Efficient Power Generating Portfolio in Brazil: Conciliating Cost, Emissions and Risk

Edmar Fagundes de Almeida
Instituto de Economia, Universidade Federal do Rio de Janeiro

Gustavo A. Marreiro
Facultad de Ciencias Económicas, Universidad de La Laguna

Francisco Javier Ramos-Real
Facultad de Ciencias Económicas, Universidad de La Laguna

Luciano Losekann
Faculdade de Economia, Universidade Federal Fluminense

Abstract

The main purpose of this paper is to assess the current situation and the energy policy objectives proposed in the 2020 Decennial Plan for Energy Expansion in Brazil. The analysis follows the mean-variance portfolio theory to evaluate the efficiency of electricity generation mix (in terms of cost and risks). The planned portfolio in Brazil is relatively close to the efficient frontier. As there is currently no CO2 price in Brazil, the tendency is that diversification increases fossil fuel share in the energy mix, but the introduction of a CO2 price can be an option to promote renewables. This type of large general market framework can contribute to reduce market uncertainties by reducing the level of government's discretionary activism.

Keywords: mean-variance portfolio theory, Brazil, CO2 price, electricity generation mix.
JEL Classification: L59, L94.

Resumo

O objetivo desse artigo é avaliar a situação atual da matriz de geração de eletricidade brasileira e os objetivos de política energética contidos no Plano Decenal de Expansão de Energia – PDE 2020. A teoria de portfólio é utilizada para analisar a eficiência da matriz de geração em termos de custos e riscos. O portfólio planejado do PDE 2020 é relativamente próximo à fronteira eficiente. Como não há precificação de emissões de CO2 no Brasil, a tendência é que a diversificação da matriz amplie a participação de fontes fósseis. A introdução de preço do carbono implicaria na promoção de fontes renováveis, o que seria coerente com as diretrizes de política energética brasileira. Esse instrumento de mercado pode reduzir as incertezas decorrentes de medidas discricionárias utilizadas atualmente.
Palavras-chave: teoria do portfólio, precificação do carbono, matriz de geração de eletricidade
Códigos JEL: L59, L94.

1 Introduction

The Brazilian electricity generation mix is characterized by the predominance of hydropower that currently represents 79% of total generating capacity. However, the share of hydropower is expected to decrease over the next decade due to environmental constraints on the remaining hydro potential. A relevant goal of the Brazilian energy planning is to maintain current share of renewable energy sources in the generation mix, which account for 84%. Other planning objectives are to minimize the cost of the generation portfolio and improve security of supply. To pursue these objectives, Brazilian government has a 10-year plan indicating the expected evolution of the generation portfolio.

At present, it is widely accepted that the diversification of the Brazilian generation mix is not a policy choice, but mainly a result of the restrictions on the hydropower potential. Thus, one of the most important policy objectives is to prioritize the renewable generation in the diversification process for the generation mix. However, this policy has not been very successful as a significant amount of non-renewable projects has been selected by the power auctions in the regulated market (fuel oil, coal and natural gas).

One can say that there are two main research questions regarding the current Brazilian electricity policy. First, how efficient (in terms of cost and risk) is the Decennial Plan for Energy Expansion (DPEE)?; second, what is the feasibility of DPEE upon considering the relative cost of the different generation sources? The main purpose of this paper is to assess the current situation and the energy policy objectives proposed in the 2020 Decennial Plan for Energy Expansion in Brazil, taking into account the average cost and the risk associated with the different electricity generation alternatives available. Our analysis follows a set of studies that applies the mean-variance portfolio theory (Markowitz, 1952; Merton, 1972) to evaluate the efficiency of electricity generation mix (Awerbuch and Berger, 2003; Roques et al., 2008; Marrero and Ramos-Real, 2010 or Delarue et al. 2011). We use the estimated efficiency electricity generation frontier for Brazil to evaluate the 2020 plan and aim at indicating the opportunities for improving the efficiency of the government planning.

Another important energy policy challenge is the reduction of CO2 emissions. To study this issue, the paper also evaluates the impacts of difference scenarios of CO2 prices in the efficient generation portfolios. Since Brazilian generation portfolio depends on the competition between different generation sources, this exercise can indicate the impacts of different price scenarios for CO2 on the evolution of generation electricity portfolios in Brazil.

This paper is divided into five sections, after this introduction. Section 2 is dedicated to discuss the energy planning in Brazil. This section presents the characteristics of the Brazilian power sector's institutional framework and the characteristics of the 2020 energy plan. Section 3 describes the methodology used in the paper to estimate the efficiency frontier for the power generation portfolio in Brazil. Section 4 shows results on average cost and risk estimates for the alternative technologies considered. Section 5 presents and discusses the estimated efficiency frontiers, evaluates the 2020 plan and proposes how to achieve better results in terms of average cost and risk. This analysis is made for the different scenarios of CO2 price considered. Finally, Section 6 concludes and discusses the implications for the electricity policy in Brazil.

2 Electricity Energy Planning in Brazil

2.1 The structure of Brazilian electricity industry

There are three main characteristics of the Brazilian power system: i) it is a continental-sized interconnected system; ii) electricity consumption increases fast and continuously; and iii) hydro power generation is the predominant source of generation.

Brazil has an interconnected electric system able to supply the main consumption centers (Figure 1). This system provides 98% of the national electricity consumption, totaling 415 TWh in 2010 (EPE, 2011). Interconnection has historically been motivated to exploit hydroelectric potential located far from consumption centers and to take advantage of complementarities between regional hydrology. So, if there is a drought in one region, hydro generation in the others can compensate it. The interconnected grid allows the operation of an integrated electricity wholesale market in Brazil.

Figure 1 – Brazilian Interconnected Power System

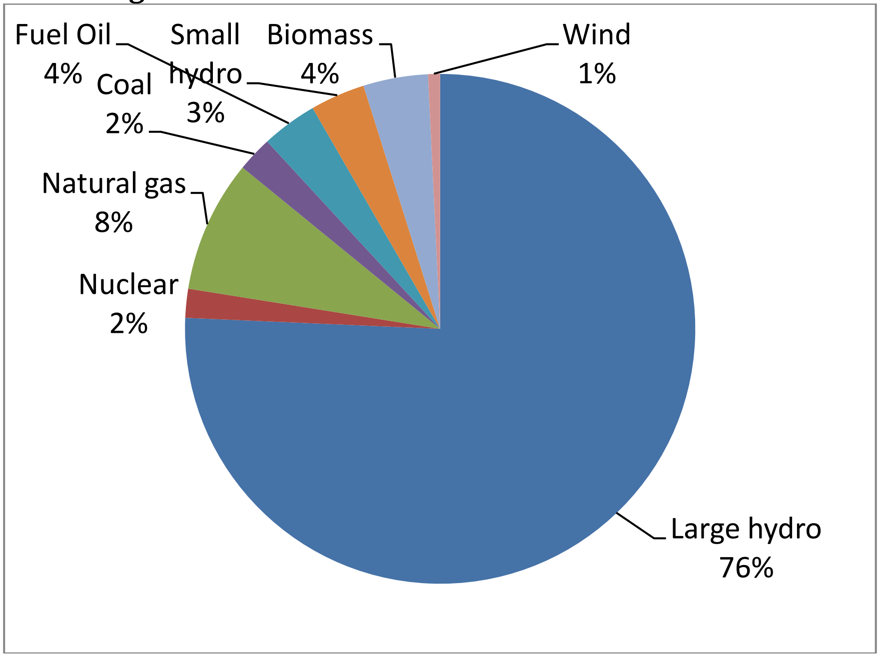
Source: ONS (2012)

After electricity rationing in 2001, Brazilian electricity consumption has raised 4.5% a year. As per capita consumption is still quite low (2.370 KWh/year), a sustained growth can be expected in the long term. It creates a necessity for a continuous expansion of generating capacity. Hydropower plants (large and small) correspond to 79% of the system's 110 GW (Figure 2). As many plants share the same river basin, most of the decisions are interdependent. The Brazilian hydro-electric plants count on reservoirs with great storage capacity that operates in a multi-annual scheme. Brazilian hydro reservoirs can store half of the annual electricity consumption in Brazil (Losekann et al., 2009).

