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Policies to Encourage the Sustainable Development of Brazilian Electricity System with Distributed Generation

University of Cambridge

A thesis submitted for the degree of
Master of Philosophy

August 2011

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Declaration

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text.

Daniel Vieira
August 2011

Acknowledgments

I acknowledge the contribution and support of:

- Dr Richard McMahon, Dr Richard Fenner, Dr Heather Cruickshank and Professor Peter Guthrie from the Department of Engineering, University of Cambridge.
- The Brazilian Electricity Regulatory Agency – ANEEL
- My friends from the MPhil in Engineering for Sustainable Development 2010-2011

Abstract

Brazil is a developing economy that is growing fast and expects a massive increase in electricity demand in the next decades. That will require, in addition to the traditional central generation schemes, efficient usage of the distributed resources to generate electricity close to the load centres. This would entail government intervention with adequate policies to suitably encourage the best options of distributed generation.

In order to do that, five distributed generation technology options were chosen in the present work (small hydro, biomass, photovoltaic solar systems, wind energy and cogeneration) with the aim of establishing which of these alternatives would be the most appropriate to be encouraged by policymakers in Brazil in a holistic approach that takes into account economic, environmental, social and technical aspects of each option.

The conclusions point out several positive impacts of possible policies to encourage small hydro, biomass and wind energy technologies and shows that the contribution of photovoltaic systems to the sustainable development of Brazil is very limited. The work also includes further discussion of the results and the trade-offs involved in the decision making process, as well as a sensitivity analysis to assess the vulnerabilities of the assumptions used and the robustness of the results presented.

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1 Introduction

Electricity is not only one of the most important infrastructure sectors, but also a commodity that facilitates the development of an economy; bringing quality of life to people and creating necessary conditions for education levels improvement and health care facilities. Besides, the options chosen by a country to produce electricity have serious implications regarding tariffs, carbon emissions, environmental impacts, fossil fuel security from politically unstable regions, social inclusion, industry development, etc.

In this sense, policies to encourage or discourage the development of certain types of electricity sources must take into account a variety of reasons why they should be implemented and what would be their impacts, which can vary significantly according to the characteristics of the country and the electricity sector. This means that each country should evaluate its own particularities and establish what could affect, and be affected by, the deployment of a particular energy technology or a different source of electricity.

Among the different technologies for the expansion of electricity supply, countries have been encouraging the deployment of Distributed Generation (REN21, 2010). This is because of possible better usage of electricity grids and, mainly, because DG usually is linked with renewable sources of energy (solar, wind, biomass) or more efficient ways of using traditional fuels (combined heat and power – CHP, or cogeneration).

The utilization of small, dispersed power plants in opposition to the traditional central generation schemes can often be justified by the potential benefits of these technologies. Or, as stated by Schumacher (1993, p.49), *'for his different purposes man needs many different structures, both small and large ones'*. However, this paradigm shift can hide negative impacts that are not always realised by policymakers when deciding which way to go.

Hence, the aim of this work is to deeply investigate the potential impacts of different distributed generation technology options in the Brazilian context and establish which ones should be supported by policies with general incentives and subsidies.

In order to do that, Chapter 2 presents the necessary background to understand the characteristics of the Brazilian electricity sector, the general aspects of distributed generation, reasons why it is encouraged worldwide and what could be relevant to the Brazilian case. In Chapter 3, the choice of the possible distributed generation alternatives and the methodology used to assess their impacts is shown. Then, a deep analysis of the impacts of the alternatives in promoting sustainable development in Brazil is presented in Chapter 4 and the results obtained are examined in Chapter 5. Finally, Chapter 6 provides some conclusions and recommendations for policymakers and points out the potential areas for further work.

2 Context and Motivation

In this section, the basis for the development of the studies performed is shown. First, an explanation of the Brazilian electricity sector is given, together with its main characteristics and features. Then, the definition of distributed generation is explored, followed by the reasons why countries implement policies to support this technology and which of those reasons could be applied to the Brazilian context. As a final point, the country's current policies to encourage distributed generation are investigated.

