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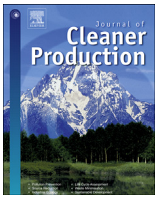

Scenarios for the future Brazilian power sector based on a multi-criteria assessment

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ABSTRACT

The Brazilian power generation sector faces a paradigm change driven by, on one hand, a shift from a hydropower dominated mix and, on the other hand, international goals for reducing greenhouse gas emissions. The objective of this work is to evaluate five scenarios for the Brazilian power sector until 2050 using a multi-criteria decision analysis tool. These scenarios include a baseline trend and low carbon policy scenarios based on carbon taxes and carbon emission limits. To support the applied methodology, a questionnaire was elaborated to integrate the perceptions of experts on the scenario evaluation process. Considering the results from multi-criteria analysis, scenario preference followed the order of increasing share of renewables in the power sector. The preferable option for the future Brazilian power sector is a scenario where wind and biomass have a major contribution. The robustness of the multi-criteria tool applied in this study was tested by a sensitivity analysis. This analysis demonstrated that, regardless of the respondents' preferences and backgrounds, scenarios with higher shares of fossil fuel sources are the least preferable option, while scenarios with major contributions from wind and biomass are the preferable option to supply electricity in Brazil through 2050.

1. Introduction

The Brazilian power sector faces a paradigm shift, which raises additional concerns about security of supply to decision-makers. The Brazilian power sector relies heavily on hydropower plants (around 80% of the power supply came from hydropower over the last ten years) (EPE, 2013). However, the expansion of hydropower faces severe local environmental challenges and what might be considered a feasible potential hydropower generation should be fully used by 2030 (Nogueira et al., 2014). Additionally, being highly dependent on rainfall, changes in climate conditions can put in question the large contribution of hydropower for energy production in the country in the future (Pao and Fu, 2013; Schaeffer et al., 2012; Lucena et al., 2009).

On the demand side, projections for future power consumption reveal an expected annual increase of 5% (EPE, 2014; Nogueira et al., 2014), which implies in a fast expansion of the power generation capacity. In this context, renewable energy technologies, such as wind, solar and biomass power, may complement hydropower units. However, in a reference scenario, studies show a higher penetration of fossil fuel power plants into the future (Lima et al., 2015; Lucena et al., 2015; Nogueira et al., 2014; Portugal-Pereira et al., 2016). These scenarios show that coal and natural gas would play an increasingly important role in power generation, changing natural gas' current role as backup generation at peak load or when hydrological conditions are poor. A higher penetration of these primary energy sources, however, will mean that fossil fuel imports may push Brazil to a more foreign dependent position.

Some renewable energy technologies are usually referred to as non-competitive when compared with conventional fossil fuel alternatives (Lins et al., 2012). However, if the competitiveness includes not only economic aspects, but also social and environmental externalities, power generation expansion planning could take other directions. Eventually the integration of renewable energy sources in the system may even be enhanced (Lins et al., 2012).

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Multi-criteria decision analysis (MCDA) is an efficient technique to tackle decision-making problems under different and conflicting criteria (Linares, 2002; Martin, 2015).

Most of the work developed for the power sector using MCDA relies on comparing different power generation technologies. In this work, the technologies themselves are not evaluated. Instead, different power generation scenarios composed by different technologies and different contribution rates of renewable/non-renewable sources are analysed. Additionally, a MCDA technique was coupled with a Life Cycle Assessment (LCA) to compare scenarios in terms of global and local environmental impacts. Thus, the main objective of this work is to identify the most preferable scenarios, according to stakeholders' preferences regarding economic, social and environmental dimensions, to promote a sustainable power sector for Brazil until 2050.

The paper is organized as follows. Section 2 presents a literature review on MCDA, analysing different techniques and studies that applied them. Then, section 3 briefly reviews the context of Brazil's power sector. Section 4 presents the methodology used in this study. Subsequently, in section 5, results and discussion are presented, followed by final remarks.

2. Multi-criteria decision techniques applied to energy systems

Multi-criteria decision techniques are gaining increase attention, and applications in the energy management and sustainability fields are emerging. These techniques provide a better understanding of inherent features of decision making problems when compared to a single criterion. Additionally, they promote the role of participants in decision making and provide a good platform for understanding the perception of models and analysts in a realistic scenario (Pohekar and Ramachandran, 2004).

The decision process in MCDA follows five sequential steps: 1) defining the problem; 2) generating alternatives; 3) formulating criteria to judge the alternatives; 4) collecting the judgments on the importance, or relative importance, of criteria; and 5) ranking the alternatives (Khalili and Duecker, 2013).

There are several methods for applying MCDA and, along with its own particularities, they share the common characteristics of dealing with conflicting criteria, incomparable units and difficulties in the selection of alternatives (Pohekar and Ramachandran, 2004). The most common methods applied for energy planning and management are WSM (Weighted Sum Method), AHP (Analytical Hierarchy Process), PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation), ELECTRE (Elimination and Choice Translating Reality), MAUT (Multi-Attribute Utility Theory) and Fuzzy methods (Abu-Taha and Daim, 2011; Pohekar and Ramachandran, 2004).

Maxim (2014) used MAUT and WSM methods for ranking a large number of power generation technologies based on their compatibility with sustainable development of the industry. Although the work provides a comprehensive sustainable assessment of thirteen technology types, the sample of participants included in the criteria weighting process included only academics from Romanian universities and, thus, the perspectives of other actors in the energy field were not considered.

The potential of renewable energy sources to power generation in rural areas was studied by Rahman et al. (2013), which applied a decision aiding tool, the SMAA-2 (Stochastic Multi-criteria Acceptability Analysis), and by Fuso Nerini et al. (2014), which applied a WSM method to the case of Brazilian Amazon rainforest. Diakoulaki and Karangelis (2007) applied the PROMETHEE method to evaluate scenarios for the expansion of the Greek power sector, while Kowalski et al. (2009) applied the same method to analyse renewable energy scenarios for Austria. Stamford and Azapagic (2014) also support that the use of stakeholders preference weights in multi-criteria analysis can be a robust approach for the analysis of future power generation scenarios.

While relevant to the field, most of the aforementioned studies focused particularly on the potential for renewable energy technologies, dealing with each option as single individual projects. Although these studies provide good understanding of the technical requirements and externalities of each technology, they do not reflect the existent interactions and synergies that characterize the power sector.

The work described in Santos et al. (2015) presents a multi-criteria analysis of electricity scenarios for a Portuguese case study, considering different perspectives of possible stakeholders' preferences: economic, technical, social, environmental and equitable weights for these four dimensions. The dilemma however prevails, which is to find the scenario that best fits the desired goals in a multidimensional context, but where the dimensions have not the same weight on those goals. In the work of Santoyo-Castelazo and Azapagic (2014), a new framework is proposed in order to support decision making considering three sustainability dimensions: environmental, economic and social, and demonstrated for the future power supply in Mexico. However, for the demonstration purpose, the authors used the multi-attribute value theory (MAVT) for deciding the possible stakeholder preferences, not considering the preferences of the stakeholders themselves.