Other renewable sources are present in the Brazilian generation mix. Biomass represents 4% of total installed capacity. Most of it corresponds to cogeneration plants in sugar and ethanol mills that use sugarcane bagasse as fuel. Wind power represents only 1% of total capacity, but its share is increasing at a rapid pace as there are about 7 GW under construction. As renewable share is high (84%), the power sector is not a relevant source of CO_2 emissions in Brazil.

Natural Gas is the most important fossil fuel, with 8% of total installed capacity. Its share increased sharply after the power rationing in 2001. This trend stalled when political changes in Bolivia implicated uncertainty in Brazilian gas supply. Oil products and coal stand for only 6% of generating capacity. The two nuclear plants account for 2% of the mix.

Figure 2 - Current Generation Portfolio in Brazil



Source: DPEE – 2020

2.2 Institutional Organization in Brazilian Electricity Industry

After the power rationing in 2001, the institutional reshape of the Brazilian electricity sector was an electoral commitment of Lula's government. The new regulatory framework was implemented in 2004. This reform aimed at ensuring a new supply crisis would not happen and avoiding the rise of electricity prices (Losekann, 2008). In order to do that, the government took back the planning of the sector and changed the wholesale market implemented during the liberalization process in the 1990s (Losekann, 2008; Almeida and Pinto Jr, 2005).

EPE (Energy Research Company, in English) was established to assist the Energy Minister on sector planning and Aneel (Electricity Regulatory Agency) to organize the auctions in order to acquire new generation capacity. Two market environments were created for contracting electricity in the wholesale market: regulated market environment (RME) and free market environment (FME). Distribution companies buy electricity in public auctions at the RME. They submit demand projections in a five-year horizon to EPE. Based on those projections, EPE sets the total amount of electricity to be acquired in the auctions. The electricity price is defined by the bids of generation companies. The lower price projects win the auctions. The model distinguishes the energy coming from already existing plants ("old energy") of the energy that comes from the new ones ("new energy"), being both negotiated in the RME at different levels. The old energy was oriented to respond to the existing market at the moment when the model was created. The "new energy" is turned to expansion of the distribution market.

At the FME, large consumers are free to choose their suppliers outside the centralized auctions. The energy is negotiated through bilateral contracts with generators and traders. The contracts last for different periods, and short-term contracts are predominant.

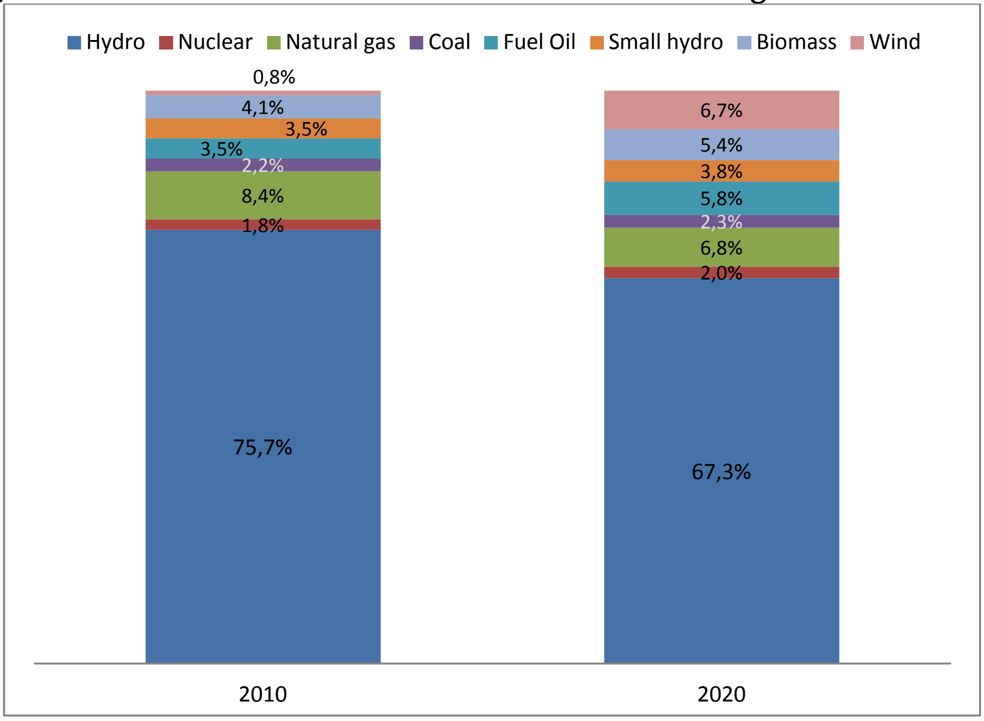
Even though there is no carbon charge in Brazil, the Brazilian energy policy incentives renewable power sources. PROINFA (Incentive Program to Alternative Sources of Electricity) program was implemented in 2002 to promote small hydro, bagasse and wind power plants. It was feed-in tariff scheme, where Eletrobras offered long-term contracts (20 years) with different prices for each source. As the new model for the Brazilian power sector was implemented, the mechanism to promote renewables changed to auctions dedicated to alternative sources.

2.3 The Decennial Plan for Energy Expansion (DPEE)

DPEE is one of the most important energy planning tools in Brazil. Such tool is the main guideline for the expansion of the energy sector in Brazil, especially for the power sector. Every year, the

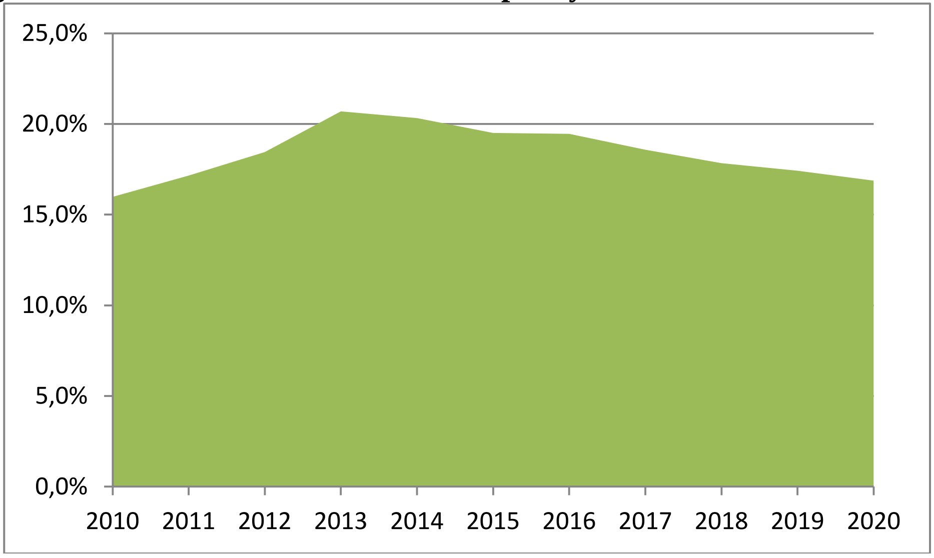
government publishes a revised version of the DPEE, with forecast for the 10-year expansion of the energy sector.
The government is provided with several instruments to try to put into practice the DPEE. The first instrument is to promote auctions, where distribution companies acquire a certain amount of energy by considering only projects related to a specific power generation source. The government can choose to not submit some generation sources to competition with other cheaper sources. This is a form of incentivizing cleaner sources that are still more expensive than the conventional sources of generation.
The second instrument is related with environmental licensing of hydro generation projects. According to the power sector law, the federal government is responsible for the inventory and environmental licensing of hydro generation projects (except for small hydro generation). Therefore, the government has a central role in determining the importance of hydro generation in the competitive auctions. In general, a hydro project offered in the auctions is competitive with other generation sources. Up to now, almost all hydro projects offered by the government in the competitive auctions have been taken by investors. Third, the Brazilian government has the exclusive right to invest in nuclear generation. This mean that this type of generation is not submitted to auctions, and the government decides directly the importance of the nuclear one in the generation matrix.
Finally, an important tool for guiding public and private investment in the power sector is the public intervention in the energy sector, to change the relative prices of different generation sources. Brazilian government has been very active to reduce the costs for renewable generation, through fiscal incentives and regulation. Renewable generation has been exempted of some federal taxes. In addition, the government has tried to reduce the cost of renewables by socializing the cost of connecting these projects to the grid. The government has also established some regulations that increase the cost of thermal generation by requiring environmental compensations.
The last DPEE approved (MME/EPE, 2011) forecasts energy production and consumption in Brazil until 2020 (see Figure 3). The 2020 DPEE estimates that the Brazilian power consumption will increase from 479 TWh, in 2011, to 730 TWh, in 2020, growing at an average of 4.8%. The installed capacity is expected to grow from 110 GW to 171 GW during this period. The generation mix is expected to change significantly in the period. The share of the hydro generation will reduce from 75.7% to 67.3%. The share of natural gas is also expected to reduce from 8.4% to 6.8%. The share of wind generation, on the other hand, will grow very rapidly from 0.8% to 6.7%.
Figure 4 shows how the share of non-renewable energy sources is expected to evolve in the next 10 years. The share of non-renewables tends to grow significantly until 2013. This is due to the fact that a large number of oil-based generation projects won the auctions between 2008 and 2010, due to the lack of hydro projects in those auctions. Nevertheless, the government expects to reverse this trend after 2013, when some large hydro projects in the Amazon region will come on stream. The government also projects that some renewable sources will improve their competitiveness in the following auctions. For this reason, DPEE expects that only renewable energy will be selected in the new auctions until 2020. Half of the acquired capacity on the new actions will be hydro and the other half will be alternative sources, such as wind, biomass and small hydro.