2.1 Brazilian Electricity Sector

Brazil has a large, interconnected power system with around 60 million end-users, and an installed capacity of around 105GW[1] and 461.1TWh[2] of annual electricity generation (U.S. EIA, 2010). The characteristics of generation, transmission system, costs of electricity and regulation are presented in this section.

2.1.1 Electricity Generation

Brazil has an enormous potential for hydropower. Since it is a cheap, renewable energy source, the government has been encouraging its deployment for a very long time. This leads the country to a position where most of the electricity production comes from renewable sources (mainly hydro). For instance, while in the entire world only around 19% of the electricity comes from renewable sources this percentage reaches the amount of 89% in Brazil (U.S. EIA, 2010).

And yet the potential of hydropower in the country is still underused. From the 260GW available, only around 25% has been used so far (ANEEL, 2005). The main reasons why the country keeps on investing in this kind of energy is that it is a low-carbon technology, relatively low in impacts and very cheap when compared to the other sources of electricity available and implemented in Brazil (MME, 2007).

[1] In 2008
[2] In 2009

2.1.2 National Interconnected Grid

One of the drivers for this expansion of hydropower plants is the weather pattern in the country (north and south complement each other) and a robust transmission system that interconnects 96.6% of the country's electricity load – part of the Amazon Rainforest region and some isolated areas account for the remaining 3.4% (ONS, 2011).

These interconnected high voltage transmission lines, commonly referred to as the National Interconnected System (SIN – Figure 2.1), are managed to help improve the usage of the hydropower plants reservoirs, in order to produce the cheapest electricity without compromising the water levels of the dams.

