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Strategies to promote renewable energy in Brazil

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ABSTRACT

The present study is the result of recent research that has been developed in Brazil in cooperation with international research centers. The aim is to analyze the best strategies for maintaining the high share of renewable sources in Brazil's electric power generation system. The results show that, for the time horizon considered, the country still has plentiful energy resources available, notably its hydroelectric potential, and that the introduction of mitigation measures in the electricity sector has only a small impact on the price of electricity. The study also shows that the country has made a significant contribution to the struggle against global warming.

Contents

1. Introduction

Brazil possesses a large variety of climates and the planet's greatest biodiversity. This characteristic places the country in a very advantageous position in terms of the availability of natural resources but, at the same time, poses the considerable management challenge of assuring that these resources are exploited in a sustainable fashion.

That is why economic growth and environmental conservation, as Motta [1] underlines, are usually considered to be mutually exclusive objectives. Industrial activities, the expansion of the agricultural frontier and the urbanization process that degrade water resources, destroy forests and pollute the atmosphere, are examples of the way in which economic activity jeopardizes the environment.

Until the beginning of the 1970s, the environment variable was neglected in the development of economic policies. This confirmed the idea that economic growth necessarily degraded the environment. As from the United Nations Conference on the Human Environment held in Stockholm in 1972, scientists began to concern themselves with the concept of sustainability [2], showing that the present generation could meet its needs without compromising the ability of future generations to meet their own.

This led to the development of techniques to internalize the environmental costs (see [3]) that private players incur in their economic activities. Once these environmental costs have been identified, cost benefit analyses can be undertaken in order to develop environmental controls that can form the basis for sustainable economic policies.

However, Motta [1] shows that some environmental cost internalization mechanisms can be inefficient and expensive. According to this author, these limitations are recognized by policymakers in developed economies, who suggest that economic

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tools in the form of premiums or prices that act as incentives should be adopted in environmental management. The former basically involve tax incentives and thus depend on political decisions. This probably explains why their use in the environmental area is still relatively rare. Price incentives are market mechanisms that enable the prices of environmental goods and services to be established by attributing a social value to them. The "polluter/payer" principle lies behind this type of mechanism. These incentives can act directly on prices, if applied through rates or tariffs, or indirectly if they take the form of certificates or property rights.

The CDM (Clean Development Mechanism) is an example of a price incentive applied by means of tradable pollution emission certificates. According to Pereira [4], this mechanism was created within the framework of the Global Climate Change Convention, whose aim was to stabilize the concentration of GHG (greenhouse gases) in the atmosphere at levels that would not represent a danger to human life based on the principles of precaution and common but differentiated responsibilities. The convention was ratified at the United Nations Conference on Environment and Development at Rio de Janeiro (ECO-92). 1997 saw the signing of the Kyoto Protocol (an international agreement on the environment that came into force in February 2005) which stipulated that, between 2008 and 2012, developed countries should reduce their GHG emissions by an average of 5.2% in relation to 1990 levels. Thus the CDM could be used by these countries to fulfill their commitment to emission reduction through the promotion of sustainable development in non-Annex 1 countries.

No commitments are envisaged for the developing countries during this first phase (2008–2012), as the priority of countries like Brazil is to improve their populations' living standards. However, during the second period of the Kyoto Protocol (after 2012) countries that are not in Annex 1 of the Climate Convention may have to agree to reduction commitments.

Various initiatives have been implemented in Brazil to foster sustainable development, such as the proposal to create a Green Protocol, the creation of the Business Council for Sustainable Development, the National Environment Fund, the National Environment Program, the Water Law and the Environmental Crimes Law. This shows that the environmental dimension has become a determining factor, not only in public policy decisions, but also in private sector strategies.

The country has also signaled that it is engaged in the struggle against global warming. The Federal Government recently launched the National Climate Change Plan [5], in order to encourage domestic actions that contribute to mitigating the consequences of global warming, without jeopardizing the population's welfare. The Plan's objectives are to:

- Foster efficiency improvements in the economy's various sectors in a constant quest to attain best practices;
- Seek to maintain the high share of renewable energy in the electricity sector, thus maintaining the outstanding position that Brazil has always occupied in the international sphere;
- Promote a sustainable increase in bio-fuels' share of the domestic transportation sector and, in addition, act to structure a sustainable international bio-fuels market;
- Foster the sustained reduction of deforestation rates in all Brazilian biomes, until achieving zero illegal deforestation;
- Eliminate the net loss of forest-covered areas in Brazil by 2015;
- Strengthen intersectoral actions that aim at reducing population vulnerability; and
- Seek to identify environmental impacts caused by climate change and promote the development of scientific research in order to formulate a strategy that minimizes the socio-economic costs of the country's adaptation.

This study analyzes greenhouse gas mitigation strategies for the Brazilian power sector, based on recent research developed in the country. The aim is to contribute to the second item proposed in the National Climate Change Plan.

