives, to establish the renewable energy and energy efficiency market in the State of Minas Gerais. This should be able to flow linked to lower transaction costs and according to the opportunities that the regulatory and technological exchange allows.

3.3.11. Cooperation

Cooperation is an important development tool for the State and allows the transfer of resources, knowledge, successful experiences and technologies, collaborating effectively with the training of human resources and strengthening of the institutions of the receiving state.

3.3.12. Main Expected Products

This strategy should serve to support the creation of the following instruments:

- A law establishing the Minas Gerais State Energy Transition Policy - PETE;

- Decree regulating the State Renewable Energy Expansion Program;

- Decree that regulates the State Program for Low Carbon Technologies and Energy Efficiency;

- Energy Transition Coordination Strategy;

- PETE's financing strategy.

4. Final Considerations

The transition to more sustainable energy systems has already started in several parts of the world, and that actions range from the scope of international agreements, such as the Paris Agreement, to the national, subnational and local levels. In this context, the state transition, through low carbon development, will largely depend on energy policies initiated and implemented in the future.

The three scenarios developed in this study (REF, ETM and ETA) bring future perspectives on what could happen if no additional policies are implemented (REF scenario), and if policies and strategies are adopted aiming at a low carbon path in the projected future (ETM and ETA) in the case study of Minas Gerais.

The ETM and ETA scenarios proved to be viable options in terms of changing future prospects, which are carbon-intensive and costly, through the implementation of medium and long-term policies aimed at more sustainable energy systems. The ETA scenario was the one that presented the best cost-benefit ratio, since it manages to increase the share of renewable energies, excluding large hydro, by 50% by 2030 and 60% by 2050, reducing GHG emissions by around 50% compared to the REF scenario, with no significant increase in costs compared to the ETM and cheaper, in the medium to long-term, compared to the REF. The ETA scenario also considers the possible transition to electric vehicles in the transport sector, which will significantly increase the need for electricity, without polluting the electrical matrix by increasing the insertion of fossil sources. In addition, the ETA scenario has an installed capacity 62% greater than the ETM scenario, 2.6 times greater than the REF scenario. In this sense, the ETA scenario is the most effective in terms of low carbon development, increased energy security and combating climate change. The ETA scenario indicates that the transport sector may have a significant impact on the electric matrix due to the significant insertion of electric vehicles, and although it is considered the best option among the three scenarios analyzed, it shows that the energy efficiency goals from NDC may not be compatible to the Paris Agreement pathways, once it implies in a considerable increase of energy consumption.

In terms of GHG mitigation, the results show that the transformation sector is an important ally in the search for reducing emissions, but the transport and industry sectors are also important since together they represent more than 50% of the allocated emissions in energy demand. Although the ETM scenario already proposes a transition in the transport sector, the results also showed that it is necessary to carry out studies to propose a transition with the same purposes for the industry sector.

The cost-benefit analysis carried out in this study confirmed that in the medium-long term, investment in renewable energy projects is lower than fossil energy projects. This result is a key factor in instructing the decision-making process regarding both the formulation of public policies and the convincing of investors in the energy sector.

The proposal of the PETE incorporated all the results of the ETA scenario, as well as the best international practices to promote the energy transition aimed at the subnational and local levels. We can consider that PETE has ambitious goals and objectives. As presented in this study, ambition is one of the key factors to create an energy transition policy that aims to spread sustainable energy systems. Thus, instituting a state energy transition policy is necessary to act effectively against short-term government policies. In this sense, PETE is an opportunity for the consolidation of a state policy, thus guaranteeing the principle of continuity, and at the same time guaranteeing a healthy environment with access to safe and reliable energy for all.

For last, it is important to highlight that the methodology used to build the model that supported this work was based on the same assumptions used to build the NDC of Brazil, which means that the assumptions used on this work were based on the data available until 2015, and in line with the scenarios developed to subside the current NDC [25]. In the Brazilian context of such a year, it was expected a linear growth of GDP and industry developments, which implies a significant increase in energy consumption. Since the main goal of this work is to provide a methodology and framework to enable the distribution of the Brazilian NDC goals, it was kept the same assumptions used at the national level in order to have a comparison basis. However, times have changed, and new data shows that the GDP growth and developments may not be so optimistic as it was back in 2015. In this sense, we can consider that the current NDC may be outdated, and as a very next step all the analyses both, national and subnational, must be updated to reflect the current changes in the world. Still, it does not mean that this work loses its effect, once it is important to have all the perspectives analysed under the eyes of that the Brazilian NDC is the current framework approved to fight against climate change in Brazil, which means that till this date, all states must implement actions to achieve the national goals presented on this instrument.