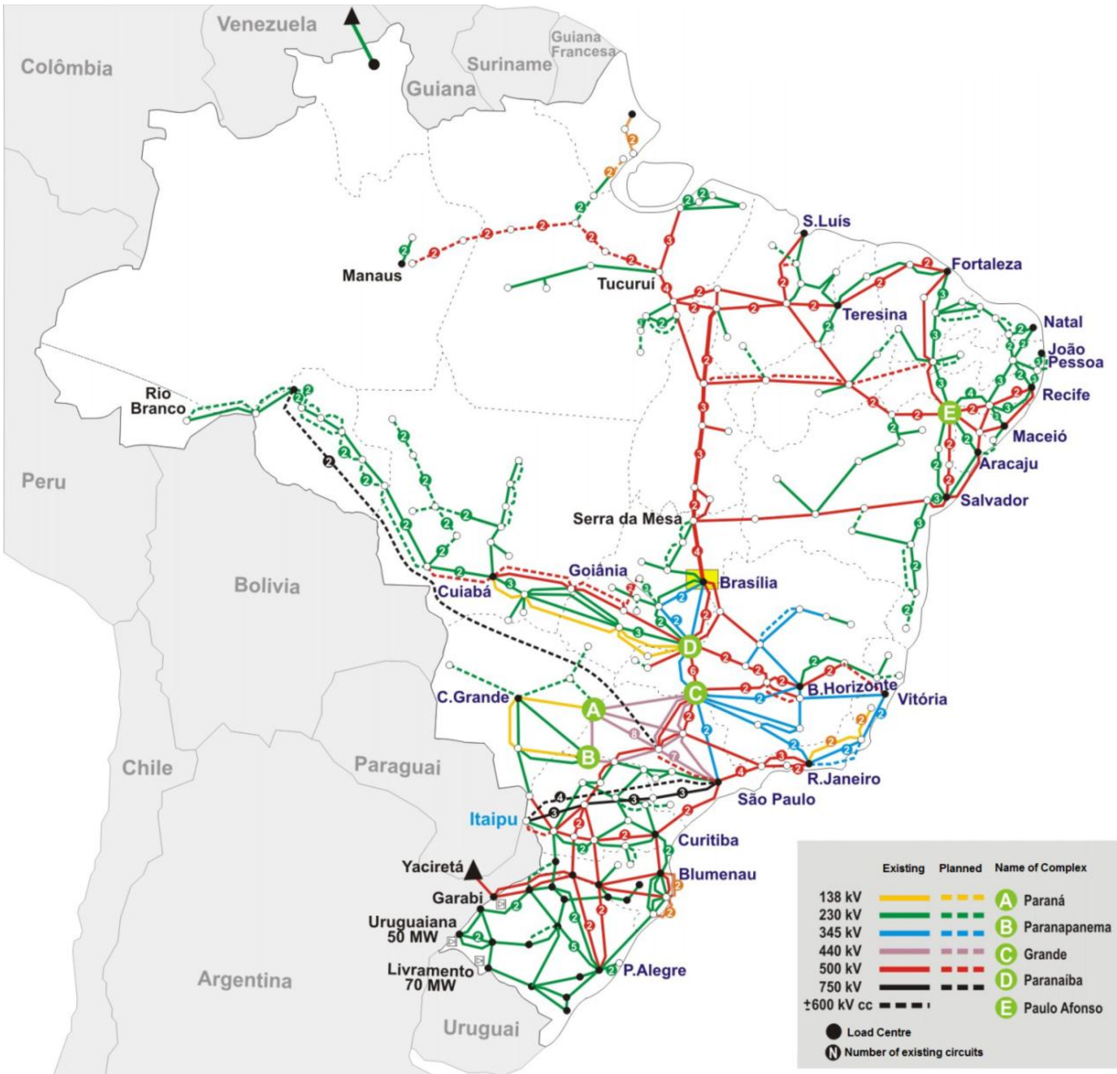

Figure 2.1 – Brazilian Interconnected Transmission System. Source: adapted from (ONS, 2011)

2.1.3 Regulation

Before the end of the last century, the electricity sector was mainly run by the State, which was responsible for planning, investing, controlling and operating the system. In 1996, privatisation occurred in the sector, splitting it into four main branches: Generation, Transmission, Distribution and Commercialization.

Transmission and Distribution sectors, which are natural monopolies, are strongly regulated, with tariffs defined by the regulatory body and grid connection requirements and availability closely controlled by the State. On the other hand, generation and commercialization are open markets, where investors can freely participate (to a certain extent), choosing whether or not to build a power plant and who to sell the energy produced to (CCEE, 2011).

Nevertheless, as stated by Laws 9074/1995 (BRAZIL, 1995) and 10848/2004 (BRAZIL, 2004), regular residential end-users and most of the commercial consumers cannot buy electricity from any supply company. In their case, the distribution company is responsible for buying the energy in auctions promoted by the government and pass the costs to the end-users. Only if the load is bigger than 3,000MW can the consumer buy energy from any provider (at the open market) and just pay the distribution and transmission companies for the usage of the grid (regulated tariffs).

Current regulation also puts a huge bureaucratic burden on generators. Their obligations include: installing the metering system; accessing the grid; executing the contracts with consumers and transmission and distribution companies; registering at the Chamber of Electricity Commercialization (CCEE); complying with very accurate and costly standards. These procedures are justifiable when regarding big generators, which deal with enormous amounts of energy and need very close regulation. However, they are a barrier to the connection of small scale power plants to the grid.

Finally, in this scenario, among other things, Government is responsible for (MME, 2011):

- planning the market growth to keep the energy mix relatively low in carbon emissions
- promoting the development of certain technologies
- guaranteeing best practices and usage of natural resources
- ensuring fair electricity tariffs and sustainability

2.1.4 Electricity costs

Costs of electricity are an important drive for the choice of energy sources and the policy that countries could apply to encourage them. In Brazil, the distribution system is responsible for a big share of the total cost of electricity, and generation costs are also relevant (Figure 2.2). Conversely, transmission costs are relatively low.

The electricity price analysis is important to the present study because it shows that options of energy sources that could reduce the price of generation or make better use of the distribution system should be supported. In contrast, impacts on reduction of transmission costs are not as relevant as those on the distribution system costs.