2. Promotion of renewable in the Brazilian power sector

The Brazilian power sector is hydrothermal, characterized by the strong presence of large reservoirs, located in various hydrographical basins, and which are far from the main consumption centers. This is why the system is inter-connected by huge transmission lines. Hydroelectric capacity is complemented by conventional thermal and nuclear plants, totaling 107 GW of installed power capacity [6].

However, this profile may change considerably, due to the growth in electric power demand and the availability of generation resources, as well as the costs of exploiting these resources. Various studies, such as those performed by the Brazilian Energy Research Company [7], the International Energy Agency [8], the European Commission [9] and the CentroClima/COPPE/UFRJ [10], show that, until 2030, electricity consumption should grow more than 3% a year, thus creating the need to add at least 100 GW to current installed capacity.

The country posses a great variety of natural resources, but their exploitation may need large investments and cause significant environmental impacts, as shown by Pereira et al. [11]. In the case of hydroelectric power, Brazil exploits a mere 30% of its potential, but the remainder is mainly located in the environmentally sensitive Amazon region. On the other hand, the expansion of fossil energy sources involves large investments in the recovery of natural gas and/or coal. In the latter case, the country would lose its great comparative advantage of possessing a clean energy sector. There is also the possibility of expanding the nuclear program, that would also require considerable investments both in R&D and the infrastructure necessary to mine and process uranium and build power plants. Brazil could also invest more in renewable sources, that are also widely available in the country, but whose technology is not as mature as in the case of the previously cited ones.

The country has indicated that it is committed to maintaining a large share of renewable in its energy matrix, as shown by the institution, through Law no 10.438 of 2002, of the Alternative Sources Incentive Program (PROINFA). This initiative's main objectives are to promote the diversification of electric power generation sources, in order to increase supply security; prioritize action that exploit regional and local characteristics and potentialities, such as job creation and labor force training; and the reduction of greenhouse gas emissions. To this end, a target was established during a first phase lasting until the end of 2008, to construct 3300 MW of installed capacity equivalent, divided equally between wind, biomass and small hydroelectric power plants (SHP).

However, the PROINFA, did not fully attain its objectives. The biomass-based electricity generation projects presented were insufficient to fulfill this source's 1100 MW quota, as producers thought that they could obtain better prices for power generated under other contract regimes. The installed capacity needed to meet PROINFA's 3300 MW target was achieved by contracting other wind and SHP-based projects. Of the 3299.40 MW contracted during the program's first stage, 1191.24 MW were provided by 63 SHPs, 1422.92 MW by 54 wind power plants 685.24 MW by 27 biomass-fired power plants. It should also be highlighted that delays have been observed in the coming on stream of wind power plants, due mainly to the fact that, under the terms of the program, 70% of equipment must be supplied by domestic firms that are not yet able to meet this demand, a situation that is reflected in the prices they charge.

Table 1
Results of PROINFA and auctions (MW).

Source	PROINFA	Auctions			
		2005	2006	2007	2008
Biomass	685	245	426	542	2489
Wind	1423	–	–	–	–
Small hydro plants	1191	73	129	102	–
Coal	–	350	–	1050	360
Natural gas	–	2042	1530	500	1628
Oil	–	117	992	2207	5050
Hydro	–	6663	6332	5533	3650
Total	3299	9490	9409	9934	13 177

Source: [6].

In addition, the government has, since 2005, held annual energy purchase and sale auctions, which have included renewable sources. In 2007, there was also a specific auction for these sources and another one in 2008 to promote bio-electricity. The latter case involved a power reserve auction, whose aim was to introduce biomass generation to complement hydroelectric output. Table 1 summarizes the results achieved by PROINFA and the last auctions held to trade energy of new power plants.

It is noteworthy that, of all the technologies included in PROINFA's program, only wind power plants were unsuccessful in the auctions. This shows that in order to introduce these technologies into the domestic energy sector special conditions like those provided by PROINFA, which have incorporated characteristics of a feed-in tariff system, are necessary.

According to Costa et al. [12], the international literature groups renewable source incentives into three different mechanisms: the tender system, the quota system and feed-in tariff system. The latter is considered to be the most efficient, mainly because of Germany's successful experience that has served as a reference for various other countries.

In this article, the idea is to propose strategies developed in studies undertaken by La Rovere et al. [13] and La Rovere [14]: the Cost Assessment for Sustainable Energy Systems (CASES) Project and the Energy Compensation Mechanism (ECM). The latter was adopted by the State of Rio de Janeiro.

3. CASES project

The CASES project was funded by the European Union and is the result of joint action developed by various European and developing country research institutions (see www.feem-project.net/cases/downloads_deliverables.php). It contributed to the assessment of different policies that could be implemented in order to foster greater energy use efficiency, using as a reference a consistent and detailed picture of the items that make up the social cost (that is, private costs and externalities) incurred in the countries analyzed in the study. For the purposes of the project, external costs (or externalities) were defined as the impact on third parties of the various sources of electric power generation, that are not internalized by the producer.