Figure 3 – Evolution of the Generation Portfolio According to the 2020 DPEE



Source: 2020 DPEE

Figure 4 – Evolution of the Installed Capacity of Non-Renewables Sources



Source: 2020 DPEE

3 Methodology: the mean-variance energy portfolio approach

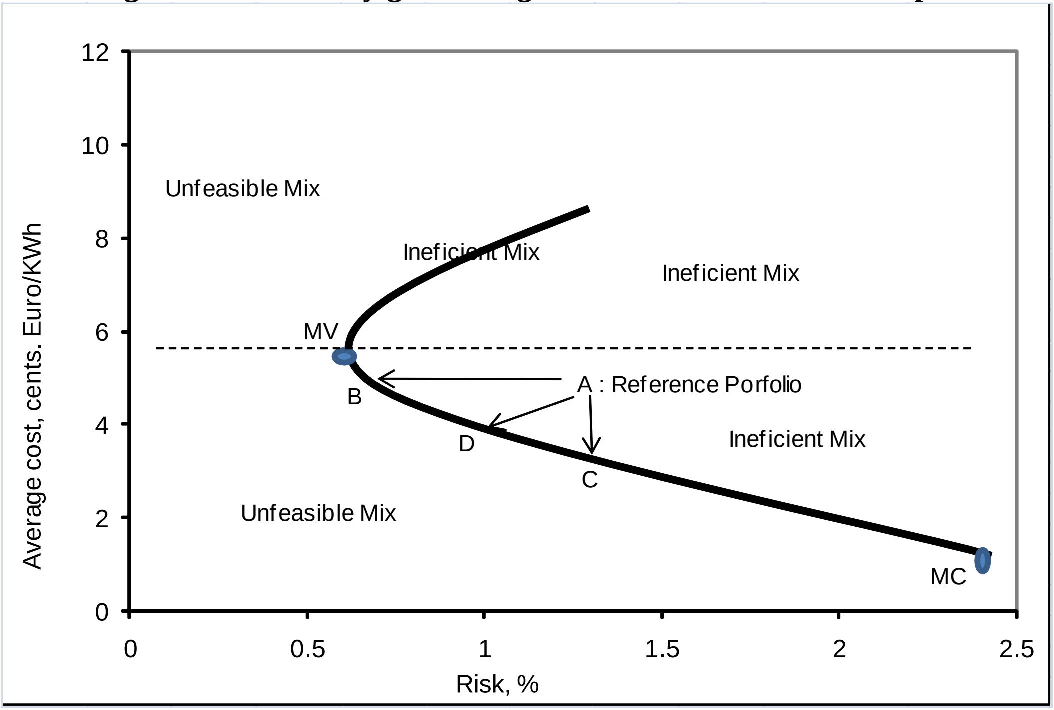
In this paper we apply the mean-variance portfolio theory to calculate the efficiency frontier for power generation technologies in Brazil. In this Section, we briefly describe this methodology without delving into the technical aspects. As used in the mainstream literature, our analysis adopts the perspective of maximizing social well-being (Awerbuch and Berger, 2003). This approach interprets an electricity mix as an electricity generation portfolio. Thus, it is given by a set of weights, say each between zero and one, adding up to unity and related to all feasible alternatives. Each weight is subject to certain technological restrictions that determine the range of variation of each energy source in the portfolio.

This approach combines the information of average and risk costs associated to each feasible portfolio. Such portfolio cost is simply given by a weighted sum of all individual average costs. Measuring risk is a more difficult task. The usual way of measuring risk is by means of rolling historical volatility: the greater the cost's volatility, the greater the uncertainty and associated risk. In the case of a single technology, its risk can be calculated by using a measure of its cost dispersion (i.e., the standard deviation). However, when estimating the electricity portfolio risk, it is also necessary to consider the cross-correlations costs among all different technologies. Once the average cost and risk of all feasible generating portfolios are determined, an efficient mix minimizes the volatility, for a given level of the average cost and over every feasible combination given technological restrictions. The set of all efficient portfolios comprises the so-called Efficient Frontier.

Figure 5 shows a hypothetical efficient frontier. The average cost is along the y-axis, and the measure of risk along the x-axis. The minimum cost (MC) mix includes the cheapest technologies, given technological restrictions. Starting from this mix, moving left along the frontier, more diversified portfolios would presumably increase the average cost while, simultaneously, reduce the variance until the minimum variance (MV) mix is reached. Being to the left of the frontier would be unfeasible, while any portfolio above the MV or to the right of the frontier would be inefficient. In order to use a benchmark efficient mix, we consider that in the mean of the MC and the MV portfolio, i.e., the MC-MV mix.

The estimated frontier also allows us to assess specific portfolios and offer directions for improvement. For instance, we suppose that we wish to assess portfolio A, which is inefficient. We can define two portfolios, B and C, of particular interest with respect to portfolio A. One is a portfolio with the same risk as the initial one (say, B), which involves the same risk but a lower cost by virtue of being close to the frontier. The other portfolio has the same cost as the initial one (say, C), and involves moving closer to the frontier by reducing risk. In reality, any mix between portfolio B and C, as portfolio D, will be more efficient than the reference mix, since it improves in both dimensions.

Figure 5 - Electricity generating Efficient Frontier: an example



Source: Based on Marrero and Ramos-Real (2010).

4 Cost-risk analysis of energy portfolios in Brazil

This Section presents the main elements required to estimate the Brazilian electricity efficiency frontier. In Section 5, we will explore the relevant combinations in the Brazilian electricity generation mix, in light of the evidence on the average costs, and risks of the different technologies as described in Section 4.

4.1 Probabilistic analysis of electricity generating costs

The cost calculation for the various technologies is the first step to estimate the electricity efficiency frontier. The most utilized method is the Levelized Busbar Cost (LBC), which calculates the costs over the electric plants' useful lifetimes and averages them to yield a total production cost. This Section presents the general aspects considered for calculating each technology's costs and an overview of the results.