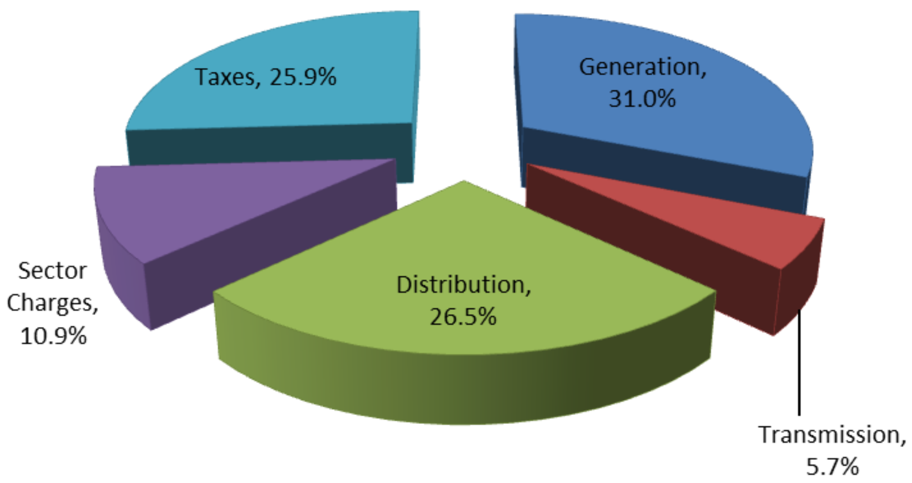

Figure 2.2 – Electricity costs breakdown (ANEEL, 2011)

2.2 Distributed Generation

Ackermann et al. (2001) define Distributed Generation (DG) as *'an electric power source connected directly to the distribution network or on the customer side of the meter'*. However, national and regional regulations usually take into account other aspects when defining DG, such as the size of the power plants (U.S. Energy Information Agency, 2002), type of connection and relationship with the distribution utility (Bayod Rújula et al., 2005).

For the purpose of this research, DG is simply the generation plants that can be connected directly to the distribution grid, which denotes the lower voltage levels, up to 138kV in Brazil (ANEEL, 2008). This can include all kinds of sources of energy, renewable or not. However, in some low-carbon technologies, the source of electricity is usually close to the end-user and is expensive to be transported (Jenkins et al., 2010), which creates a favourable scenario to the development of power plants that are renewable energy based, small scale and connected directly to the distribution grid.

2.3 Reasons why Distributed Generation is Encouraged Worldwide

Distributed Generation can potentially help the electricity system in many ways. However, since DG options are usually more expensive than the traditional sources of energy and demand high initial capital inputs and industry development, they need to be encouraged by policies so that these technologies can be competitive and well established. Additionally, the outcomes of these kinds of power plants depend strongly on the reasons why they are being implemented and on the characteristics of the electricity sector and the society where they are installed.

Climate change, fossil fuel prices volatility, the need to meet future demand of electricity and social awareness regarding energy consumption and environmental impacts have been changing the way countries explore and use energy resources.

Many countries have established targets for the reduction of greenhouse gases (GHG) emissions to cope with the tendency for better usage of resources and fight climate change (REN21, 2010). Particularly in developed countries, most of the carbon emissions come from the energy supply, transport and heating (DECC, 2011). Amongst these causes of global warming, the easiest one to be dealt with and that can provide a quick and cheaper response for the demand of GHG emissions reduction is the electricity sector.

Hence, policymakers are trying to provide good scenarios for the development of renewable energy sources, as well as maximizing the usage of the electricity grid to avoid energy losses and unnecessary expansion of the transmission and distribution lines (REN21, 2010). In this context, DG appears as a way of potentially producing electricity more efficiently (for example, via Combined Heat and Power), using renewable energy sources (such as hydro, wind and solar) and improving the capacity of the network by connecting the generation in the distribution grid, closer to the end-users (Jenkins et al., 2010).

Additionally, countries are struggling to find ways of meeting future demand for electricity, either because the current sources are becoming scarcer (such as local coal and gas) or because sources that used to be imported from other countries are not as available as they were before or their origin is from politically unstable regions. Hence, the volatility of fossil fuel prices and the scarcity of coal and nuclear sources can also contribute to the encouragement of DG, in order to use other new and usually renewable sources of energy that can be found locally (Lopes et al., 2007).