In the field of political decision-making, the project's intention is to contribute to the debate regarding technological options, based on the dynamics of the present energy scenario and respective social costs, as well as to the analysis of the variables taken into consideration by participant countries to determine policies to be followed.

Within the terms of this proposal, the project undertook a consistent survey and treatment of data and information relating to alternative electric power scenarios with a time horizon of 2030, as well as the growth of social costs resulting from the use of various electric power generation technologies in the 25 countries of the European Community that took part in the studies, as well as Bulgaria, Turkey, Brazil, India and China – developing countries that also participate in the project and for which specific parameters will be defined based on the models applied in participating countries. Inasmuch as differences naturally exist between the assumptions and criteria adopted for the development of the various country scenarios, including as regards the energy sources and technologies used, the results of this study may provide inputs for decisions relating to when and where particular electric power generation options may best be applied.

Within the framework of the CASES project, the study was coordinated by the following institutions: UNEP Risoe Centre on Energy, Climate and Sustainable Development (URC), Netherlands Environmental Assessment Agency (MNP) and the International Institute for Environment and Development (IIED). The participants from developing countries are the Indian Institute of Management (IIM), Ahmedabad, India; Environnement et Developpement du Tiers Monde (ENDA), Senegal; Bangladesh Centre for Advanced Studies (BCAS), Bangladesh; Energy Research Centre (ERC), University of Capetown, South Africa; Center for Integrated Studies on Climate Change and the Environment (CentroClima/COPPE/UFRJ), Brazil; Energy Research Institute (ERI), State Development Planning Commission, China. Finally the participants fro developed countries were Stanford University, United States; International Institute for Sustainable Development (IISD), Canada; Potsdam Institute for Climate Impacts Research (PIK), Germany; Centre International de la Recherche sur l'Environnement et le Developpement (CIRED), France; Plant Research International, the Netherlands.

The Brazilian contribution to the study consisted of building a scenario for the expansion of the power sector's generation capacity, considering greenhouse gas emission penalties. These penalties derive from the marginal costs of avoided emissions, proposed within the framework of the CASES project (see Table 2), based on the above-mentioned social costs. These values are calculated using the EcoSence model which is based on the application of the Impact Pathway Approach (IPA) developed within the framework of the ExterneE study (see http://ecosense-web.ier.uni-stuttgart.de).

It should be noted that the calculation of the marginal cost of damage caused by global warming is extremely imprecise, given that impacts of GHG emissions are global, spread over time and are still not completely known, thus making the cost range of the damage extremely broad. Given these factors, the present study chose to base the value of the marginal cost of avoided greenhouse gas emissions on the value attributed to their reduction in GHG emission mitigation projects. These costs were calculated in the new study of the NEEDS Project. Even this calculation abounds with uncertainties.

Table 2
Marginal cost of avoided emissions (Euro-2005/ton).

	2010	2015	2020	2025	2030	2040	2050
CO_2	21	21	21	23	30	46	61
CH_4	441	441	441	483	630	966	1281
N_2O	6510	6510	6510	7130	9300	14 260	18 910

Source: [13].

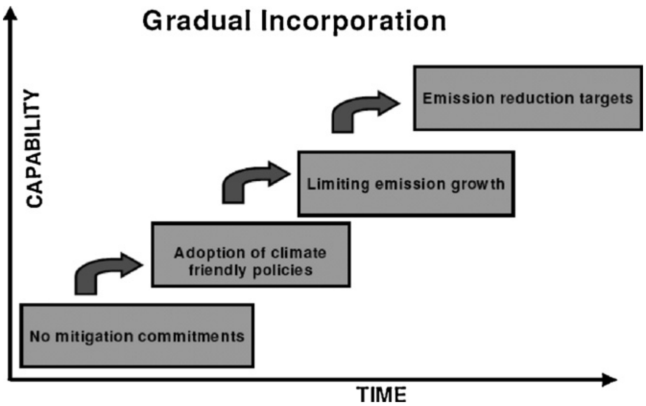

Fig. 1. Gradual incorporation of commitments.Source: [16].

These data alter the variable O&M costs of plants that emit greenhouse gases. As possible emissions of hydroelectric plants are not being considered, the emission penalty may be added to the cost of fuel.

Although the application of these penalties may be more appropriate in the case of countries that possess GHG emission targets established by the Kyoto Protocol, it is important that developing countries analyze the possibility of implementing them, given that the protocol expires in 2012 and the new proposals that are being negotiated for the post-2012 period may include commitments for countries that do not belong to Annex 1 of the Climate Convention. However, reduction targets will probably be lower than those for developing countries, in keeping with the principle of "common but differentiated responsibilities". In this context, Torre et al. [15], propose the gradual incorporation of climate mitigation commitments for emerging countries so as not to hinder their development. Thus, they could begin by implementing climate "friendly" policies, and as their GHG reduction emission capability increased, they could evolve towards the adoption of emission growth limits and could, in due course, have reduction targets. Fig. 1, taken from Figueres et al. [16], provides a good illustration of this proposal.