The potential to combine multi-criteria tools with other methods is an important topic for research with the objective of increasing the robustness of the multi-criteria results, and LCA is one of the methods that have been attracting interest in several areas. The combination of LCA with MCDA is described in Agarski et al. (2016) with the purpose of evaluating four different waste treatment processes, or in Domingues et al. (2015) for the assessment of six vehicle types, differing on their powertrains.

The use of multi-criteria tools for assessing the Brazilian power sector was also addressed in previous works, although most of them focused on technologies and with limited collection of data from stakeholders or experts of the sector. Rovere et al. (2010) selected environmental, social, economic and technological indicators to evaluate power generation alternatives and used a data envelopment analysis (DEA) to establish the relative efficiency of production units and of their hierarchy. Fuso Nerini et al. (2014) focused on a specific geographical region (Amazon) and used a multi-criteria approach to compare five electrification options based on interviews with experts, with results pointing to a clear preference towards renewables. This study aims to proceed further with this analysis targeting the entire country, as MCDA is used for the comparison of scenarios designed for the whole Brazilian power sector, comprising a set of technologies and reflecting not only the least-cost options but also the judgment of experts on environmental, economic, technical and social criteria. In addition, the research demonstrates the potential to integrate LCA methods with MCDA tools relying on a participative approach for the assessment of a real case study with a final goal of supporting energy policy making. Finally, this study has an innovative character since it applies a new methodology to evaluate future scenarios derived from a cost optimization approach to the Brazilian power sector, a work that has not been done before.

3. The Brazilian power sector

Brazil is the World's 7th largest economy and the 8th largest total energy consumer (IMF - International Monetary Found, 2015). Surprisingly, Brazil has one of the most renewable energy mixes in the world. According to the Brazilian Energy Balance (EPE, 2014), power generation in the country is predominantly composed by renewable energy sources (RES) distributed in 77% hydro, 7% biomass and 1% wind. Natural gas and oil products have a share of 8% and 3% respectively, while coal products account for 2% and nuclear 3%.

Despite the high hydropower share, there are several risks for the Brazilian power sector if it keeps relying mainly on hydropower sources. Firstly, rainfall is vulnerable to climate conditions and to the effects of extreme weather events, thus the water availability is an uncertainty. Supporting this point, several droughts have occurred in Brazil in the last decade, which have risen problems concerning power supply (Juárez et al., 2014; Lucena et al., 2009; Schaeffer et al., 2012). Recent droughts have occurred in 2007, the most serious in the State of Minas Gerais, another in 2012, the most rough in the Northeast Region of Brazil in the last 30 years, and a last one in 2014 which continued until 2015 and highly affected the Southeast Region of Brazil. Due to the persistent drought and erratic rainfall patterns, there is a risk for water and electricity rationing programs in some parts of the country in the near future, which may have negative consequences for economic activities and income of the most vulnerable and bottom of the pyramid population (ONS, 2015).

In addition to the vulnerability of hydropower sectors towards extreme weather events, the new hydropower capacity is expected to be depleted by 2030 (Nogueira et al., 2014; J Portugal-Pereira et al., 2016). According to the official 10-year expansion plan (MME/EPE, 2015) eighteen hydropower units are projected to begin operation in 2019–2023, adding up to 14,679 MW of capacity to the Brazilian power sector.

Thus, the expansion of hydropower sectors is slower than the power demand predicted for the next decade and is mainly limited to run-of-river and small hydro projects. One measure to contribute to the safety of supply is to have a diversified electricity mix, composed by technologies that could efficiently complement hydropower to match the power demand at any moment. In Brazil, this is mainly conducted by fossil-based thermal power plants. Currently, natural gas power plants are used as backup systems. However, given the current pressure on the power supply sector, the low price of coal in international markets and the development and exploitation of domestic pre-salt oil reserves, Brazil may invest in natural gas and coal-based technologies for power generation (Nogueira et al., 2014).

As of today, coal-based power plants in Brazil make up 2 GW. Three new coal power units are under construction, with a combined capacity of 1.4 GW, and this number is expected to increase in the near future (Lucena et al., 2015; Nogueira et al., 2014). Nonetheless, domestic coal brings many limitations, since it has a high ash content resulting in a low-heating-value for this fuel (Hoffmann et al., 2012; Nogueira et al., 2014). Thus, future coal-based technologies are expected to run with coal mostly imported from Colombia (Lucena et al., 2015). Carbon Capture and Storage (CCS) could be an effective alternative to contribute for the GHG emission reduction, coupling this technology with thermal power units (Lucena et al., 2015; Nogueira et al., 2014).

However, there are several options for increasing the power supply in Brazil without having to turn to fossil fuels.

Brazil has the world's second highest biomass power capacity generation (Pao and Fu, 2013) and has also the world's most competitive program for development and production of biofuels (Pereira et al., 2012). Power generation with biomass is mostly derived from combined-heat-and-power facilities fuelled with sugarcane bagasse (Lucena et al., 2015). The projects for the expansion of installed capacity of biomass power plants are forecasted to be implemented in 2016 (60 MW) and in 2018 (698 MW) in the southeast and northeast regions of Brazil (EPE, 2014; MME/EPE, 2015). There is further potential to generate bioelectricity from agricultural and industrial wastes, which is currently not recovered, and has a technical potential to make up one third of the country's total power demand (Portugal-Pereira et al., 2015).

Wind power generation is a suitable hydropower complement for the future Brazilian power sector since Brazil has very strong winds throughout the year, especially in low rainfall seasons (Pao and Fu, 2013). The estimated potential of wind in Brazil is about 300 GW (GWEC, 2011) and it is expected that wind power generation will contribute to about 10% to all the power generation in the next 15 years (Juárez et al., 2014). Future projects, mainly in the northeast region of the country, include additional power capacity in 2016 (1797 MW), 2017 (283 MW) and 2018 (2340 MW) (MME/EPE, 2015).

Total installed capacity of solar photovoltaic remains residual in the power sector at the moment, with an estimated 15 MW. Nevertheless, new small scale decentralized photovoltaic power is expected in coming years, under national programs such as Light for All (Luz para Todos), a governmental program intended to supply electricity to isolated communities of Brazil (Pereira et al., 2012). According to Miranda et al. (2015), installed photovoltaic panels on residences could reach a 55% increase until 2026. Concentrated solar power (CSP) systems are yet to be implemented in Brazil. While not competitive in the Brazilian power market at the moment, there are economic and political motivations for the development and implementation of the technology (Soria et al., 2015). CSP systems could be an option to reduce the external dependence of fossil fuels and GHG emissions and, according to Malagueta et al. (2014), the Northeast region of Brazil could become energy independent and provide electricity to the Southern and Southeast regions.