Marrero and Ramos-Real (2010), drawing on the work of Feretic and Tomsic (2004), propose a methodology to derive the average cost of different types of generation from a set of parameters specific to each technology (i.e., the efficiency factor, the load factor, the price of fuel and raw material, the fixed costs of operation and maintenance, the emission factors, the price of CO2 emission rights, etc.). Since no one knows the exact value of these parameters, we postulate a probability distribution for each of them based on the information available (IEA, NEA, questions to experts in Brazil, etc.). Appendix A1 shows the range of these parameters for the alternative technologies considered. Given these range of the parameters, a Monte Carlo experiment is performed to calculate the cost distribution of each technology. Their mean would be our estimates of each technology's average cost.

As commented in the Introduction, three different scenarios are considered. The first one assumes a zero cost for CO2 emissions. The second one assumes a relatively low cost of CO2 emissions (20-30 $/metric ton, which is about the current price level for CO2 in Europe). The third scenario is based on the assumption that power generation companies would buy emission certificates at 50-80 $/metric ton, a more realistic assumption for the mid- or long-term according to current IEA forecasts. For illustrative purposes, Appendix A2 shows the estimated frequency histograms of the costs for the zero emissions cost scenario.

Table 1 summarizes the main results of the estimation of the generation costs for these three scenarios. It shows the estimated average and the percentile 5 and 95 from the simulated distributions.

Table 1. Individual levelized electricity generating costs in Brazil

	Zero CO2 emissions cost			Intermediate CO2 emissions cost (20-30$/TM)			High CO2 emissions cost (50-60$/TM)		
	Percentil 5	Mean	Percentil 95	Percentil 5	Mean	Percentil 95	Percentil 5	Mean	Percentil 95
Gas CC old	7.669	**9.901**	12.877	8.887	**11.114**	14.063	10.350	**12.587**	15.600
Gas CC new	7.225	**9.277**	12.035	8.460	**10.524**	13.347	9.959	**11.973**	14.781
Coal old	9.188	**11.556**	14.132	11.900	**14.279**	16.880	15.169	**17.525**	20.093
Coal new	9.112	**11.118**	13.266	11.671	**13.795**	15.994	14.927	**16.985**	19.191
Nuclear old	8.730	**10.126**	11.569	8.731	**10.133**	11.595	8.767	**10.123**	11.589
Nuclear new	8.610	**10.011**	11.463	8.635	**10.024**	11.477	8.661	**10.025**	11.499
Fuel-oil old	14.977	**19.098**	23.772	16.625	**20.800**	25.389	18.794	**22.854**	27.456
Fuel-oil new	13.021	**16.468**	20.423	14.780	**18.195**	22.097	16.764	**20.214**	24.138
Biomass Old	12.733	**14.039**	15.461	12.763	**14.052**	15.440	12.775	**14.063**	15.475
Biomass New	12.219	**13.456**	14.795	12.242	**13.474**	14.817	12.241	**13.463**	14.767
Hydro old	3.464	**4.120**	4.840	3.486	**4.122**	4.832	3.487	**4.132**	4.857
Hydro new	4.223	**5.024**	5.927	4.206	**5.015**	5.912	4.198	**5.006**	5.899
Wind old	9.235	**10.986**	12.996	9.319	**11.002**	13.096	9.281	**11.003**	13.126
Wind new	9.213	**10.444**	11.776	9.204	**10.461**	11.829	9.223	**10.469**	11.803
Small hydro old	5.799	**6.885**	7.999	5.813	**6.884**	8.007	5.805	**6.902**	8.026
Small hydro new	5.843	**6.909**	8.024	5.818	**6.900**	8.014	5.811	**6.909**	8.051

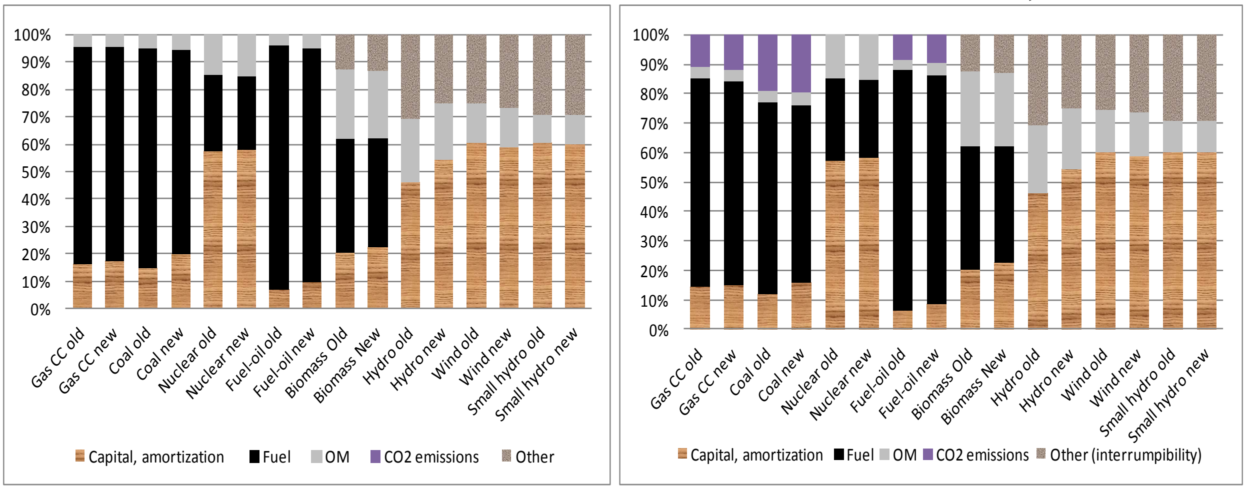
Source: Own Elaboration

For the first scenario (the zero emissions cost), the estimations show that hydro generation is so far the cheapest generation option. The most expensive generation option is the fuel oil and biomass. .

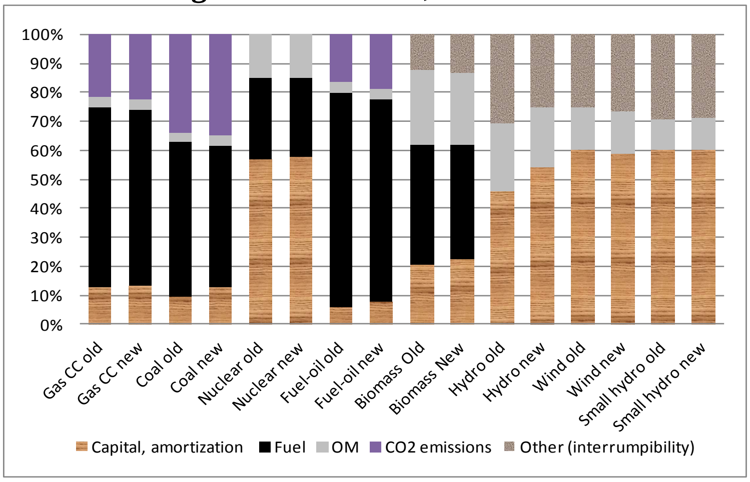
Fuel oil plants are highly inefficient, as well-known, due to low fuel efficiency and high price of fuel. Note that how gas plants exhibit costs significantly lower than those fuel oil plants in every category. The cost of biomass plant is affected by the low load factor as this type of plant operates only during the sugarcane crop season (6 months per year). Wind generation is the cheapest renewable energy source after the hydro generation. Another interesting point to note is the fact that, except for the hydro generation, there is a lower cost of the new option due to efficiency improvements driven by technical change. The main difference between the old and the new hydraulic is because the latter assumes an investment risk that the foster has paid off, and as the best sites are exploited first, hydropower cost increases along the time.
The most important difference between the first scenario and other two scenarios is that all fossil fuel technologies increase their costs. By comparing the mean value for new technologies, the incorporation of CO2 means increasing costs about 10% for gas and fuel oil plants, and about 20% for coal plants, when moving from one scenario to the next one. Thus, the average cost of new coal plants in the third scenario is about 40% higher than in the first one. Meanwhile, renewable technologies and nuclear costs remain unchanged. The small differences observed are due to the different simulations in the each Monte Carlo experiment.
Lastly, we briefly comment the cost structure for each technology, which seems to be important information for understanding the changes of average and risk costs for each technology. For example, depending on the cost structure, the risk associated to fuel fluctuations would be more or less important on overall risk. Figure 5 shows the results for each technology and three aforementioned scenarios. The cost structure for fossil fuel plants differs considerably from that for renewable energy plants (also for nuclear). In the former, fuel accounts for a majority of the cost (about 75% of the total, reaching 85% for the case of fuel oil), while in the latter, it is the cost of the initial investment, which is the most significant component (about 60% for new plants in all cases, similar values for nuclear plants). Operation and maintenance costs are small in all case, though their weight is not negligible for biomass (25%) and renewables (between 15% and 20%). Interruptibility costs for renewable are located between 20% and 30%, while for the biomass is estimated around 10%. When incorporating the cost of CO2 emissions, the most affected technology is coal, whose, in the case of the higher CO2 prices, importance exceeds even 30% of total cost. As discussed in the next Section, this will have important implications for the optimal mix of generation and, therefore, the Brazil's Energy Policy.