Another reason why the expenditure of public funds to finance the development of DG can be justified is to reduce other costs, such as those of transmission and distribution grids (U.S. Department of Energy, 2007). Well-managed and well-placed DG power plants can potentially avoid (or at least postpone) investments on new transmission lines and make better usage of the whole grid (Rawson, 2004).

Finally, new technology options can help generating industry development in a country, producing economic growth and creating new jobs. Hence, the opportunity to develop a new national or regional industry sector associated with clean electricity generation is an important reason that can lead policymakers to encourage the expansion of DG.

2.4 Which of the Reasons could be applied to Brazil?

The reasons why some countries establish policies to promote DG, presented in section 2.3, is that it allows them to (in summary):

1. Increase the amount of Renewable Energy sources (reducing CO_2 emissions)
2. Meet future demand for electricity
3. Reduce transmission (high voltage) costs
4. Reduce distribution (medium and low voltage) costs and increase grid capacity
5. Promote industry development

However, developing countries should not only ‘copy and paste’ what is being done in other countries and just assume that it would be suitable for their own reality. Each region needs to be assessed with the intention of finding the *appropriate technology* (Darrow & Saxenian, 1993). In this sense, the present section discusses which of those reasons could possibly be a motivation to encourage the progress of certain DG technologies in Brazil.

Regarding the amount of renewable energy and the reduction of GHG emissions, Brazil has already one of the biggest renewable energy based electricity sectors in the world, as shown in section 2.1.1. Additionally, most of the GHG emissions in the country come from deforestation (Salomon, 2009), which is cheaper and simpler to handle. Hence, the support of DG options for only this reason would raise the costs of electricity without any particular benefit.

The Brazilian economy is growing fast and energy consumption follows the same pattern. Hence, the need for future cheap and clean electricity sources is a reasonable concern. The National Energy Plan for 2030 foresees that the consumption of electricity will roughly double in the next 20 years (MME, 2007). However, the country can still rely on hydropower for the majority of the additional demand, since there is yet a huge potential (as explained in section 2.1.1) and the hydrological characteristics of the basins, associated with a strong national transmission grid, can make it a secure and inexpensive option. Also in this case, there would be no strong reason for extra expenditure of public funds to support DG.

The analysis of the final costs of electricity in section 2.1.4 shows that the costs associated with transmission lines represent only around 5.7% of total costs. This means that their share is not very big when compared to the other costs and, hence, increasing generation costs with DG to reduce the transmission costs might not be reasonable.

On the other hand, distribution costs account for more than 26%, which makes it very attractive to encourage DG in order to improve the capacity of the distribution systems and avoid new expansions in Brazil.

Along with this reason, a developing country should analyse industry options very carefully with the purpose of creating opportunities for the population and bringing social and economic development.

In conclusion, from the five reasons why countries worldwide might encourage the increase of DG, only the last two are really applicable to the Brazilian case. The appropriate analysis of the reasons why the country should encourage DG is a key point and is substantially used to assess the impacts of the DG technologies in this report.

2.5 Current policies towards the development of DG in Brazil

In 2002, the Government created the PROINFA (*Programa de Incentivo às Fontes Alternativas de energia elétrica*, in Portuguese), which is a set of subsidies to encourage the expansion of small scale hydro power plants, wind energy and biomass to produce electricity. The first phase of the programme aims to introduce 3300MW of renewable energy in the national grid, by acquisition of electricity by the state owned utility ELETROBRAS in contracts for 20 years. The costs of electricity from this program (higher than the normal costs of electricity negotiated at the public electricity auctions) are shared out by the consumers (BRAZIL, 2002).

After completion of Phase I, the second stage sets a target of 10% of the electricity produced in Brazil to be from these three sources: small hydro, wind and biomass.

Another interesting aspect of the programme is that at least 60% of the equipment and services used in those power plants must be of Brazilian origin, which aims to establish a national industry that can meet future demand.

By 2010, ELETROBRAS had already signed the contracts with generators to produce the 3300MW from Phase I and most of it is from wind energy (Figure 2.3). Additionally, the average size of the power plants is less than 23MW (MME, 2010).