4. Methods

The methodology used in this work follows the diagram presented in Fig. 1 and is described in the sections below. It encompasses five stages: (i) scenario design, (ii) criteria definition, (iii) criteria weight attribution, (iv) determination of scenarios' relative impact, and (v) scenario ranking.

Based on the outcomes of the Latin America Modelling Project and Integrated CLImate Modelling and CAPacity building in Latin America (LAMP-CLIMACAP) (Lucena et al., 2015; van der Zwaan et al., 2015), five scenarios of the Brazilian power generation sector in 2050 under different climate mitigation strategies were selected. These scenarios were then characterized in terms of power generation mix, GHG emissions, dependence on foreign energy resources and total generation costs.

In the criteria definition, key indicators were identified to portray the three pillars of sustainability, i.e., economic, social and environmental dimensions. This is a critical stage because the analysis is intended to be as pluridimensional as possible, considering however the minimum time consumption and no ambiguities among criteria. Overall, 15 criteria were selected, which are detailed

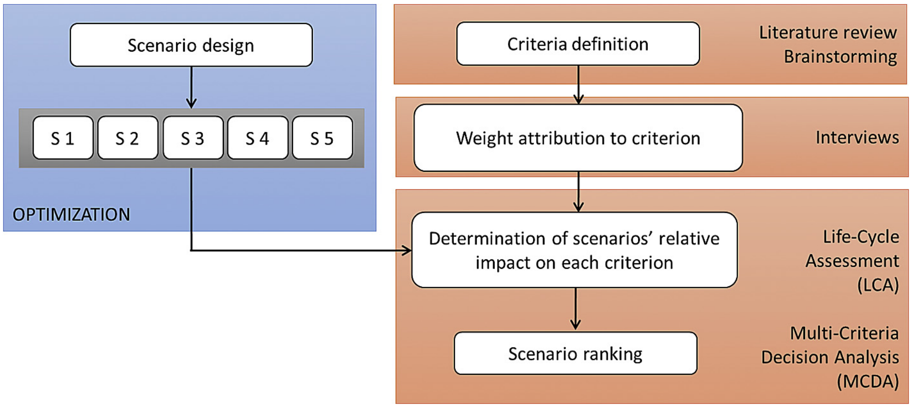

Fig. 1. Methodology used in this work.

in section 4.2. Then, for each criterion was attributed a weight, which reflects its contribution to the overall impacts of each scenario.

Questionnaires sent to experts in the energy planning were used to determine a single weight to selected criteria. Multi-criteria analysis was finally applied in order to compare the five scenarios and, at last, a sensitivity analysis was conducted in order to decide the robustness of the methodology applied in this study.

4.1. Scenarios design

The analysed scenarios were developed under the LAMP-CLIMACAP project (Lucena et al., 2015; van der Zwaan et al., 2015) and modelled using the MESSAGE-Brazil v.1.3 integrated model (Model for Energy Supply System Alternatives and their General Environmental impacts), originally developed by the International Atomic Energy Agency. MESSAGE-Brazil v.1.3 is a mixed integer programming model used for the optimization of energy systems and is designed to formulate and evaluate alternative strategies for energy supply, considering constraints related to investments, availability, fuel prices, environmental regulations and renewable energy penetration rates (Nogueira et al., 2014; Lucena et al., 2010).

A baseline scenario and four alternatives pathways in a 2050 horizon were selected in this study in accordance to Lucena et al. (2015). Scenario 1 (S1) represents a business-as-usual scenario, gauged on baseline assumptions at regional and global levels, and was used as a reference for the other scenarios. This scenario does not include any new policy except those implemented prior to 2010. Alternative climate policy scenarios, on the other hand, evaluate more stringent mitigation strategies and consider two different climate strategies, including carbon price mechanisms and emission cap reduction to fossil fuel related emissions. Thus, scenario 2 (S2) and scenario 3 (S3) admit carbon price paths starting, respectively, at 10USD\$/t CO_{2e} and 50USD\$/t CO_{2e} in 2020 and growing at 4% yearly. Scenarios 4 and 5 (S4 and S5), designated

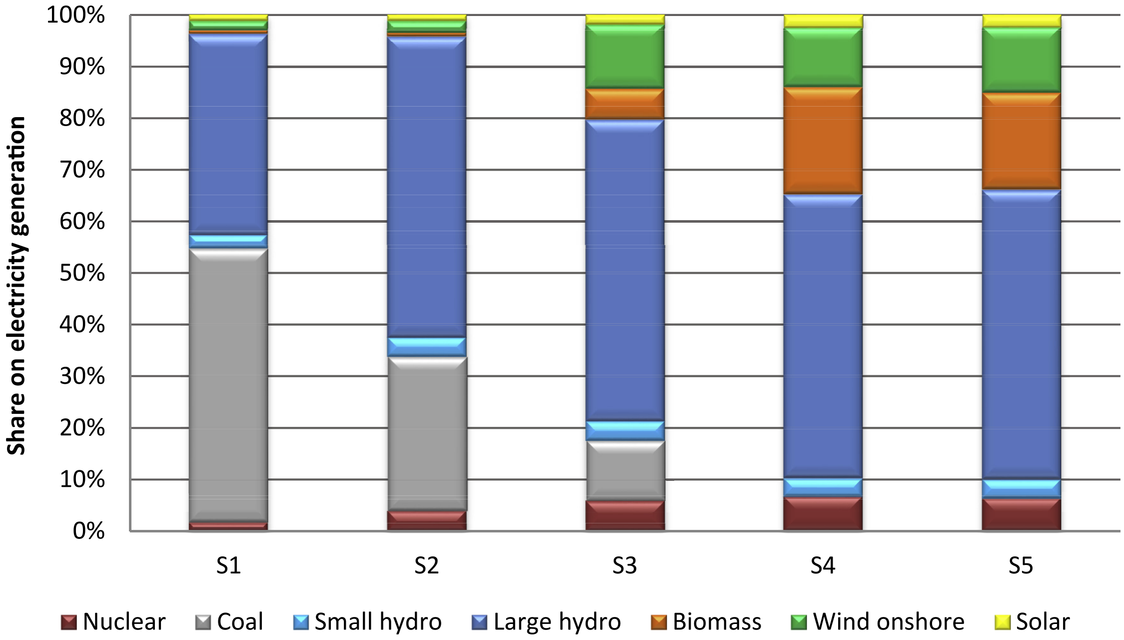

Fig. 2. Power generation for each scenario, by source share in Brazil 2050

as “cap scenarios”, describe an abatement reaching 20% and 50% by 2050, respectively, applied to CO_{2e} emissions from fossil fuel combustion.

The contribution of each source in power generation mix in 2050 for each scenario is presented in Fig. 2. The scenario 1, which reflects a baseline trend without considering the implementation of new climate or energy policies, assumes that the power matrix expansion will mostly rely on conventional fossil thermal power plants. Thus, by 2050, conventional coal-based technologies would account for more than 50% of the total installed capacity of the power supply sector. This reflects the expected low cost of conventional fossil fuel technologies relative to CCS technologies and renewable power generation systems.