Acknowledgments

Abbreviations and Nomenclatura

ANEEL	=	National Electric Energy Agency
ANP	=	National Petroleum, Natural Gas and Biofuels Agency
BEEMG	=	Energy Balance of the state of Minas Gerais
CO_{2e}	=	Carbon dioxide equivalent
EPE	=	Energy Research Company
ETA	=	Advanced Energy Transition Scenario
ETM	=	Moderate Energy Transition Scenario
GDP	=	Gross Domestic Product
LEAP	=	Long-range Energy Alternatives Planning System
MME	=	Ministry of Mines and Energy
MG	=	Minas Gerais
NDC	=	Nationally-Determined Contributions
ONS	=	National Electric System Operator
PETE	=	State Energy Transition Policy
REF	=	Reference Scenario
t_{CO2e}	=	tons of CO_{2e}

References

[1] IPCC, Intergovernmental Panel on Climate Change. Climate Change 2014 Synthesis Report Summary for Policymakers. 2014. http://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf. [Accessed: September 9, 2018].

[2] IEMA, *Instituto de Energia e Meio Ambiente. Emissões de GEE do Setor de Energia, Processos Industriais e Uso de Produtos*. (Institute of Energy and Environment. GHG Emissions from the Energy Sector, Industrial Processes and Product Use) http://seeg.eco.br/wp-content/uploads/2016/09/FINAL-16-09-23-RelatoriosSEEG-PIUP_.pdf. [Accessed: September 15, 2018].

[3] FEAM – Fundação Estadual do Meio Ambiente de Minas Gerais. Estimativas de Emissões de Gases de Efeito Estufa do Estado de Minas Gerais Período de Referência: 2005-2014. (State Foundation for the Environment of Minas Gerais. Estimates of Greenhouse Gas Emissions for the State of Minas Gerais Reference Period: 2005-2014), 2016. http://pemc.meioambiente.mg.gov.br/images/Estimativas_GEE_2005_2014_MG_FEAM_v02-1.pdf [Accessed: November 9, 2018].

[4] Sanchez A. *Atividades Humanas e Mudanças Climático-Ambientais: Uma Relação Inevitável.* (Human Activities and Climate-Environmental Change: An Inevitable Relationship.) São Paulo, 2009. http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/43/130/43130587.pdf. [Accessed: September 29, 2017].

[5] Melo LB, Estanislau FBGL, Costa AL, Fortini A. Impacts of the hydrological potential change on the energy matrix of the Brazilian State of Minas Gerais: A case study. Renew Sustain Energy Rev. 2019; 110: 415-422 https://doi.org/10.1016/j.rser.2019.05.018

[6] BRASIL. Pretendida Contribuição Nacionalmente Determinada Para Consecução do Objetivo da Convenção-Quadro das Nações Unidas sobre Mudança do Clima. (Intended Nationally Determined Contribution to Achieving the Goal of the United Nations Framework Convention on Climate Change.) 2015. em:http://www.mma.gov.br/images/arquivo/80108/BRASIL%20iNDC%20portugues%20FINAL.pdf [Accessed: February 15, 2019].

[7] EPE, *Empresa de Pesquisa Energética, Brasil. Balanço Energético Nacional 2018: Ano Base 2017*. (Energy Research Company, Brazil. National Energy Balance 2018: Base Year 2017.) http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-303/topico-419/BEN2018__Int.pdf. [Accessed: February 10, 2019].

[8] CEMIG, *Companhia Energética de Minas Gerais. 32° Balanço Energético do Estado de Minas Gerais - BEEMG 2017: Ano Base 2016.* (Minas Gerais Energy Company. 32nd Energy Balance of the State of Minas Gerais - BEEMG 2017: Base Year 2016.) Companhia Energética de Minas Gerais. Belo Horizonte: CEMIG, 2018.

[9] ANEEL, *Agência Nacional de Energia Elétrica – Regulação do Setor Elétrico* (National Electric Energy Agency - Regulation of the Electric Sector). Brasília, 2015. http://www.aneel.gov.br/mercado-de-eletricidade. [Accessed: February 20, 2019].

[10] MME, *Ministério de Minas e Energia. Plano Nacional De Eficiência Energética: Premissas e Diretrizes Básicas* (Ministry of Mines and Energy. National Energy Efficiency Plan: Basic Assumptions and Guidelines). Brasília, 2011. http://www.mme.gov.br/documents/10584/1432134/Plano+Nacional+Efici%C3%AAncia+Energ%C3%A9tica+%28PDF%29/74cc9843-cda5-4427-b623-b8d094ebf863?version=1.1. [Accessed: November 20, 2018].