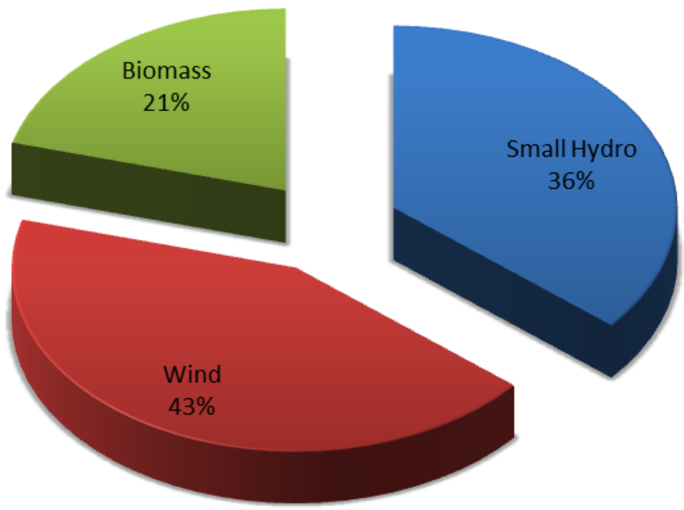

Figure 2.3 – Share of PROINFA installed capacity per source. Source: (MME, 2010)

In addition to the PROINFA, since 2003, solar, wind, biomass, co-generation and hydro with an installed capacity of less than 30MW have a 50% discount on the use of the electricity transmission and distribution systems. For projects that use as a source at least 50% of biomass from municipal solid waste, biogas from landfill, biogas from vegetable or animal waste or sludge from sewage treatment plants, this discount raises up to 100%. On top of that, these small power plants do not have the obligation to spend 1% of their revenues in R&D, whilst the other ones do (Castro, 2010).

Recently, the regulatory agency (ANEEL) published a Technical Note in which it states the intention to increase the subsidies to encourage DG with (Castro et al., 2011):

- Net metering for power plants of less than 1MW
- Simplification of the administrative process to install power plants of less than 1MW
- 80% discount on transmission and distribution tariffs for solar power plants smaller than 30MW (for the other renewable sources the discount remains 50%)

This penchant towards photovoltaic solar panels can also be observed in the Report of the Working Group on Distributed Generation with Photovoltaic Systems, published by the Ministry of Mines and Energy (MME, 2009).

3 Methodology

The method used in this research consists of first choosing the potential options of DG to be encouraged by policies in Brazil. Then, the impacts of each of these alternatives are analysed under a sustainability context. Since there are several alternative options and they share multiple criteria, a multicriteria analysis tool is used. In particular, the PROMETHEE method is chosen due to its properties regarding the elimination of scaling effects (each criterion can have different units without compromising the final results), the allocation of weights to the criteria, relative simplicity in theory and calculations and the availability of sensitivity analysis tools to improve the robustness of the study.

3.1 Technology options for Brazil

Several different technologies can be used to produce electricity in small scale and inject it directly into the distribution system. Since each technology depends on a variety of aspects that change considerably from one place to another, policies must take into account which of the technologies are going to be supported and how the policies are going to be established for them so as to achieve the desired results for the electricity sector.

In this context and based on the availability and maturity of the options, five different alternatives were chosen to be analyzed for the Brazilian case: small hydro, biomass, solar photovoltaic panels, wind energy and combined heat and power (CHP or cogeneration). The particular reasons why they were chosen and a brief explanation of each technology option are presented below.

3.1.1 Small Hydro

Section 2.1.1 showed that Brazil has a huge potential for hydro power. These resources are spread throughout the country (ANEEL, 2005) and their use can be optimized by the construction of small scale power plants, along with the big ones that are predicted by the government (MME, 2007).

The technology behind hydroelectricity is well established and in Brazil in particular there is a traditional national industry of turbines, machines and small components that provides the necessary scenario for a bigger spread of small hydro power plants (MME, 2007).