The reference scenario used in the present article draws on the study "Development First: Linking Energy and Emission Policies with Sustainable Development", also developed by the CentroClima/COPPE/UFRJ [10] within the framework of the Development and Climate Project. This study's aim is to identify paths and actions for the development of large emerging economies that enable positive climate results to be obtained and facilitate the dialogue between decision-makers, in both the domestic and international spheres, and producers and the scientific community. The project was funded by the UNEP and participants included the Risoe Centre and centers of excellence in China, India and South Africa.

The development of scenarios for Brazil was based on the following assumptions for the 2005–2030 period:

- *Brazil's GDP* – an annual average growth of 4%;
- *Population* – an average annual growth of 1.09%;
- *Hydroelectric potential* – utilization of 191 GW of the total potential 230 GW available. The coming on stream of the Belo Monte hydro power plant was also considered: half of its capacity (5500 MW) in 2010 and the other half as from 2015;
- *Nuclear* – It was considered that the Angra III nuclear power plant would come on stream in 2014, taking into account the date its construction was approved by the National Energy Policy Council (CNPE). The possibility of expanding this segment with two more 1000 MW nuclear plants was also included.

This information formed the basis for a simulation of the reference scenario for the Brazilian energy sector using the MESSAGE model (Model for Energy Supply System Alternatives and their General Environmental Impacts), developed originally at the IIASA (International Institute for Applied System Analysis) for the optimization of an energy system [17]. The International Atomic Energy Agency (IAEA) acquired the latest version of the model and various up-dates have been performed, especially the introduction of a friendly interface in order to facilitate its application.

The result for the expansion of the electricity sector is presented in Table 3, where the "Hydro" technology column also includes small hydroelectric plants.

GHG emissions were calculated in accordance with IPCC methodology. The results presented in Table 4 are expressed in CO_2 equivalent.

For purposes of comparison and to verify their consistency, the results presented above were compared with those of other contemporary studies, as shown in Table 5, where the technology entitled "others", encompasses nuclear plants and other renewable sources.

It should be emphasized that the study undertaken by the EPE, the National Energy Plan (PNE) 2030, considered an economic growth rate of 4.1% a year, very close to the 4% rate projected by the Climate Center. In contrast to the CentroClima's calculations, the expansion presented in the PNE considers only the inter-connected system, with the NEP inter-connecting all separate systems at the end of the period. The studies undertaken by the International Energy Agency (IEA) – the World Energy Outlook (WEO), and the European Commission – the World Energy Technology Outlook (WETO) 2050, consider that Brazil will grow only 3% a year until 2030. Hence the lower expansion projected compared with the NEP and Development First.

With the increase in the cost of generation the new optimum solution scenario points to a different technology arrangement for the expansion of generation capacity, as shown in Table 6.

In this case, hydroelectric expansion, and to a lesser extent nuclear power, replace fossil sources. It should be emphasized that in the reference scenario, both biomass and SHPs expand until reaching the potential limit assumed in the study. This shows that, with the exception of the wind power plants, the renewable sources considered in this study are competitive in Brazil. Table 7 shows this scenario's emissions.

Table 3
Generation capacity (GW).

Year	Annual electricity capacity (GW)							
	Coal	Oil	Natural gas	Hydro	Nuclear	Biomass	Wind	Total
2010	2.42	1.43	13.50	78.74	1.97	6.44	0.65	105.15
2015	2.42	1.43	17.50	95.13	1.97	10.44	1.35	130.23
2020	2.42	1.93	18.00	121.60	3.31	13.44	1.85	162.55
2025	3.42	1.93	20.00	150.06	3.31	13.44	2.85	195.01
2030	3.42	2.43	22.00	169.82	3.31	15.44	2.85	219.27

Source: [10].

Table 4
CO_2 emission ($MMtCO_2$).

Year	Coal	Oil	Natural gas	Total CO_2
2010	16.61	4.46	31.93	53.00
2015	16.61	4.46	41.39	62.46
2020	16.61	6.02	42.57	65.20
2025	23.47	6.02	47.30	76.79
2030	23.47	7.58	52.03	83.09

Source: [10].

Table 5
Comparison of results (GW) – 2030.

Technology	Development first [10]	PNE [7]	WEO [8]	WETO [9]
Hydro	169.82	156.3	128.12	114.00
Natural gas	22.00	21.03	11.50	53.00
Oil	2.43	5.50	12.00	4.00
Coal	3.42	6.01	–	10.00
Others	21.60	36.08	28.38	24.00
Total	219.27	224.9	180.00	205.00

The new results show that the penalization of GHG emissions makes plants that burn fossil fuels less competitive, with their share declining during the period. Thus, GHG emissions decline from 83 $MMtCO_2$ to 62 $MMtCO_2$, that is, a reduction of 25%. On the other hand, there is an increase in expansion costs, as shown in Table 8.