[11] MME, Ministério de Minas e Energia. Renova Bio – Brasília, 2017. http://www.mme.gov.br/web/guest/secretarias/petroleo-gas-natural-e-combustiveis-renovaveis/programas/renovabio/principal. [Accessed: November 20, 2018].

[12] FEAM – Fundação Estadual do Meio Ambiente de Minas. Plano de Energia e Mudanças Climáticas de Minas Gerais: Resumo Executivo / Fundação Estadual do Meio Ambiente; com apoio de Agência Francesa do Meio Ambiente e da Gestão de Energia, Conselho Regional de Nord Pas-de-Calais. (State Foundation for the Environment of Minas. Minas Gerais Energy and Climate Change Plan: Executive Summary / State Foundation for the Environment; with support from the French Agency for the Environment and Energy Management, Regional Council of Nord Pas-de-Calais). Belo Horizonte, 2015.

[13] Dos Anjos MM, Tenenwurcel D, Ferreira WR, Costa AL, Pereira EMD. The Role of the Renewable Energy Program in the State of Minas Gerais in the Process of Renewable Sources Expansion. Global J Energy Technol Res Updat. 2019; 6: 1-11. http://dx.doi.org/10.15377/2409-5818.2019.06.1

[14] ANEEL, *Agência Nacional de Energia Elétrica – Regulação do Setor Elétrico* (National Electric Energy Agency - Regulation of the Electric Sector). Brasília, 2015b. http://www.aneel.gov.br/mercado-de-eletricidade. [Accessed: November 22, 2018].

[15] Roinioti A, Koroneos C, Wangensteen I. Modeling the Greek Energy System: Scenarios of Clean Energy Use and Their Implications. Energy Policy, 2012; 50: 711-722. https://doi.org/10.1016/j.enpol.2012.08.017

[16] Park NB, Yun SJ, Jeon EC. An Analysis of Long-Term Scenarios for the Transition to Renewable Energy in the Korean Electricity Sector. Energy Policy, 2013; 52 288-296. https://doi.org/10.1016/j.enpol.2012.09.021

[17] Emodi NV, Emodi CC, Murthyc GP, Emodi ASA. Energy Policy for Low Carbon Development in Nigeria: A Leap Model Application. Renew Sustain Energy Rev. 2017; 68: 247-261. https://doi.org/10.1016/j.rser.2016.09.118

[18] Hu G, Maa X, Jia J. Scenarios and Policies for Sustainable Urban Energy Development Based on Leap Model – A Case Study of a Postindustrial City: Shenzhen China. Appl Energy 2019; 238: 876-886. https://doi.org/10.1016/j.apenergy.2019.01.162

[19] SEI, Stockholm Environment Institute. User Guide, Leap: Long Range Energy Alternative Planning System. Stockholm Environment Institute, Boston; 2011.

[20] Melo LB. *Análise Integrada do nexo Água-Energia-Emissões e Mitigação das Externalidades para o Estado de Minas Gerais* (Integrated Analysis of the Water-Energy-Emissions nexus and Mitigation of Externalities for the State of Minas Gerais), Thesis: Postgraduate Program in Nuclear Sciences and Techniques, Federal University of Minas Gerais, Brazil, 2020.

[21]   MME/EPE, Ministério de Minas e Energia, Empresa de Pesquisa Energética (Brasil). Plano Decenal de Expansão de Energia 2027. (Ministry of Mines and Energy, Energy Research Company (Brazil). 2027 Ten-Year Energy Expansion Plan), 2018. http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/Documents/PDE%202027_aprovado_OFICIAL.pdf.   [Accessed: September 15, 2018].

[22]   EPE, *Empresa de Pesquisa Energética, Brasil. Plano Nacional de Energia 2030*. (Energy Research Company, Brazil. National Energy Plan 2030),   2007.   http://epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-165/topico-173/PNE%202030%20-%20An%C3%A1lise%20Retrospectiva.pdf. [Accessed: September 15, 2018].

[23]   EPE, *Empresa de Pesquisa Energética, Brasil. Plano Nacional de Energia 2050*. (Energy Research Company, Brazil. National Energy Plan 2050), 2014. http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/Plano-Nacional-de-Energia-2050. [Accessed: September 15, 2018].

[24]   IRENA, International Renewable Energy Agency. Planning for the Renewable Future: Long-Term Modelling and Tools to Expand Variable Renewable Power in Emerging Economies. 2017. https://www.irena.org/energytransition/Energy-Planning-Support/National-Energy-Master-Plan-Development. . [Accessed: February 15, 2018].