Figure 6. Distribution of different costs for alternative technologies

Zero emissions cost | **Intermediate emissions cost, 20-30$/TM**



High emissions cost, 50-60$/TM



Source: Own Elaboration

4.2 Risk estimations

This subsection is based on Awerbuch and Yang (2007) research. As these authors - and many others - emphasize, risk is commonly estimated by annual fluctuations in the electricity generation cost, and the standard deviation, expressed in percentage changes, is the most commonly used measure. After inquiring electricity sector experts in Brazil, we have adapted some of the values provided by these authors to the case of this country. Next, we just comment most important aspects related to these estimated individual risks.

For each technology, the estimated risk incorporates the fluctuation of fuel costs, OM costs and the risk related to the investment disbursements during the construction period of the plant. If the cost of CO2 emissions affects a particular technology, the volatility of its price would be an additional source of risk. Finally, the cross-correlation of all these costs may also affect overall risk. Thus, all these terms must be appropriately weighted depending on their importance on aggregate cost (recall the cost structure shown in the previous Section).

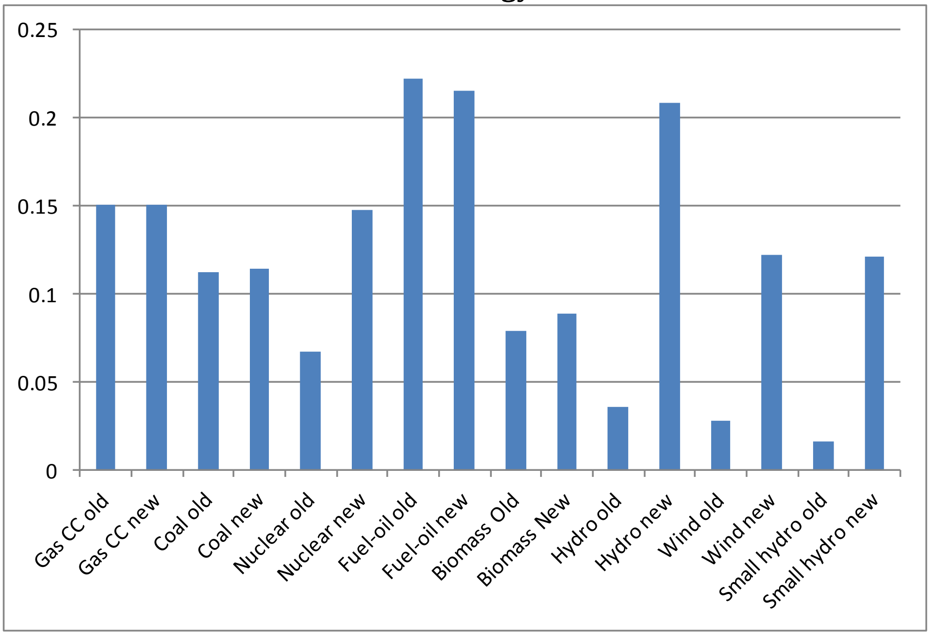
For illustrative purposes, Figure 3 summarizes individual risk value used for each electricity generation technology, expressed as the standard deviations in percent. We only show the values for the zero emissions cost scenario. For the other two scenarios, major changes only occur for coal plants, which is the most polluting technology as commented previously.

Several aspects should be highlighted regarding the different risks. First, construction (or capital) cost risk highly depends on the complexity and length of the construction period. Thus, large and uncertainty projects, such as new Hydro, Coal or Nuclear plan, would show the highest capital risk. Hence, 'New' plants are riskier than 'Old' ones, especially in those cases where investment cost represents an important share of total cost. This fact is easily appreciated in Figure 3 for Hydro, Coal and Nuclear plants, which compares the proposed individual risks for old and new plants. The estimated construction risks for Wind, Gas, Fuel Oil or Biomass plants are much smaller than those for large Hydro, Nuclear and Coal plants.

With respect to fuel cost risks, they are traditionally estimated based on historical annual fuel data. Awerbuch and Yang (2007) estimated that the standard deviations of fuel cost range from 0.14, for coal, to 0.24, for oil. Following the literature, we assume that renewable technologies show a zero fuel cost risk, and Nuclear is almost half of that for coal. In the case of risks for OM outlays, it is difficult to estimate them. Moreover, they represent a small proportion in the overall generation cost in most cases. For this reason, many authors do not consider them in the analysis. Indeed, Awerbuch and Yang (2007) and many other authors conclude that results do not vary significantly when the OM cost risk is excluded from the analysis. Finally, regarding the risk associated to the CO2 emissions cost, which is relevant only for fossil fuel technologies, these authors estimates standard deviation for CO2 about 26%.

As the case of new hydropower plants has relevant implications for our results, we have to discuss it in more detail. According to Awerbuch and Yang (2007) estimates, investment risk for new hydropower plants is very high (43%). Indeed, the Brazilian experience is illustrative as capital cost of hydropower projects can get much higher than budget. Then main reason for that has been delayed building schedule. As it is a capital intensive technology and Brazilian interest rate is very high, it has a major impact on the cash flow. In fact, the three largest hydropower projects under construction in Brazil – Jirau (3,300 MW), Santo Antônio (3,150 MW) and Belo Monte (11,000 MW), are facing problems that will certainly cause delays and over budget (Carvalho, 2008). Most of these problems are related to environmental restraints.

Figure 7. Risk estimates (standard deviation, percent) for each electricity generation technology



Source: Own Elaboration

Once individual variances are estimated, we also need a cross-correlation costs matrix as a last ingredient to estimate the overall portfolio risk. We use the correlation matrix proposed in Awerbuch and Yang's paper. These authors conclude that the most important correlations are found among the different fossil fuel prices. The other important correlation comes from the relationship between fossil fuel prices and emissions cost. For the other cases, the assumed cost correlations are very small, and they could be set equal to zero without altering final results.

Table 2 shows the assumed correlations between fuel and CO2 costs. Most important correlations are positive and exhibit quantitatively meaningful differences. However, several important facts must be highlighted. For the case of fuel correlations, there exists a strong positive correlation among most fuels, with the exception of biomass, which shows a negative – though small – correlation. A number of researchers have found a negative fuel correlation for nuclear and fossil fuels (Awerbuch and Berger, 2003; Roques 2006), but the evidence is unclear. A standard assumption is to set their correlation close to zero. For the case of CO2 cost/fuel cost correlations, it is negative between CO2 and coal prices, but it is positive correlated between CO2 and gas prices. Intuitively, as gas becomes more expensive, electricity generation shifts to coal, putting upward pressure on CO2 prices. On the other hand, rising coal prices shift generation to gas, which emits about half as much CO2, and the price of CO2 falls.