Based on the results presented above an analysis was made of the additional costs resulting from GHG emission penalization. Fig. 2 shows the total cost of avoided emissions, where the axis of the abscissas represents total avoided emissions and that of the ordinates the total cost between 2015 and 2030.

Table 6
Generation capacity (GW) – penalty analysis.

Year	Coal	Oil	Natural gas	Hydro	Nuclear	Biomass	Wind	Total
2010	2.42	1.93	13.50	78.74	1.97	6.44	0.65	105.65
2015	2.42	1.93	15.50	98.13	1.97	10.44	1.35	131.73
2020	2.42	1.93	15.50	126.60	3.31	13.44	1.85	165.05
2025	2.42	1.93	15.50	160.06	3.31	13.44	2.85	199.51
2030	2.42	1.93	16.50	178.38	4.31	15.44	3.85	222.83

Source: [10].

Table 7
CO_2 emission ($MMtCO_2$) – penalty analysis.

Year	Coal	Oil	Natural gas	Total CO_2
2010	16.61	6.02	31.93	54.56
2015	16.61	6.02	36.66	59.29
2020	16.61	6.02	36.66	59.29
2025	16.61	6.02	36.66	59.29
2030	16.61	6.02	39.02	61.65

Source: [13].

Table 8
Comparison of scenarios.

Year	Generation (TWh)	Cost (10^6 US$ – 2005)		Emissions ($MMtCO_2$)	
		Reference	Alternative	Reference	Alternative
2015	648.15	4293	4522	62.46	59.29
2020	808.23	5873	6074	65.20	59.29
2025	964.19	5732	6016	76.79	59.29
2030	1083.39	4172	4358	83.09	61.65

Source: [13].

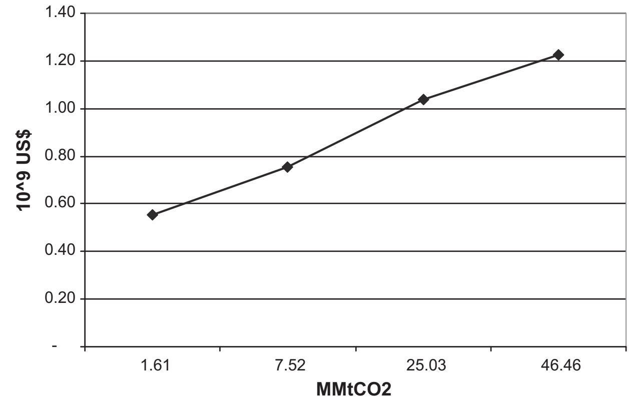

Fig. 2. Total abatement cost of GHG emissions – penalty analysis.Source: [13].

It is noteworthy that the total reduction cost curve is practically linear. This fact is explained by the availability of energy resources, mainly hydroelectric ones that, for the time horizon considered in the study, means that there is no upward pressure on energy's production cost. This is also indicated by the negative slope of the marginal reduction cost curve, shown in Fig. 3.

However, it should be emphasized that the exploitation of the remaining hydroelectric potential will be performed at a higher cost, given its location in environmentally sensitive areas and distance from the main consuming centers, that will require the adoption of various environmental impact mitigating measures, as well as a greater investment in power transmission lines. Thus, a study with a time horizon stretching beyond 2030 may show a marginal cost curve with a steeper slope.

According to this proposal, penalties would be applied from 2010 onwards. Thus, during the 2010–2030 period, 46 $MMtCO_2$ would be avoided at an average abatement cost of 26 US$/$tCO_2$.

The study also analyzed the impact on the average tariff for new energy, that is, the energy produced by expansion. To this end, the total generation cost of new plants in the alternative scenario was compared with the reference scenario, without taking taxes levied on generation into account. This analysis presupposes a tariff-setting model that is adherent to the marginal cost of expansion, as is the case of Brazil. Fig. 4 shows the impacts referred to.

It can be seen that the impact could attain approximately 9% in 2030, due to the higher hydroelectric expansion costs. They are much lower in the first years of the analysis. These values may not be so high, but the fact of including yet another tax to the energy bill may hamper the introduction of the measure referred to. This could be circumvented if penalty revenues could be returned to the population in the form of government transfers (as proposed by

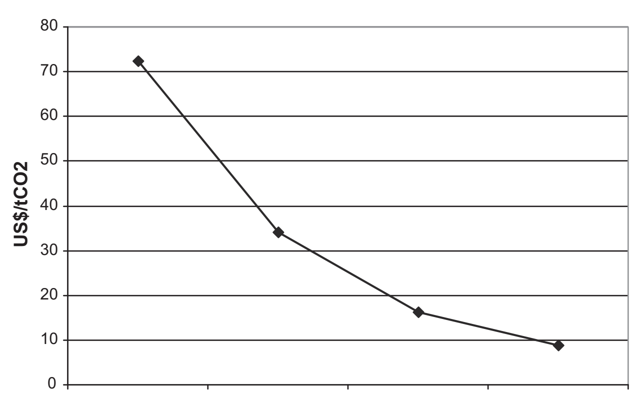

Fig. 3. Marginal abatement cost of GHG emissions – penalty analysis.Source: [13].