[25]   Rathmann R, *et al*. *Trajetórias de Mitigação e Instrumentos de Políticas Públicas Para Alcance das Metas Brasileiras no Acordo De Paris* (Mitigation Paths and Public Policy Instruments to Achieve Brazilian Targets in the Paris Agreement), Ministério da Ciência, Tecnologia, Inovações e Comunicações, ONU Meio Ambiente, 2017. 64 p. https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/cgcl/clima/arquivos/opcoes-de-mitigacao-de-emissoes-de-gee-em-setores-chave/trajetorias-de-mitigacao-e-instrumentos-de-politicas-publicas-para-alcance-das-metas-brasileiras-no-acordo-de-paris.pdf [Accessed: January 21, 2019].

[26]   IBGE, *Instituto Brasileiro de Geografia e Estatísticas. Projeção da População do Brasil e das Unidades da Federação.* (Brazilian Institute of Geography and Statistics. Projection of the Population of Brazil and Federation Units). https://www.ibge.gov.br/apps/populacao/projecao/. 2019. [Accessed: January 19, 2019].

[27]   FJP, *Fundação João Pinheiro. Produto Interno Bruto (PIB) de Minas Gerais: Relatório Anual 2010-2013* (João Pinheiro Foundation. Gross Domestic Product (GDP) of Minas Gerais: Annual Report 2010-2013). 2014. http://fjp.mg.gov.br/index.php/docman/cei/informativos-cei-eventuais/590-monitor-fjp-relatorio-anual-do-pibmg-2010-2013-atualizacaodez-20152/file. [Accessed: January 19, 2019].

[28]   ANEEL, *Agência Nacional de Energia Elétrica – Banco de Informações de Geração – BIG* (National Electric Energy Agency - Generation Information Bank - BIG). Brasília, 2019. http://www2.aneel.gov.br/aplicacoes/capacidadebrasil/capacidadebrasil.cfm. [Accessed: January 21, 2019].

[29]   IEA ETSAP, International Energy Agency – Energy Technology Systems Analysis Program. Technology Brief Coal-Fired Power. (2010). http://www.iea-etsap.org/Energy_Technologies/Energy_Supply.asp [Accessed: January 21, 2019].

[30]   IEA ETSAP, International Energy Agency – Energy Technology Systems Analysis Program. Technology Brief Gas-Fired Power. (2010). http://www.iea-etsap.org/Energy_Technologies/Energy_Supply.asp [Accessed: January 21, 2019].

[31]   IEA ETSAP, International Energy Agency – Energy Technology Systems Analysis Program. Technology Brief Hydropower, 2010. http://www.iea-etsap.org/Energy_Technologies/Energy_Supply.asp [Accessed: January 21, 2019].

[32]   IEA ETSAP, International Energy Agency – Energy Technology Systems Analysis Program. Technology Brief Biomass for Heat and Power, 2010. http://www.iea-etsap.org/Energy_Technologies/Energy_Supply.asp [Accessed: January 21, 2019].

[33]   IEA ETSAP, International Energy Agency – Energy Technology Systems Analysis Program. Technology Brief Combined Heat and Power, 2010. http://www.iea-etsap.org/Energy_Technologies/Energy_Supply.asp [Accessed: January 21, 2019].

[34]   IEA ETSAP, International Energy Agency – Energy Technology Systems Analysis Program. Technology Brief Photovoltaic Solar Power, 2013. http://www.iea-etsap.org/Energy_Technologies/Energy_Supply.asp [Accessed: January 21, 2019].

[35]   IEA ETSAP, International Energy Agency – Energy Technology Systems Analysis Program. Technology Brief Biogas and Bio-Syngas Production, 2013b. http://www.iea-etsap.org/Energy_Technologies/Energy_Supply.asp [Accessed: January 21, 2019].

[36]   Moura GNP. Long-term Power Systems Integration Using Osemosys Samba - South America Model Base - and the Bargaining Power of Countries: A Cooperative Games Approach. Thesis: Postgraduate Program in Energy Planning, COPPE, Federal University of Rio de Janeiro, Brazil. Rio de Janeiro, 2017.

ANNEX I

Table 4:   General Assumptions - LEAP - case of Minas Gerais.

General Assumptions	Scenarios REF – ETM - ETA		
	2010	**2030**	**2050**
Population (millions)	20	22.2	22.05
Pop. growth (%)	-	0.29	-0.29
GDP (Billion R$)	351.4	439.6	613.3
Growth GDP (%)	-	2.2	1.6
Per capita income (thousand R$)	17.6	19.5	26.3
VA growth rate VA - Agricultural	-	1.7	1.6
VA growth rate - Services	-	1.7	1.2
VA growth rate - Industry	-	2.5	2.0

Source: [25-27].