Table 2. Fuel and CO2 correlation estimates

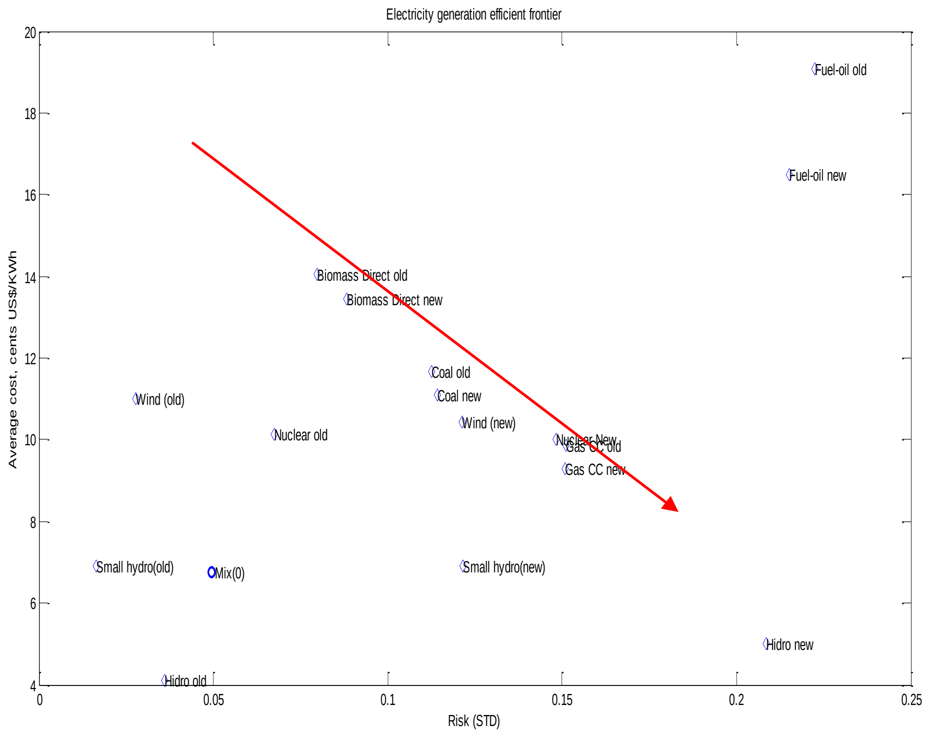
	Coal	Oil	Gas	Uranium	CO2	Biomass
Coal	1.0	0.3	0.5	0.1	-0.5	-0.4
Oil	0.3	1.0	0.5	0.1	0.2	-0.2
Gas	0.5	0.5	1.0	0.1	0.7	-0.4
Uranium	0.1	0.1	0.1	1.0	0.0	-0.2
CO2	-0.5	0.2	0.7	0.0	1.0	0.0
Biomass	-0.4	-0.2	-0.4	-0.2	0.0	1.0

Source: Awerbuch and Yang (2007)

4.3 The average Costs-Risks trade-off

When we compare the cost and risk of the available technologies for the expansion of power generation, the existence of a clear trade-off between average cost and risk generation (see Figure 8) is evident. As noted by the arrow in the Figure, most technologies with lower generation cost, such as new hydroelectric power, have higher risks, while technologies with lower risk, such as biomass, face higher average costs.

Figure 8 – Costs versus Risks for different Generation Technologies in Brazil



Source: Own Elaboration

Several 'old' technologies, with lower average costs and with zero investment risk and low fuel risk, show a good performance in both dimensions (i.e., old small and big hydro). However, in order to increase the size of these technologies, new plants must be constructed, and hence the risk increases notably. In general, we do not find 'new' technologies that meet both goals (minimize costs and risk) at the same time. An important message of this mean-variance analysis is that diversification contributes to reduce the risk of the overall generating mix. This analysis is extremely relevant to identify opportunities to improve efficiency on generating capacity expansion.

5 Efficient Energy Mix in Brazil

In this section we present the estimated results of the efficient electricity generation mix in Brazil. This frontier is estimated under alternative CO2 price emissions scenarios: zero, low and high. Then, the efficiency electricity generation frontiers are used to evaluate the 2020 DPEE indicating the opportunities for improving the efficiency (in terms of average cost and volatility) of this government planning.

In order to estimate the frontier, we need to impose some logical restrictions on the weights associated to each technology. These restrictions are generally based on technology, feasibility or just simplicity reasons.

The first important assumption regards the nuclear power plants. We do not intend to address to the current nuclear debate, hence we only assume a limited expansion for the nuclear according to the 2020 DPEE (recall from Figure 3). Hence, for any scenario, we keep the old and new nuclear weighs at 1.2% and 0.8%, respectively. At this moment, Brazilian government has halted the discussions regarding further expansion of the nuclear generation, observing the developments of the Japanese nuclear crises.

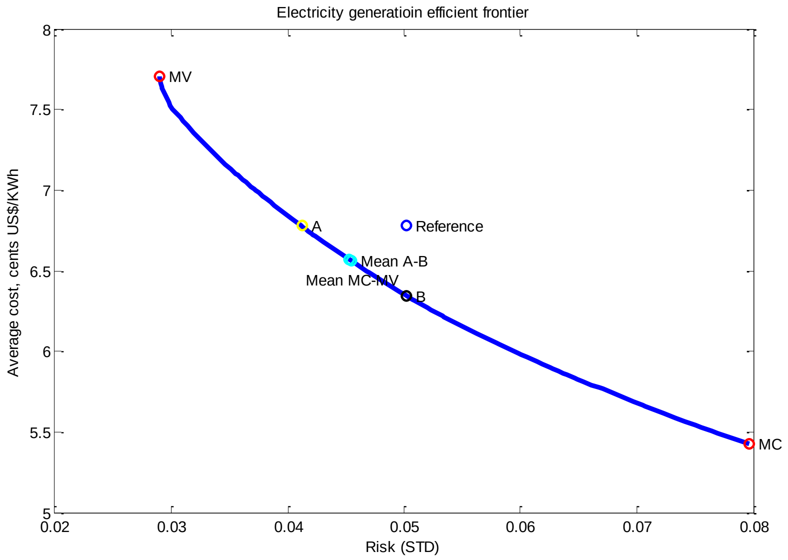
Second, in order to guarantee power supply, we must impose certain technological constraints that limit the weight of the technologies in the portfolio due to the non-storability of electricity and the technical specifications of various technologies. Some renewable energy, such as wind and small hydro (solar energy should be considered as well), are intermittent. Therefore, and to ensure the security and reliability of supply given the current state of technology, some upper bounds should be imposed. We considered the following restrictions regarding the maximum share that some generation options can reach in the expansion of generation capacity: i) 70% for large hydro and 3% for small hydro due to the restriction regarding hydro potential; ii) 10% for biomass and 15% for wind due to the intermittence of these sources and their potential impacts for the security of supply.

Finally, an important and realistic assumption: we assume that the old plants for all technologies have a lower bound whose value is that of 2020 DPEE (reference portfolio). Thus, we keep fixed the weights of old plants. Moreover, any increase in size of each technology must be with 'new' plants. Although the restriction for the old plants should not be imposed from the point of view of social efficiency, it is a realistic one because 'old' plants are already almost amortized.

5.1 Results for the zero-CO2 price scenario

Figure 6 and Table 4 present the results for the first scenario with zero CO2 price. It is important to note that the reference portfolio (the portfolio of the 2020 DPEE) is relatively close to the efficiency frontier. However, it is possible to improve the efficiency of this portfolio moving toward A (reducing risk) or B (reducing cost). Table 4 shows that the minimum cost portfolio is mainly constituted by large hydropower; new biomass and wind are zero. Hydropower predominance results in a high risk of this portfolio, as these sources have high investment risk. The minimum variance portfolio has a more diversified power mix. Its volatility is four times lower than MC portfolio. However, its expected cost is 38% higher.