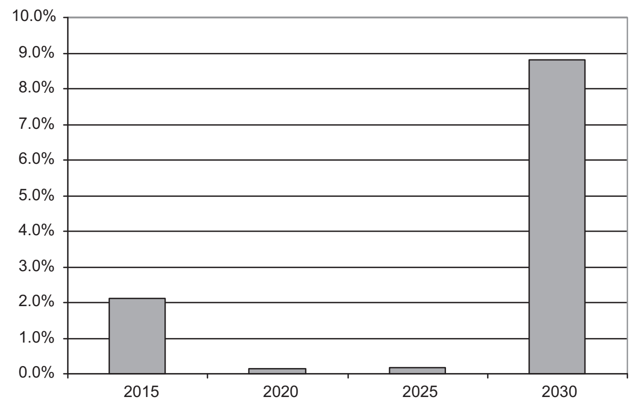

Fig. 4. Impacts on tariffs – penalty analysis.Source: [13].

Timilsina and Shrestha [18]) or channeled to a fund dedicated to investments in renewable sources. In Brazil, however, taxes cannot be earmarked for specific expenditures and thus it is difficult to use these funds to foster renewable resources.

4. Energy compensation mechanism (ECM)

The principle that justifies the ECM is the need to compensate for the greenhouse gas emissions of coal, oil and natural gas fired thermal plants. The proposal, published in La Rovere [14], was directed to the government of the State of Rio de Janeiro and suggested that new fossil-powered thermal plants should be required to invest in renewable resource based electric power generation when requesting an environmental license.

The idea was to choose a level of energy compensation for thermal plants without excessively raising the total price of electric power sold by the producer, considering the sum of electricity generated by fossil and renewable sources. This level should be determined in terms of the level of electricity generated from renewable sources that is needed to compensate for the CO_2 emissions of fossil sources.

The level of compensation proposed was 179 kWh/tCO_2, and in order to prevent the impact on the producer's final selling price from being greater than 1%, its calculation was based on the selling price for new energy established by the 2007 auction. The proposal was analyzed by the Environmental Secretariat of the State of Rio De Janeiro (SEA-RJ) which, after consultations with other government bodies, sector firms and specialists, created the ECM through Decree no 41.318 of May 27, 2008. The text of the decree was, however, different from the initial proposal. One of the reasons was that, as the SHP and biomass-fired power plants sold their energy at a lower price than some fossil fuel plants, the impact on the tariff was negative.

The decree established an Energy Compensation Factor (ECF) that was determined by the fuel used. In contrast to the initial proposal, the ECF is applied to the plant's installed capacity. Moreover, the decree also foresees compensations by means of investments in energy efficiency. Table 9 shows the factors for each kind of fuel.

Table 9
Energy compensation factor.

	ECF	Renewable sources (ECF1)	Energy efficiency (ECF2)
Coal	5%	4%	1%
Oil	5%	4%	1%
Natural gas	3%	2%	1%

Source: SEA-RJ.

The ECF is the sum of the percentage compensation through renewable sources (ECF1) and compensation through energy efficiency (ECF2). Thus the producer that builds a fossil fuel plant in the State of Rio de Janeiro will apply an ECF to the power of the undertaking in order to obtain the value to be compensated, in the following manner:

$$PC = ECF \times PI$$

where PC is the total power to be generated from renewable sources and in energy efficiency and PI is the power of the fossil-fuel plant.

The power to be installed as a form of compensation (CP) is broken down into renewable energy undertakings (RCP) and in energy efficiency (EECP), where:

$$RCP = ECF1 \times PI; \text{ and}$$

$$EECP = ECF2 \times PI$$

To convert the energy conserved by the application of energy efficiency measures, the decree determined a capacity factor of 80%.

In addition, the decree establishes that obtaining carbon credits resulting from the Clean Development Mechanism (CDM) is the sole responsibility of producers.

This article analyzed the application of the ECM to the Brazilian electricity sector. However, no simulation was performed, as in the case of the penalty analysis presented in the previous item. The ECM was simply applied in the thermo-electric expansion of the reference scenario. The renewable source used for this study was wind, the only one considered in the study that is not yet competitive. Energy efficiency was measured in relation to the highest price in the National Energy Plan [7] – 80 US$/MWh. Table 10 presents the expansion in this case.