As stated by the International Energy Agency (IEA, 2010), the decision making process to decide whether or not to support hydro power plants should consider compensation to people directly affected by the project, floods and droughts control, environmental protection, the impacts of the project, and economic equity. Particularly regarding small hydropower plants, the problems related to social and environmental impacts are considerably reduced, since usually there is no reservoir and the amount of people affected by the plant is small. In contrast, the electricity generation by small plants is not as reliable as that from big ones with damns (the generation pattern in this case is more dependent on the river flows and seasons).

Another negative aspect of small hydro power when compared to large ones is that the initial costs are significantly higher. For instance, the initial costs per MW of a 10MW power plant can be four times higher than those of a 300MW and maintenance can be up to twice as expensive (IEA, 2010).

To cope with Brazilian regulation that establishes a size limit for hydro power plants to be considered as DG (BRAZIL, 2004), the maximum size of small hydro considered in this study is 30MW.

3.1.2 Biomass

Biomass is a source of energy from living organisms that can be used for heating and producing electricity and on Combined Heat and Power (CHP) systems. Since the biomass has a lower energy density than the fossil fuels, its conversion into electricity must not be far from the source of biomass, which makes it a good alternative for DG (House of Commons, 2008).

Types of biomass that can be used to produce electricity include sewage sludge, residues from certain industries, animal manure, dedicated crops and agricultural residues (IEA, 2007). The bagasse from sugar cane, a by-product of the production of sugar and ethanol, is an efficient source of electricity production that has been used in Brazil for decades (MME, 2007).

Electricity production in this case is a regular thermal process – the bagasse is burned to generate electricity. Even though the generation technology is similar to that used in fossil fuelled power plants, biomass is considered as a low-carbon source of energy since the carbon emitted was previously captured by the plants being burned (IEA, 2007).

3.1.3 Solar Photovoltaic Panels

Solar Photovoltaic (PV) Panels are modules of solar cells arranged in series/parallel that directly convert sunlight into electricity (Jenkins et al., 2010). The technology dates back to some decades ago but was used mainly to produce electricity in isolated communities where it would be too expensive to connect to the regular distribution grid. This is because the initial costs of this technology are significantly higher than the traditional ones (Castro, 2010). Recently, however, the amount of solar PV panels has been growing rapidly worldwide, since countries like Germany and Spain have been supporting the installation of grid-connected solar panels on rooftops, through policies such as feed-in tariffs (Jenkins et al., 2010).

In Brazil, solar irradiation is high and provides a good milieu to the spread of photovoltaic technology. However, the costs to produce electricity from solar panels are usually three times higher than the average price (Castro, 2010) (Rüther, 2010). In a developing country, with major poverty, educational and health issues, it might not be economically viable or socially acceptable to highly subsidize an electricity source without an adequate analysis of its impacts. Then, the analysis of this technology option in the present study is essential.

3.1.4 Wind Energy

In the past two decades wind energy has experienced an enormous increase. From the 7,644 TWh produced in 1995, wind generation raised to 209,915 TWh in 2008 (U.S. EIA, 2010). It is a clean, renewable source of energy but the location where it is going to be installed depends strongly on the wind speed, which leads to a scenario where the connection to the grid plays an important role. In this sense, wind power plants that can be directly connected to strong distribution grids (hence, are distributed generation) could have a great potential to sustainably develop the energy sector of a country. However, a careful analysis of the impacts should be performed, taking into account the particularities of the country before any subsidy policy is applied.

Wind energy faces some opposition regarding its intermittency, difficulties to predict and impossibility to store. This might be a genuine concern in small isolated systems where wind power plants would have to be used to make sure that the electricity production meets the demand at all times. However, the Brazilian electricity system is big, interconnected and robust. And so, wind energy could be used anytime it is being produced, while other sources of energy (such as thermal and hydro) are dispatched to make sure that the demand is met by the generation. These and other impacts of wind energy in the Brazilian electricity sector are going to be assessed further in this report.

3.1.5 Cogeneration or Combined Heat and Power (CHP)

Combined Heat and Power (CHP) systems suitably use the heat that would otherwise be rejected when producing electricity. Because of this characteristic, these plants are usually much more efficient than conventional separated heating and electricity systems. Hence, CHP systems reduce fuel consumption and GHG emissions (Jasmab et al., 2006, pp.218-219;365-366).