Figure 9 – Efficient frontier of the no-CO2 price scenario



Source: Own Elaboration

Table 3 – Main Results for the No-CO2 Price Scenario

	Reference Mix	MC	MV	A	B	Mean A-B	Mean MV-MC
Coste,c.euro/KWh.	6.7710	5.6610	7.8990	6.7750	6.3970	6.5860	6.7800
Riesgo	0.0500	0.0791	0.0282	0.0426	0.0510	0.0464	0.0424
CO2, TM/KWh.	0.0798	0.0459	0.1196	0.0923	0.0669	0.0738	0.0924
Gas CC old	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Gas CC new	1.5	0.0	0.0	3.5	5.1	4.9	3.5
Coal old	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Coal new	0.8	0.0	8.1	3.5	0.0	0.8	3.5
Nuclear old	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Nuclear New	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Fuel-oil old	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Fuel-oil new	3.5	0.0	0.0	0.0	0.0	0.0	0.0
Biomass Direct old	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Biomass Direct new	2.7	0.0	15.0	0.6	0.0	0.0	0.7
Hidro old	48.5	48.5	48.5	48.5	48.5	48.5	48.5
Hidro new	18.8	34.9	1.2	12.7	18.5	15.2	12.6
Wind (old)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Wind (new)	6.3	0.0	7.8	11.8	8.5	11.2	11.8
Small hydro(old)	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Small hydro(new)	1.5	0.2	3.0	3.0	3.0	3.0	3.0
			Aggregate Weights (old + new)				
Gas	7.2	5.8	5.8	9.3	10.9	10.7	9.3
Coal	1.9	1.0	9.2	4.5	1.0	1.9	4.6
Nuclear	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Fuel-oil	5.8	2.3	2.3	2.3	2.3	2.3	2.3
Biomasa	5.4	2.6	17.6	3.3	2.6	2.6	3.3
Big Hidro	67.3	83.4	49.6	61.1	67.0	63.7	61.1
Wind	6.7	0.5	8.3	12.3	9.0	11.7	12.3
Small Hidro	3.8	2.5	5.2	5.2	5.2	5.2	5.2

Source: Own Elaboration

Indeed, it is interesting to compare the mean A-B portfolio and the DPEE one. Moving to A-B, it is possible to improve results in both dimensions (costs and risks). Large hydropower share decreases from 67.3% to 64.3%. For fuel oil and biomass, new capacity would not be installed, remaining only old plants (2.3% and 2.6%, respectively). Shares of small hydro reach the upper bound (5.2%) and natural gas (10.7%) and wind (11.7%) increase to reach 10.7% and 11.7%, respectively. Coal represents the same value in both mixes (only 0.8% of new coal). It is important to notice that not only the risk (3%) and the cost (8%) diminished when moving from DPEE to A-B mix, but also CO2 emissions by 8%.

5.2 Results for the Low CO2 Price Scenario

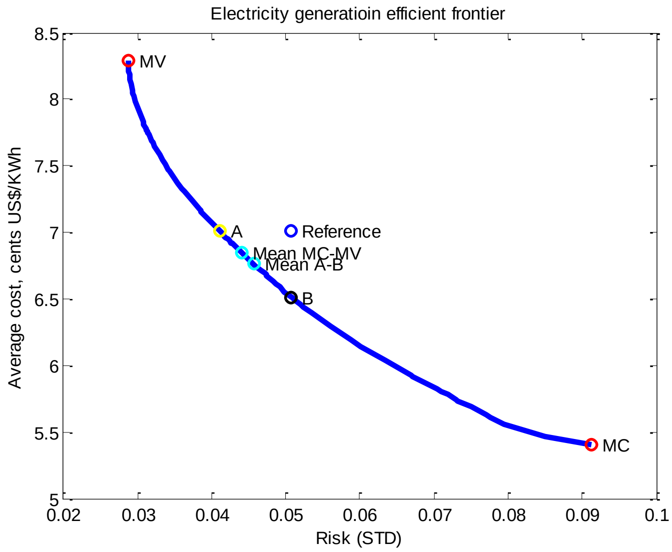
The efficient frontier shifts right as energy costs increase (Figure 7). As a cheap CO2 price is considered (about the current prices in Europe), CO2 emissions in the mean A-B portfolio fall by 38% related to 2020 DPEE (Table 5); expected cost and risk are 3.5% and 11% lower, respectively.

Table 4 – Main Results for the low CO2 Price Scenario

	Reference Mix	MC	MV	A	B	Mean A-B	Mean MV-MC
Coste,c.euro/K	7.0100	5.7860	8.3160	7.0020	6.5560	6.7790	7.0510
Riesgo	0.0502	0.0787	0.0279	0.0407	0.0500	0.0449	0.0399
CO2, TM/KWh.	0.0798	0.0459	0.1388	0.0581	0.0510	0.0577	0.0580
Gas CC old	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Gas CC new	1.5	0.0	0.0	3.0	1.2	2.9	3.0
Coal old	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Coal new	0.8	0.0	10.3	0.0	0.0	0.0	0.0
Nuclear old	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Nuclear New	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Fuel-oil old	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Fuel-oil new	3.5	0.0	0.0	0.0	0.0	0.0	0.0
Biomass Direct old	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Biomass Direct new	2.7	0.0	15.0	3.2	0.0	0.0	4.0
Hidro old	48.5	48.5	48.5	48.5	48.5	48.5	48.5
Hidro new	18.8	35.1	1.3	12.7	19.1	15.0	12.2
Wind (old)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Wind (new)	6.3	0.0	5.6	13.3	11.9	14.3	13.0
Small hydro(old)	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Small hydro(new)	1.5	0.0	3.0	3.0	3.0	3.0	3.0
			Aggregate Weights (old + new)				
Gas	7.2	5.8	5.8	8.7	7.0	8.6	8.7
Coal	1.9	1.0	11.3	1.0	1.0	1.0	1.0
Nuclear	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Fuel-oil	5.8	2.3	2.3	2.3	2.3	2.3	2.3
Biomasa	5.4	2.6	17.6	5.9	2.6	2.6	6.6
Big Hidro	67.3	83.6	49.8	61.1	67.5	63.5	60.6
Wind	6.7	0.5	6.1	13.8	12.4	14.8	13.5
Small Hidro	3.8	2.2	5.2	5.2	5.2	5.2	5.2

Source: Own Elaboration

Figure 10 – Efficient frontier of the low CO2 price scenario



Source: Own Elaboration

Under this cheap CO2 price scenario, the following decisions would be involved to reach efficiency (move to A-B) taking the DPEE plan as reference: increasing the gas to 2.9% (1.5% in DPEE), not to install new coal, new biomass and new fuel, to set new hydro until 15% (18% in DPEE), but to increase the wind to 14.43% (6.3% in DPEE) and small hydro to 3% (1.5% in DPEE).

Compared to the zero CO2 price scenario, the A-B energy mix shows the following major differences: an increase of global wind share that nearly reaches its upper limit (15%), there is no new coal (only the old plants, 1%) and gas decreases its weight. Emissions in the mean A-B portfolio fall by 36% related to mean A-B in zero price scenario. Clearly, low carbon energy sources replaces fossil fuels when there is CO2 pricing.

5.3 Results for the High CO2 Price Scenario

A higher CO2 price induces further substitution of fossil fuels, even natural gas. In fact, only the old fossil plants remain in the power system. Not only small hydro share but also wind share reaches its highest (upper bound) level, biomass increases its participation in the efficient energy mix (mean A-B portfolio) regarding the results in the previous scenario (Table 6).

Comparing the reference mix with mean A-B, costs, risks and emissions decrease by 4%, 12% and 42%, respectively. To reach efficiency (move from DPEE to A-B) the following decisions are involved: not to install new coal, new gas and new fuel; to set new hydro until 15% (18% in DPEE), to reach the wind and small hydro upper bounds of (15% and 3%, respectively). New Biomass capacity is similar in these two mix scenarios.