Instead of adding wind generation and energy efficiency to fossil generation, the latter was replaced by the former two to facilitate the building of this scenario. Thus, there was a 2% reduction in greenhouse gas emissions in relation to the reference scenario, as shown in Table 11.

The total abatement cost of ECM is presented in Fig. 5, where one can also note a linearity, as in the case of the penalty analysis performed in the previous item.

It should be emphasized that, in this analysis, possible income from the trading of carbon credits was not deducted.

The marginal abatement cost curve's slope steepens slightly from 2020 onwards, for in the ECM proposal thermal generation

Table 10
Generation capacity (GW) – ECM analysis.

Year	Coal	Oil	Natural gas	Hydro	Nuclear	Biomass	Wind	Energy efficiency	Total
2010	2.37	1.43	13.37	78.74	1.97	6.44	0.78	0.06	105.15
2015	2.37	1.43	17.25	95.13	1.97	10.44	1.56	0.10	130.23
2020	2.37	1.91	17.73	121.60	3.31	13.44	2.09	0.11	162.55
2025	3.32	1.91	19.67	150.06	3.31	13.44	3.17	0.14	195.01
2030	3.32	2.38	21.61	169.82	3.31	15.44	3.23	0.16	219.27

Table 11
CO_2 emissions ($MMtCO_2$) – ECM analysis.

Year	Coal	Oil	Natural gas	Total CO_2
2010	16.26	4.46	31.61	52.33
2015	16.26	4.46	40.79	61.51
2020	16.26	5.95	41.93	64.14
2025	22.78	5.95	46.52	75.25
2030	22.78	7.43	51.11	81.32

Source: Authors.

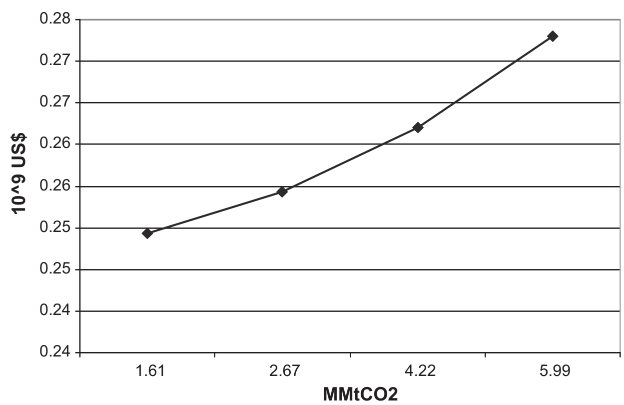

Fig. 5. Total abatement cost of GHG emission – ECM analysis.Source: Authors.

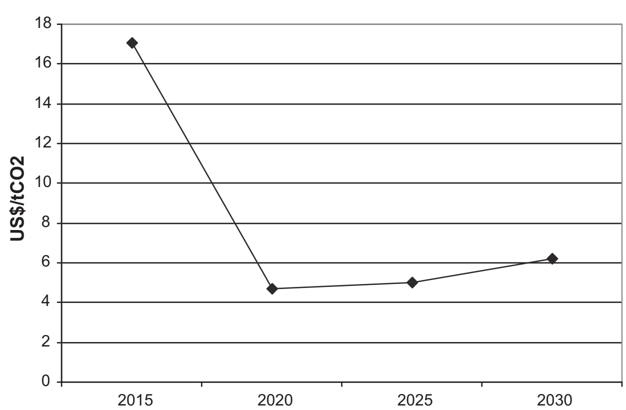

Fig. 6. Marginal abatement cost of GHG emission – ECM analysis.Source: Authors.

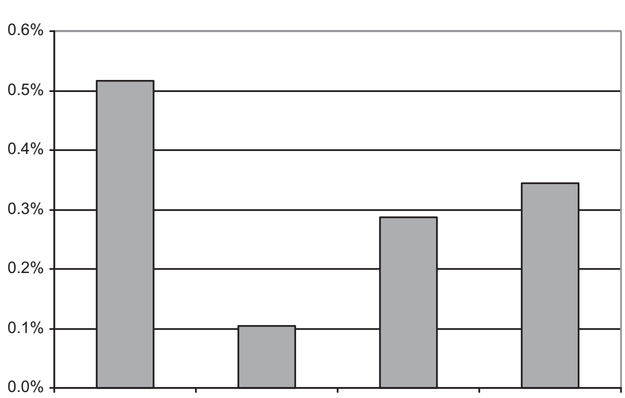

Fig. 7. Impacts on tariffs – ECM analysis.Source: Authors.

is replaced by much more expensive alternatives, as is the case of wind power plant and the efficiency measure chosen (Fig. 6).

The average abatement cost obtained in the ECM analysis is 45.61 US$/$tCO_2$, for a greenhouse gas emission reduction of 6 $MMtCO_2$ over the study's time horizon. In addition a greater value was obtained than in the penalty analysis, for the same reason as the one that caused the steepening slope of the marginal cost of abatement curve. On the other hand, the impact on the tariff – at less than 1% – is much smaller, as shown in Fig. 7.