Scenarios 2 and 3, which reflect the consequences of implementing a low and high tax on GHG emissions, reveal a significant decrease in fossil fuel contribution to the power matrix until 2050, compared to the business-as-usual scenario (S1). Thus, scenarios S2 and S3 progressively admit a higher share of non-large hydro renewable energies, mainly small hydro, wind power and bioenergy technologies, up to 8% and 24%, respectively. Scenario 3 also reveals a gradual implementation of CCS technologies in coal thermal power plants, which account for 12% of total installed capacity in 2050.

Scenario 4 and scenario 5, which describe the implementation of an emission cap, both reveal higher share of renewables than the carbon tax paths (scenarios S2 and S3) and no contribution from any fossil fuel technology. Scenario 4 and 5 reveal preference to biomass-based technologies that convert bagasse and agricultural and woody wastes into bioelectricity.

4.2. Criteria definition

Most of the criteria were selected following the proposal of Ribeiro et al. (2013), but a few others were included – namely social acceptance, energy backup needs and water consumption – deemed to be relevant for the analysis of increasing share of renewable technologies. The selected criteria are also supported by the work of IAEA (2006), which provides a comprehensive list of indicators for the sustainability of the future Brazilian energy system. Social acceptance has been assumed as a preponderant factor with respect to building new infrastructures, as local communities can create barriers to its construction or, on the other hand, can encourage its development, according to their knowledge and acquired information about renewable technologies (Akgün et al., 2012). Backup needs are an essential aspect to be considered when dealing with a high penetration of variable energy sources, such as wind and solar energy, as the generated power from these sources is highly dependent of the geographic layout, weather, season and hour of the day (Portugal-Pereira and Esteban, 2014; Esteban et al., 2012). Water is a valuable source and its consumption and withdrawal has strong impact in power generation (Macknick et al., 2012). The selected criteria are described in Table 1.

4.3. Criteria weight attribution

At this stage, a questionnaire was elaborated to obtain primary data, which served as input for the MCDA. The questionnaire comprised only rating type questions, specifically in numerical scale, except those questions related to participants' personal information. The questionnaire was divided in two stages and can be viewed on Annex I.

Whenever possible, the questionnaire was conducted by a structured interview, with a duration between 15 and 30 min. This type of questionnaire administration can provide a better understanding of the participant perceptions and the interviewer can give him/her immediately clarifications, if necessary. For the

Table 1
Description of the selected criteria for MCDA evaluation.

Criteria		Description
1	Costs (\$/MWh)	Represents the sum of the annualised costs of new installed units, as well as O&M of all units (including fuel), divided by the total amount of power generated in the planning period. Costs are obtained directly by MESSAGE-Brazil model.
2	National industry (ordinal)	For all the stages for projection, construction and maintenance of generation infrastructures the use of industry of different sectors is required. This criterion aims to capture the impact of each scenario on the dynamics of national industry.
3	Energy dependency (%)	The criterion is evaluated by the share of power generated from imported primary energy sources (coal and natural gas).
4	Employment (Jobs/MW)	Job creation by each scenario, for the project, construction and operation of the power plants. Values are estimated based on (Hashimura and de, 2012).
5	Local income (ordinal)	Revenues obtained as compensation for the establishment of new generation infrastructures can have a positive impact on local populations, associations and municipal income.
6	Visual impact (ordinal)	The establishment and the functioning of new power plant units can cause changes in the landscape.
7	Noise (ordinal)	The normal functioning of new generation infrastructures can have noise impact, causing annoyance to local population.
8	Social acceptance (ordinal)	Public preference for the deployment or utilization of a certain power generation technology.
9	Diversity of the mix (ratio)	The expression used to measure the diversity of the mix was based on Shannon-Wiener index.
10	Dispatchable power (%)	The criterion is evaluated according to the ratio between the total installed power of dispatchable technologies (reservoir hydropower, natural gas, coal, nuclear and biomass thermal power plants) and the total installed power of the system.
11	Backup needs (%)	Insure overall grid stability in the long term in the context of a growing share of intermittent generation from some renewable energy sources. Higher shares of intermittent RES power production can require higher backup capacity. This criterion was assessed by the ratio between total installed power of solar, wind and mini hydropower units and total installed power for the entire period.
12	GHG emissions (kg CO_2e/MWh)	GHG emissions (CO_2, CH_4 e N_2O) during all the project life cycle, obtained directly from Life Cycle Assessment (LCA) run on SimaPro software (Goedkoop et al., 2013).
13	Land use (m^2.a/MWh)	Represents the required land for deployment of new infrastructures. Values are obtained from LCA run on SimaPro software (Goedkoop et al., 2013).
14	Public health (ordinal)	Harmful pollutants for public health (potentially cause of cancer, respiratory and skin diseases, etc.). Values related to the results for SO_2 and PM (particulate matter) emissions obtained from LCA run on SimaPro software (Goedkoop et al., 2013).
15	Water consumption (m^3/MWh)	Ratio between water consumption by all power plants during the overall planning period and the total generated power. Values are obtained from LCA run on SimaPro software (Goedkoop et al., 2013).

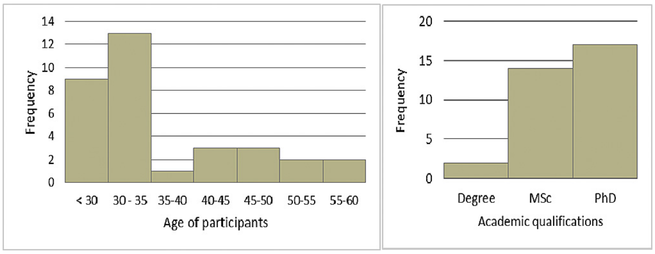

Fig. 3. Histogram of the participants' age and academic qualifications.

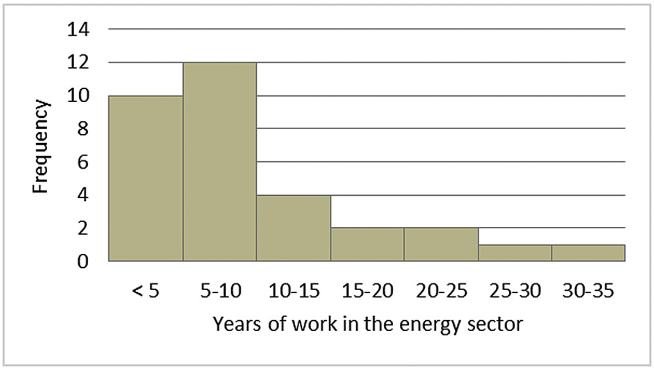

Fig. 4. Histogram of the participants' years of experience in the energy related field.