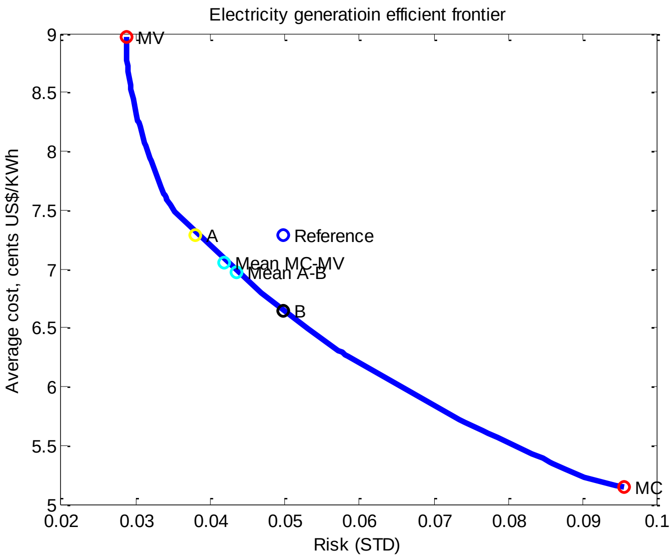
On the one hand, it is interesting to notice that if generating portfolio is efficient, as the mean A-B is, introduction of a CO2 price will change substantially the energy mix, but electricity cost will increase only 3% regarding the reference case without CO2 price. On the other hand, the cost of mean A-B portfolio is always cheaper than DPEE portfolio. Moreover, whatever the scenario considered, this diversification policy implies risk reductions of around 10% and emissions reductions of around 40%.

Table 6 – Main Results for the high CO2 Price Scenario

	Reference Mix	MC	MV	A	B	Mean A-B	Mean MV-MC
Coste,c.euro/K	7.2900	6.0280	8.6870	7.2980	6.7480	7.0230	7.3580
Riesgo	0.0498	0.0728	0.0291	0.0396	0.0503	0.0446	0.0387
CO2, TM/KWh.	0.0798	0.0459	0.1230	0.0459	0.0459	0.0459	0.0459
Gas CC old	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Gas CC new	1.5	0.0	0.0	0.0	0.0	0.0	0.0
Coal old	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Coal new	0.8	0.0	8.5	0.0	0.0	0.0	0.0
Nuclear old	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Nuclear New	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Fuel-oil old	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Fuel-oil new	3.5	0.0	0.0	0.0	0.0	0.0	0.0
Biomass Direct old	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Biomass Direct new	2.7	0.0	15.0	6.2	0.0	2.3	7.1
Hidro old	48.5	48.5	48.5	48.5	48.5	48.5	48.5
Hidro new	18.8	31.9	1.6	12.0	18.7	14.9	11.4
Wind (old)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Wind (new)	6.3	0.2	7.1	13.9	13.5	15.0	13.6
Small hydro(old)	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Small hydro(new)	1.5	3.0	3.0	3.0	3.0	3.0	3.0
			Aggregate Weights (old + new)				
Gas	7.2	5.8	5.8	5.8	5.8	5.8	5.8
Coal	1.9	1.0	9.5	1.0	1.0	1.0	1.0
Nuclear	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Fuel-oil	5.8	2.3	2.3	2.3	2.3	2.3	2.3
Biomasa	5.4	2.6	17.6	8.8	2.6	4.9	9.8
Big Hidro	67.3	80.4	50.0	60.5	67.2	63.4	59.9
Wind	6.7	0.7	7.6	14.4	14.0	15.5	14.1
Small Hidro	3.8	5.2	5.2	5.2	5.2	5.2	5.2

Source: Own Elaboration

Figure 8 - Efficient frontier of the high CO2 price scenario



Source: Own Elaboration

5 Conclusions

The comparison of 2020 DPEE with efficient generation portfolios estimated in this paper lead us to the following conclusions:

- The planned portfolio in Brazil is relatively close to the efficient frontier. The average cost of the 2020 DPEE is only 3% higher and the risk is 10% higher than the estimated average efficient portfolio. Therefore, there is more room to reduce the risk than the cost of the 2020 DPEE, through a higher level of diversification.

- As there is no CO2 price in Brazil now, the tendency is that diversification increases fossil fuel share in the energy mix. Fossil fuel, in particular, natural gas tends to be more competitive than the renewable.

The main results described above drive us for a set of important conclusions in terms of policy implications. First of all, as the 2020 DPEE is an indicative plan, it is not possible to reach governments goals in current market situation. If the government wants mostly renewable generation in the next auctions, it will be necessary to make use of some kind of mandatory mechanism. Brazilian government has been very active in introducing mechanisms to avoid non-renewable energy winning the auctions. Very frequently new rules are introduced to favor renewable to the detriment of non-renewable energy sources. This type of discretionary activism has been contributing for increasing the market risk and general cost of projects. An alternative should be to introduce a CO2 price that can also be effective in promoting renewables. This type of more general market framework can contribute to reduce market uncertainties by reducing the level of government's discretionary activism.

This paper shows that with a low CO2 price scenario, wind power will replace fossil fuel generation, mainly coal. This low price scenario is enough to keep fossil fuel share in 14.5%. If a high CO2 price is implemented, substitution of fossil fuel goes further. Biomass is more competitive and natural gas loses its share. So, fossil fuel share in the energy mix reduces to 12.2%. In the last scenario, power capacity expansion is almost entirely through renewable energy sources.

Finally, it is important to note that the introduction of a CO2 price can have a low but significant impact on the overall generation cost (approximately 3% in the low price scenario and 6% in the high price scenario). To accept this type of increase in the generation cost is a question of energy policy. Nevertheless, the estimations show that this cost increase can be partially or totally compensated by choosing a more efficient generation portfolio.

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Appendix A1 Parameters to estimate the electricity generating cost for each technology.

Based on data obtained from the IEA (2005, 2010), the RAE (2004), MME/EPE (2011) and conversations with experts on the matter in the Brazilian energy sector, we assumed a range of values and probability distributions (generally uniform or triangular, as per norm) for each parameter and technology to be analyzed. This information is summarized in Table A1. Given these distributions, a Monte Carlo experiment was then conducted, which consisted of selecting random values for the parameters in the distributions under consideration, by calculating the value of the costs, and repeating this process a large number of times (5,000 in our case). Thus, instead of finding an average cost value, we obtain a cost probability distribution. This is similar to the process used in Feretic and Tomsic (2005).

What follows is a very brief comment on the parameter values (see Table A1). The overnight investment cost is the total investment expenditure (mainly construction and planning costs) expressed as a current US dollars per KW constructed. The load factor is one of the main differences between fossil fuel plants and renewables. In Brazil, this parameter is about 80% for the former and it is between 30% and 50% for the latter. The other data required to calculate the investment cost is the time to build the plants and the discount factor, the standard value for which ranges from 5% to 10% for all sorts of plant.

As for the parameters affecting the fuel cost (also expressed in US$-cents/KWh), in addition to the plant lifetime, load factor and discount factor, there are three key parameters. First, and most important, is the actual cost to acquire the fuel. The cost of diesel is clearly the highest, followed by that of fuel oil, with natural being most economical, despite the regasification costs. The fuel cost for the renewable technologies considered is zero. As for the expected fuel acquisition growth rate over the useful lifetime of the plant, we assumed an annual range of 0%-3% for the 3 types of fuel considered. The fuel efficiency factor differs among the fossil technologies: the most efficient is for combined cycle gas plants (and the hypothetical new fuel oil plants), followed by diesel and, lagging far behind, the old fuel oil plants.

Let us now consider OM costs (fixed and variables costs being expressed in terms of KWh.). Diesel plants are the most expensive, followed by fuel and gas. These costs are lower for renewables. Lastly, we have CO2 emissions costs, which attempt to internalize the social costs of emissions within the private costs. This cost is calculated as the price of the tons emitted multiplied by the emissions factor resulting from the generation (Tm CO2 / KWh).