Table 5:   Technical data for the electricity generation module of the LEAP model for Minas Gerais.

Type of Technology	Dispatch Rule	Efficiency (%)	Capacity Installed (MW)	Production (mil tep)	Availability Factor (%)	Lifespan	Cost of Capital (US$/KW)	Fixed Cost (US$/KW)	Credit Capacity *
Hydroelectric	Base	95	12500	5025	95	60	1750	35	100
PCH e CGH	Base	95	519	350	95	60	2000	45	100
Thermal - Natural gas	Peak	35	334	108	85	30	900	36	100
UTE – Firewood	Peak	25	200	7.25	85	25	3000	100	100
UTE – Sugarcane bagasse	Peak	25	874	200	66[2]	25	3000	100	100
UTE – Fuel oil	Peak	25	131	1.5	85	25	1400	25	100
UTE – Other primary sources	Peak	25	260	56	85	25	1400	25	100
UTE Biogas	Peak	25	-	-	85	25	3000	100	100
UTE Mineral coal	Peak	46	-	-	85	40	2200	88	100
New UTE – Natural Gas	Peak	35	-	-	85	30	900	36	100
UTE – Combined Cycle - Natural Gas	Base	65	-	-	85	30	1100	44	100
Photovoltaic	Base	15	-	-	42[3]	25	2500	30	30
Wind	Base	95	-	-	35[4]	30	1620	36	30

*Credit capacity is used to calculate the reserve margin of the system, intermittent sources are not firm enough, therefore, have low credit capacity [19].

Source: Adapted from: [8, 28, 29, 30, 31, 32, 33, 34, 35, 36].

[2]The 66% availability is due to the off-season of sugarcane

[3]It was considered a maximum sun availability period of 10 hours per day.

[4]As it is an intermittent source, the average availability of wind power is 35% [19].

Table 6:　Main assumptions of the REF, ETM and ETA scenarios.

Main assumptions for the three scenarios		
REF	**ETM**	**ETA**
• Expansion at minimal cost, with the inclusion of hydroelectric and fossil fuels. • Disregard of additional policies to mitigate and adapt to climate change. • Maintenance of the reserve margin through UTE for mineral coal, natural gas and fuel oil (Installed capacity 300 MW, 500 MW, 500 MW, respectively); • Capacity expansion assumptions foreseen in the PNE and BIG ANEEL. • Reduction in the cost of capital for wind technology of 30%, in 2030, and 40%, 2050, compared to the base year [36] • Reduction of the capital cost of photovoltaic technology by 50%, in 2030, and 60%, 2050, compared to the base year (IRENA, 2018c). • For other technologies, a reduction of 10% in the cost of capital is expected in the 2030-2050 horizon, since they are considered mature technologies. • Fossil fuels are expected to double in value during the analyzed period, due to limited resources.	• Goals of Brazilian NDC, cut to Minas Gerais; • 27% to 33% of renewable sources in the electrical matrix, except for water sources by 2030, and 40 to 42% by 2050. • Installed photovoltaic capacity of 5 GW and 13 GW until 2030 and 2050, respectively. • Installed capacity of 7 GW and 15 GW biogas plants by 2030 and 2050, respectively. • Achieve energy efficiency gains in the electricity sector of 10% by 2030 and 15% by 2050. • 7% share of electric vehicles and 24% of biofuels in the transport sector by 2030. • Maintenance of the reserve margin through biogas, PCH, and combined cycle UTE with natural gas (average size 500 MW, 15 MW, 1000 MW, respectively); • It is assumed that the costs are the same as in the REF scenario.	• Freedom to select the evolution of the technological profile and the optimization of the energy matrix; • Replacement of vehicles powered by diesel and gasoline by electric vehicles, powered by biofuels or hybrids. • Minimum of 50% of renewable sources in the electrical matrix, except for water sources by 2030 and 60% by 2050. • Installed photovoltaic capacity of 10 GW and 26 GW until 2030 and 2050, respectively. • Installed capacity of 9 GW and 26 GW biogas plants by 2030 and 2050, respectively. • Installed wind capacity of 5 GW and 10 GW until 2030 and 2050, respectively. • 20% share of electric vehicles and 27% of biofuels in the transport sector by 2030. • 50% share of electric vehicles and 29% of biofuels in the transport sector by 2050. • It is assumed that the costs are the same as in the REF scenario.