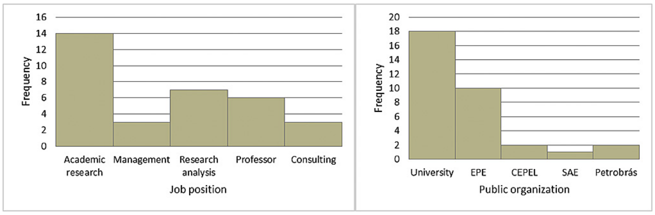

Fig. 5. Participants characteristics based on their job position and organization to which they belong.

participants unable to perform an interview, the questionnaire was self-administered via e-mail correspondence. In total, 33 questionnaires were collected from different Brazilian stakeholders, including academia, professionals from energy (transmission and distribution) companies, and governmental planning agencies, namely the Energy Research Company (EPE), the former Strategic Affairs Secretariat (SAE), which was linked to the Presidency of Brazil, and the Electrical Energy Research Centre (CEPEL).

The participants' characterization is described in Figs. 3–5.

4.3.1. Stage 1 — Weight attribution to each criterion

Each participant was asked to attribute the respective importance that he/she gives to each criterion for the power planning, as presented in Table A1 in the Annex. The importance was translated on a scale from 0 to 100, considering that a weight of 0 means that the criterion is not significant to the power planning, whereas a weight of 100 means that the criterion is extremely important to it. The 33 answers were aggregated and treated by statistical methods.

4.3.2. Stage 2 — Impact determination for each power generation technology

Each participant was asked to assign a value to each technology on each criterion. These impacts were defined in a scale from 0 to 100, having different meanings according to the criterion analysed. Nine technologies were evaluated, namely nuclear, coal, natural gas, large hydro, mini-hydro, wind onshore, wind offshore, solar photovoltaic and biomass. Only those criteria that could not be valued by the modelling output or from the literature, were included in this stage. As such, this stage focused on contextual criteria, relatively dependent on the region, city or country in which the study is carried out. Those criteria are national industry, visual impact, noise, local income and social acceptance, as described in Table A2 in the Annex.

At this stage, a LCA was also applied to estimate the environmental impacts of the evaluated energy systems per unit of kWh generated, transmitted and distributed to end-users. The analysis includes the so-called Well-to-Meter boundaries, i.e., the upstream (extraction of fuels and raw materials, fuel processing and transportation) and downstream processes (operation of power plants and transmission and distribution to the national grid up to end-users), as well as the material life cycle of the construction and thermal power plant infrastructure and the manufacture of material requirements for the construction of renewable power generation facilities. The inventory and impact assessment was developed by simulating input and output streams that describe power generation processes with the SimaPro 8.0.1® model architecture (Goedkoop et al., 2013). SimaPro is a LCA software that allows users to customize inventory libraries of all stages of the life cycle (used materials, fuel extraction, processing and delivery). Data was collected from EcoInvent database (REF), governmental agencies, namely the Ministry of Mines and Energy (MME), the Energy Research Company (EPE) and the National Electricity Regulatory Agency (ANEEL).

4.4. Determination of scenarios' relative impact on each criterion

The resultant impacts for each technology allowed creating a technology-criteria impact matrix. Then, this matrix was transformed into a scenario-criteria impact matrix. For contextual criteria, estimation of the scenarios impact was made by calculating the weighted average (WA), according to the contribution of each technology on each scenario (Equation (1)), and the resulting weighted average was normalized by a simple additive method (Equation (2)). This step was applied to criteria not directly obtained from the MESSAGE-Brazil modelling, and thus requiring the translation of scores obtained for specific technologies into scores for each scenario. The obtained normalized values compose the impact matrix. The use of the simple additive method for calculating the overall preference score for each option requires that the principle of mutually preference independence for the criteria is ensured, meaning that preference scores assigned to one criterion are not affected by the preference scores assigned to other criteria (Lindhe et al., 2013).

$$Weghted\ average\ (WA) = \frac{\sum (Ip_i \times w_{ij})}{\sum Ip_i} \qquad (1)$$

$$Normalization = \frac{WA}{Max\ Weightj} \times N.factor \qquad (2)$$

Where,

Ip_i is the installed power of technology i;

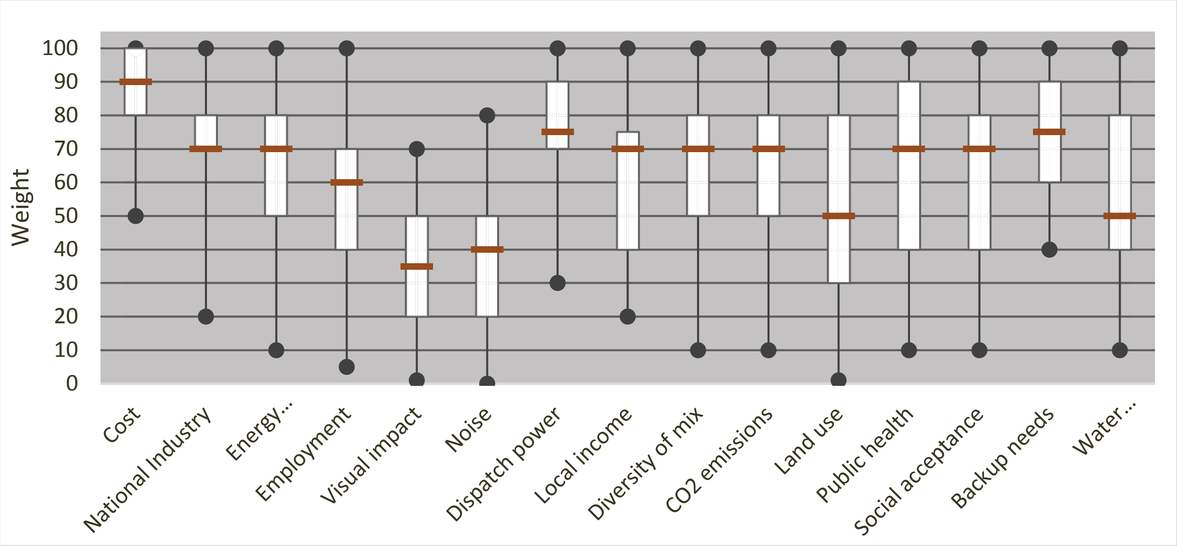

Fig. 6. Criteria weights given by interviewed participants[2].

w_i is the weight attributed to technology i, in relation to the criterion j;
$Max\ weight_j$ is the maximum weight attributed to the criterion j;
N. factor is the normalization factor for ordinal criteria, set as 5 in this work.

4.5. MCDA tool application

The method used to evaluate the scenarios was an adapted version of the Multi-Criteria Decision Tool to Support Electricity Power Planning (available on http://sepp.dps.uminho.pt/), described in Ribeiro et al. (2013). This tool is presented in an Excel worksheet which provides a framework for the inputs – scenarios and scenario-criterion impact matrix, and generates results presented in graphics of both scenario ranking and contribution to each criterion.