5. Conclusions

This article sought to contribute to the discussion regarding mitigation strategies in the Brazilian power sector. Its reference were the objectives established for the sector in the National Climate Change Plan which, in general, propose maintaining the high share of renewable sources in the country's generation system.

The two proposals analyzed resulted from the Brazilian's experience in studies developed in cooperation with international research centers.

The first analysis verified the impact of the establishment of penalties for plants that emit greenhouse gases. The average abatement cost of was around 26 US$/$tCO_2$ with an impact on new energy's average tariff of approximately 9% at the end of the study's time horizon. The implementation of such a proposal in Brazil could, however, face restrictions, as it would mean adding a new tax to the energy bill, without any assurance that revenues would be used to benefit the needier segments of the population or the environment.

The Energy Compensation Mechanism analysis, on the other hand, showed that, despite its much lower impact on tariffs – less than 1% – , the average cost of deductions is almost double that of the proposed penalties. However, the introduction of the ECM has the additional advantage of being a mechanism that provides producers who invest in plants that emit greenhouse gases with the option of compensating for their emissions by building plants that generate energy from renewable sources or investing directly in less polluting ones.

Finally, it should be highlighted that although Brazil, as it is not a member of Annex 1 of the Climate Convention, is not formally committed to limiting greenhouse gas emissions, is fully engaged in the struggle against global warming.

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References

[1] Motta RS. Indicadores Ambientais no Brasil: Aspectos Ecológicos, de Eficiência e Distributivos, Texto para Discussão no 403. IPEA; 1996.
[2] Floriano EP. In: Eduardo P, editor. O desenvolvimento de uma Economia Sustentável, Artigos e Ensaios no 2. 1ª ed., Floriano: Santa Rosa; 2004.
[3] Mattos KMC, Mattos KMC, Mattos A. Valoração Econômica do Meio Ambiente Dentro do Contexto do Desenvolvimento Sustentável. Revista Gestão Industrial 2005;1(2):109–21.
[4] Pereira AS. Do Fundo ao Mecanismo: Gênese, Características e Perspectivas para o Mecanismo de Desenvolvimento Limpo. Ao Encontro ou de Encontro à Equidade? Master in Sciences' Report. PPE/COPPE/UFRJ 2005.
[5] Ministério do Meio Ambiente – MMA. Plano Nacional de Mudanças Climáticas. Brasília: Brasil/MMA; 2008.
[6] Empresa De Pesquisa Energética – EPE. Plano Decenal de Energia 2008–2017. Rio de Janeiro: Brasil/Ministério de Minas e Energia – MME; 2009.
[7] Empresa De Pesquisa Energética – EPE. Plano Nacional de Energia 2030. Rio de Janeiro: Brasil/Ministério de Minas e Energia – MME; 2007.
[8] IEA. World energy outlook 2030. Paris: International Energy Agency; 2007.
[9] European Comission. World energy technology outlook 2050 – (WETO – H2); 2006.

[10] La rovere EL, Pereira Jr AO, Simoes AF, Pereira AS, Dubeux CBS, Costa RC, et al. Development first: linking energy and emission policies with sustainable development for Brazil. In: UNEP – United Nations Environment Programme; 2007. 88 p..
[11] Pereira Jr AO, Soares JB, Oliveira RG, Queiroz RP. Energy in Brazil: toward the sustainable development? Energy Policy 2008;36:73–83.
[12] Costa CV, La Rovere EL, Assmann D. Technological innovation policies to promote renewable energies: lessons from the European experience for the Brazilian case. Renewable and Sustainable Energy Reviews 2008;12(1):65–90.
[13] La rovere EL, Barata MML, Villar SC. Cost assessment for sustainable energy systems – CASES. CentroClima/COPPE/UFRJ; 2008.
[14] La rovere EL. Proposta de Regulamentação da Geração de Energia Elétrica de Fontes Renováveis Requerida de Centrais Termoelétricas a Combustíveis Fósseis no Estado do Rio de Janeiro. In: XII Congresso Brasileiro de Energia; 2008.
[15] Torre A, Fajnsylber P, Nash J. Low carbon, high growth: Latin American responses to climate change. Washington: The World Bank; 2009 .
[16] Figueres C, Haites E, Hoyt E. Programmatic CDM project activities: eligibility, methodological requirements, and implementation, working paper. Washington: World Bank Carbon Finance Unit; 2005.
[17] Messner S, Strubegger M. User's guide for MESSAGE III, WP-95-69. Laxenburg: International Institute for Applied Systems Analysis (IIASA); 1995.
[18] Timilsina GR, Shrestha RM. Alternative tax instruments for CO_2 emission reduction and effects of revenue recycling schemes. Energy Studies Review 2007;5(1). Spring.