In order to validate the results for the evaluation methodology, a sensitivity analysis was performed. For this purpose, 33 runs on MCDA tool were performed, each running considering the criteria weights attributed by each participant. One additional run was performed assuming equal weights assigned to each criteria, following the *insufficient reason Principle*[1]

5. Results and discussion

The data collected from questionnaires allowed the construction of a boxplot graph presented in Fig. 6, based on the weights attributed by the 33 participants. It is observed that economic criterion “Cost” has the highest weight and a symmetric dispersion between values of 80 and 100. “Visual impact” and “Noise” are the criteria with the lowest values, with a median of 35 and 40, respectively. Visual and noise impacts, often related to wind turbines operation, may not be fully acknowledged by the participants as they may be aware of these impacts but not of its extension or annoyance for local residences, since they do not reside in areas with wind farms (Brown, 2011). Also, some of the participants believe that technological development can help to mitigate the noise level of wind turbines, and as such the importance of this criterion will tend to be reduced throughout the years considered in this planning period.

The criterion “GHG emissions”, represented by “CO_2 emissions” in Fig. 6, is assigned a high weight. CO_2 emissions concern is believed to be influenced by this topic wide dissemination in the media, leading to a higher awareness for this criterion.

The high variability of the response expressed by the extension of the white box (and also extreme points) may be explained by the different backgrounds and interests of the participants.

An attempt was made to investigate possible relations between the response of one participant and his/her characteristics within the group, namely years of experience in the energy field, job category and education degree of the participants. However, no significant correlations could be found between the participants' characteristics and their responses and further tests are limited by the reduced size of the sample. The statistical inference is not the main purpose of the proposed model, but the importance of the validation of the results obtained should not be overlooked. As such, sensitivity analyses of the assigned weights were conducted, allowing to check the extend of variation in results when parameters are varied over a realist range of interests (Qureshi et al., 1999).

This analysis also accounted for correlations seeking between the weights attributed to different criteria, using the Pearson correlation method in pair-wise approach. The main correlation factor was found between the criteria “visual impact” and “noise”, with a value of 0.8. According to the Pearson correlation classification, this value represents a strong association between these two criteria, indicating that participants tend to give a relatively proportional weight to these two criteria when considering their importance to the power planning. As for all other criteria, Pearson correlation results point to the general acceptance of the mutually preference independence for the criteria allowing for the analysis with the weighted average as indicated in equations (1) and (2).

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[1] The *insufficient reason Principle* dates back from the 18th and 19th century (from Bernoulli and Laplace respectively) and it states that if there is no reason to believe that out of a set of possible, mutually exclusive, events no one event is more likely to occur than any other, then one should assume that all events are equally probable (interested readers can see the principle revisited in Sinn (1980)).

[2] The body of the boxplot consists of a “box” (represented by the white box in the figure), delimited by the first quartile (Q1) to the third quartile (Q3). Within the box, a horizontal black line is drawn at the second quartile (Q2), which represents the median of the data set.

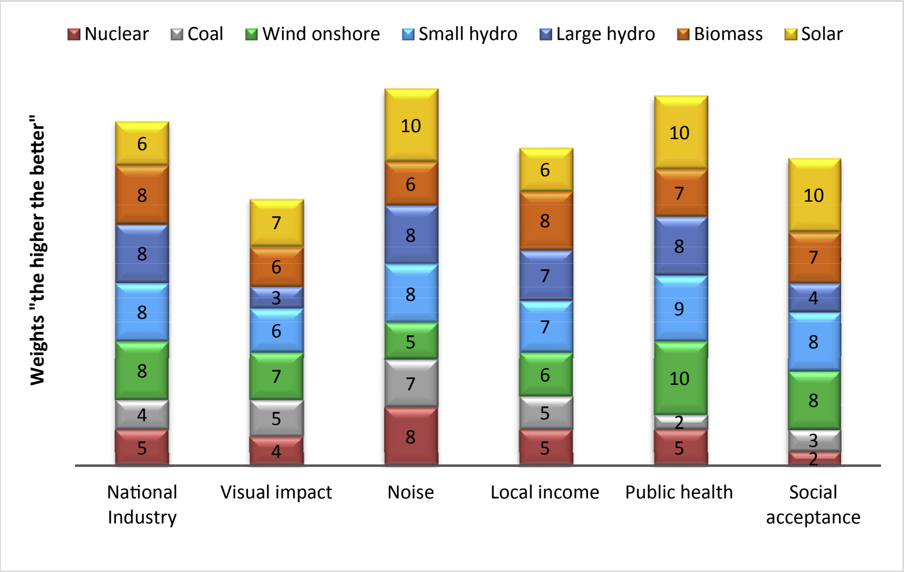
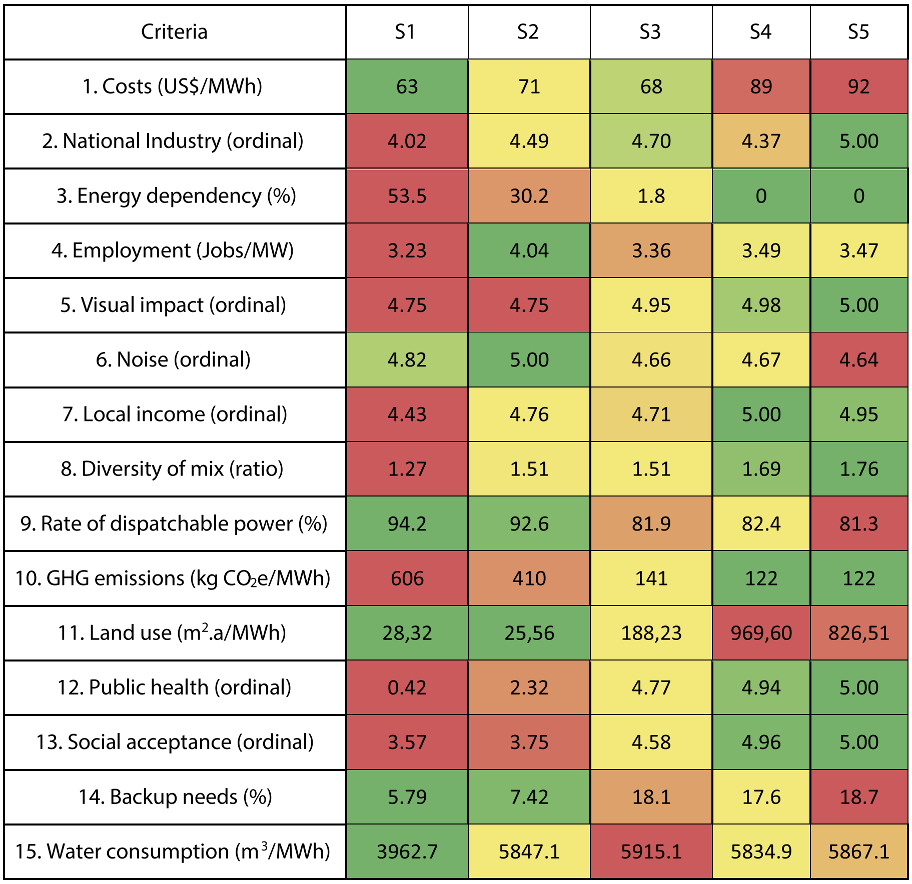


Fig. 7. Median values for the score attributed to each technology, for six subjective criteria.

Table 2
Impact matrix relating scenarios with criteria.



Criteria	S1	S2	S3	S4	S5
1. Costs (US$/MWh)	63	71	68	89	92
2. National Industry (ordinal)	4.02	4.49	4.70	4.37	5.00
3. Energy dependency (%)	53.5	30.2	1.8	0	0
4. Employment (Jobs/MW)	3.23	4.04	3.36	3.49	3.47
5. Visual impact (ordinal)	4.75	4.75	4.95	4.98	5.00
6. Noise (ordinal)	4.82	5.00	4.66	4.67	4.64
7. Local income (ordinal)	4.43	4.76	4.71	5.00	4.95
8. Diversity of mix (ratio)	1.27	1.51	1.51	1.69	1.76
9. Rate of dispatchable power (%)	94.2	92.6	81.9	82.4	81.3
10. GHG emissions (kg CO_2e/MWh)	606	410	141	122	122
11. Land use (m^2.a/MWh)	28,32	25,56	188,23	969,60	826,51
12. Public health (ordinal)	0.42	2.32	4.77	4.94	5.00
13. Social acceptance (ordinal)	3.57	3.75	4.58	4.96	5.00
14. Backup needs (%)	5.79	7.42	18.1	17.6	18.7
15. Water consumption (m^3/MWh)	3962.7	5847.1	5915.1	5834.9	5867.1

The information obtained from the second stage of the questionnaire, where it is explicit the subjective opinion of the participants about each technology in relation to six ordinal criteria, is presented in Fig. 7.

According to the results, solar technology is the only one achieving the maximum score (10) for three of the six criteria: “noise”, “public health” and “social acceptance”. Wind onshore achieves also the maximum score for the criterion “public health”

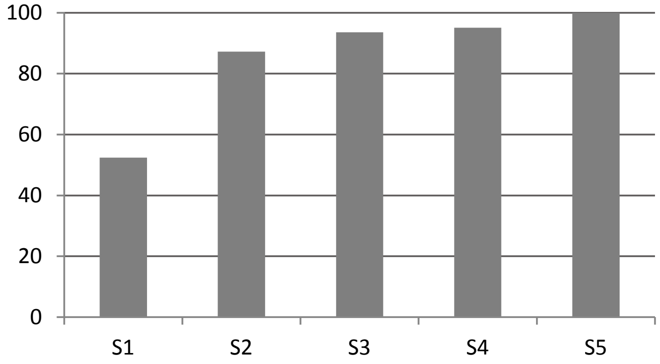


Fig. 8. Ranking for the scenarios evaluated by the MCDA tool.

Table 3
Scenario preference matrix from sensitivity analysis (%).

Scenario	Ranking				
	1st	2nd	3rd	4th	5th
S1	0	0	0	0	**100**
S2	0	6	9	**85**	0
S3	0	33	**58**	9	0
S4	0	**61**	33	6	0
S5	**100**	0	0	0	0

Bold values indicate the highest value for each row (scenario).

and high scores for “contribution to national industry” and also “social acceptance”. These results are in line with a recent work from de Sena et al. (2016) that concluded on the high social acceptance of both solar photovoltaics and wind power plants in Brazil. According to Barin et al. (2009), which investigated four renewable technologies with MCDA tools for the Brazilian case, wind onshore is the most suitable technology to meet environmental and cost sustainability indicators, compared with solar photovoltaics. This is not however a fully consensual view, and Rovere et al. (2010) work showed a higher performance for sugar cane bagasse obtained from manual harvest using back-pressure technology due to aspects such as number of jobs generated and the reduced environmental impact. Fuso Nerini et al. (2014) results also indicate high scores assigned to biomass and photovoltaic systems options for the Brazilian Amazon, with less preference given to non-renewable options. In fact, Fig. 6 also demonstrates that coal and nuclear power are the less preferred technologies for all the six indicators with the exception of the criterion “noise”. Wind onshore and biomass technologies present the lowest values for this criterion, considered to be the most harmful technologies to noise pollution, from the set of technologies included in this analysis. Large hydro is the less preferred technology on the criterion “visual impact” and presents also a low score for the criterion “social acceptance”, although higher than nuclear or coal.

The impact matrix resultant from the impact of each scenario on each criterion is presented in Table 2. For contextual criteria, the scenario impact ranges from 0 (the worst scenario in relation to the respective criteria) to 5 (the best scenario in relation to the respective criteria). For the remaining criteria, the impact is represented in specific units. To facilitate the matrix reading, in order to compare different criterion it was defined a colour scale that ranges from green (best option) to red (worst option), with the intermediate options corresponding to intermediate colours (salmon, orange and yellow).

The MCDA tool application allowed to rank the scenarios as illustrated in Fig. 8. It can be observed that the scenario preference follows the order of increasing share of renewables in the electricity system. The best option is considered to be scenario 5, where, even with the large hydropower plants which play the major role in electricity contribution, wind power plants account significantly, since they have the biggest share when compared with the others scenarios. Scenario 5 also integrates a significate contribution of biomass power plants, considered a well-developed technology in Brazil. These results are in good agreement with the results of the case study for Mexico (Santoyo-Castelazo and Azapagic, 2014). The power sectors of Brazil and Mexico are quite different today – in the first, the highest contribution is provided by hydropower, and in the latter, the highest contribution is provided by thermal power plants. However, comparing the two works, the results of both suggest that the most sustainable option to meet future power demand is a (almost) 100% renewable scenario.

The results from the sensitivity analysis are illustrated in Table 3, presenting the share percentage of respondents ranking each scenario in each position. For example, 100% of the participants ranked S1 in fifth place and 85% of the participants ranked S2 in fourth place, 9% ranked it in third place and 6% ranked it on second place, and so forth. The emphasis of the analysis is that scenarios in the extreme positions of the ranking are always the same for all the respondents, namely S1 is always the worst option and S5 is always

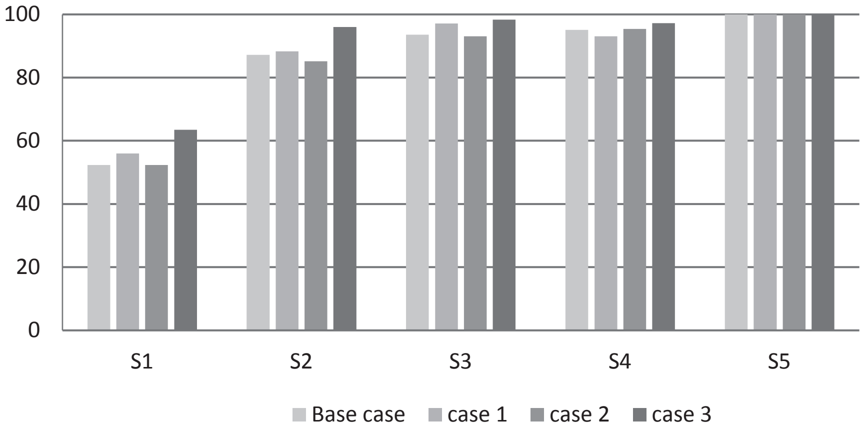


Fig. 9. Ranking for the scenarios from additional sensitivity analyses.

the best option. These results are reproduced for each MDCA run, i.e., they seem to be independent of the participants' preferences, allowing some level of confidence on the robustness of the multi-criteria tool applied to this study. S2 ranking is not as consistent as the aforementioned scenarios as its ranking position may vary between the second and the fourth places; however fourth position has a big acceptance, since it appears on that position for 85% of the respondents. S3 and S4 are ranked mainly between second and third places.

From the results obtained, it was interesting to further investigate possible changes in scenario ranking due to changes in criteria weights. For this reason, additional sensitivity analyses were performed by changing the weights accordingly: i) the weights of each criterion are those positioned in the first quartile, in Fig. 5 (case 1); ii) the weights of each criterion are those positioned in the third quartile, in Fig. 5 (case 2); and iii) a weight of 100 for the criteria "costs", "noise", "rate of dispatchable power", "land use", "backup needs" and "water consumption", and a weight of 50 for the remaining criteria (case 3). This last run was found to be relevant to observe if any change would occur on the scenario ranking when assigning the highest weight to criteria favouring the least preferred scenario (S1), according to Table 2.

The results from the additional sensitivity analyses are presented in Fig. 9. These results strengthen the same conclusions obtained from the previous sensitivity analyses, showing that, for any of the cases tested, the best option is S5 and the worst option is S1. This is also true, even for the case of increasing the possibility to select the most non-renewable scenario (case 3). The results of the sensitivity analyses provided then further confidence in the proposed MCDA model and on the overall preference towards high renewable scenarios.

6. Conclusions

The vulnerability of the Brazilian power sector calls for an intervention in the integration of new and competitive power generation technologies. Wind power is considered an emergent technology in Brazil, with a great unexplored potential in the country. And even, in some cases, at a higher cost when compared with fossil fuel technologies such as coal and natural gas power units, renewables can deliver a secure system, without foreign dependence and promoting a more environmentally friendly strategy to generate electricity.

In this paper, a methodology was proposed for the evaluation of five scenarios, developed under LAMP-CLIMACAP project, drawn for the Brazilian power generation system until 2050. The scenarios consisted in a reference scenario, two scenarios with different paths of CO_2 prices and two scenarios with different goals in GHG emission reductions until 2050. To compare scenarios, fifteen criteria were selected regarding economic, technical, environment and social aspects affecting power generation systems. The influence of each criterion in the power sector is quantified in a weight, based on the perceptions of several experts. For this purpose, a questionnaire was elaborated and presented to 33 participants.

For scenarios analysis, a multi-criteria tool (MCDA) was applied. This tool was developed in an earlier work for a Portuguese case (Ribeiro et al., 2013) and provides a ranking of the analysed scenarios, from "best" to "worst" options, considering the weights attributed by the participants. The scenario preference followed the order of increasing share of renewables in the power sector, with major contribution given by large hydro, wind onshore and biomass power units. This goes in line with Brazilian Nationally Determined Contribution (Federative Republic of Brazil (2015)) in the context of New Climate Agreement, which strives for a transition towards a low carbon economy based on renewable energies.

It is however important to highlight that the ranking of scenarios depends on the criteria included, on the weights assigned and even on the scores assigned to more subjective criteria scored. As such, changing the underlying socio-economic aspects of the country or selecting a different set of respondents is likely to influence results. Notwithstanding the proposed methodology allowed for the inclusion of different social, economic and environmental dimensions providing clear evidence that, although cost remains the fundamental criterion for most experts, other aspects, such as contribution to the domestic industry, reduction of energy dependency, local income, GHG emissions and social acceptance should not be overlooked.

The results put in evidence some aspects that can be particularly relevant for Brazilian energy policy makers. Firstly, the overall consensus among the experts towards RES in Brazil can be understood as positive foundations for the governmental objectives for the sector. Secondly the same consensus around cost and security of supply concerns among experts can, however, become an important barrier to a large scale RES strategy. Thirdly, the importance assigned to social aspects shows that the involvement of local stakeholders and the contribution for local development should be key issues to be considered on the design of future policies to ensure the acceptance of these projects and even to overcome the resistance that can come from the identified shortcomings.

Recognizing the limitations of the analysis performed, future work is recommended to focus on the expansion of the sample of participants, to capture wider participants' preferences and even proceed to a cluster analysis. This should allow for further explaining the responses according to the characteristics of the respondents, which is a valuable information for policy making.

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Annex I. Questionnaires

Table A1
Weight attribution to each criterion (Stage I).

Weighting range: 0 - 100	0 - Criterion with no importance to electricity power planning 100 - Criterion with crucial importance to electricity power planning	
Criterion	**Description**	**Weight**
Costs	Total costs (operation, maintenance, construction, fuels, …)	
National industry	National industry dynamics caused by different technologies	
Energy dependency	Imported energy sources to the electricity matrix (coal, natural gas and heavy fuel oil)	
Employment	Jobs creation	
Visual impact	Visual impact on landscape caused by new generation power plants	
Noise	Noise caused by the operation of the power plants	
Dispatchable power	Related with the flexibility of power sector (ability to start up and shut down whenever necessary)	
Local income	Local or regional benefits brought by the implementation of new power plants	
Diversity of the mix	Technology diversity composing the electricity power sector	
GHG emissions	GHG emissions (CO_2, CH_4 and N_2O) during the life cycle of the project	
Land use	Occupied area by the implementation of the power plants	
Public health	Adverse effects of pollutants on the human health (cancer, respiratory and/or skin diseases, etc.)	
Social acceptance	Acceptance by local communities to build new power plants	
Backup needs	Energy backup needed to deal with the intermittency of renewable energy sources	
Water consumption	Water consumption during the life cycle of power plant units	

Table A2
Impact determination for each electricity generation technology (Stage II).

	Impact of each technology: 1 - 10									
Criterion	Nuclear	Coal	NG	Wind onshore	Wind offshore	Small hydro	Large hydro	Biomass	Solar PV	
National industry										1 - The technology does not bring benefits to the national industry dynamics 10 - The technology brings many benefits to the national industry dynamic
Visual impact										1 - The technology causes a negative effect on landscape 10 - The technology does not affect landscape
Noise										1 - The technology makes too much noise 10 - The technology makes little noise
Local income										1 - The technology does not has income to the region and society 10 - The technology has many incomes to the region and society
Social acceptance										1 - The technology is not accepted by local society 10 - The technology is very accepted by local society

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