A popular source for cogeneration in Brazil is the bagasse from sugar cane. However, since this source is already being analyzed in a separated technology option (Section 3.1.2), the assessment of cogeneration in the present study is based only on power plants that use natural gas as a source for generating heat and power.

CHP technology was also chosen to be assessed in this study in order to diversify the options, including a non-renewable source of electricity for DG.

3.2 Analysis under sustainability aspects

After choosing the possible technology options of DG that could be encouraged by Brazilian policymakers, a thoughtful analysis of several impacts of these options for the country's sustainable development is performed.

The studies first take in consideration *economic*, *environmental* and *social* aspects (Barbier, 1987). The analysis is then complemented by the investigation of *technical* issues related to the subject. In each of these four areas, a few precise potential impacts of the DG alternatives are examined to try to address the effects of DG alternatives in a broader view.

The data gathered was extensively used. However, instead of just relying on numbers, the assessment of the alternatives for each criterion was made also taking into account qualitative issues, the context in which DG would be deployed and the influences of possible policies, as presented in Chapter 4.

To properly analyze these data and be able to compare the DG alternatives to establish which ones would be the best options to promote sustainable development in Brazil, several tools were investigated and the most suitable one found is the PROMETHEE Method, explained in the next section.

3.3 Multicriteria Decision Analysis Tools: PROMETHEE and GAIA

The PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) Method is a Multi-Criteria Decision Analysis (MCDA) tool developed by Professor Jean-Pierre Brans and Professor Bertrand Mareschal from the Université Libre de Bruxelles that allows the decision maker to compare different criteria over several alternatives and efficiently visualize their interconnections (Brans & Mareschal, 1994).

This section presents the basic theory behind the method and highlights its main properties. Theory shown here is based on (Brans et al., 1986), (Brans & Mareschal, 1994), (De Keyser & Peeters, 1996) and (Brans & Mareschal, 2005).

In an MCDA problem, for each of the alternatives (in the case of this research, each of the technology options) several criteria are analyzed, resulting in a table as Table 3.1.

Table 3.1 – Input data: alternatives and criteria

Alternatives\Criteria	$g_1(.)$	$g_2(.)$	…	$g_k(.)$
$a_1(.)$	$g_1(a_1)$	$g_2(a_1)$	…	$g_k(a_1)$
$a_2(.)$	$g_1(a_2)$	$g_2(a_2)$	…	$g_k(a_2)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$a_n(.)$	$g_1(a_n)$	$g_2(a_n)$	…	$g_k(a_n)$

The terms $g_k(a_n)$ represent the input for the method. For instance, if $g_1(.)$ is the criterion 'Greenhouse Gases Emissions' and $a_1(.)$ is the alternative 'Small Hydro', then $g_1(a_1)$ would be the amount of GHG that is produced by small hydro. Qualitative ratings such as 'bad', 'average' and 'good' can also be used and translated into numbers as 0, 1 and 2 (or 1, 10 and 100, for instance), without compromising the results.

Additionally, since the criteria shall have different levels of importance, it is necessary to establish a vector of weights:

Table 3.2 – Weights of the criteria

Criteria	$g_1(.)$	$g_2(.)$	…	$g_k(.)$
Weights	w_1	w_2	…	w_k

In this research, the n alternatives are: Small Hydro, Biomass, Solar PV, Wind and CHP. Similarly, the criteria are the sustainability impacts discussed in Chapter 4 and the weights are used to assess the importance given to each social, economic, environmental and technical criterion.

3.3.1 Preference functions

PROMETHEE uses pairwise comparison to evaluate the preference of the alternatives. In this sense, for one given criterion g_j, the deviations between two different alternatives are:

$$d_j(a_1, a_2) = g_j(a_1) - g_j(a_2)$$

Hence, the preference of alternative a_1 over a_2 is given by:

$$P_j(a_1, a_2) = F_j[d_j(a_1, a_2)]$$

The usual function of preference used in PROMETHEE is:

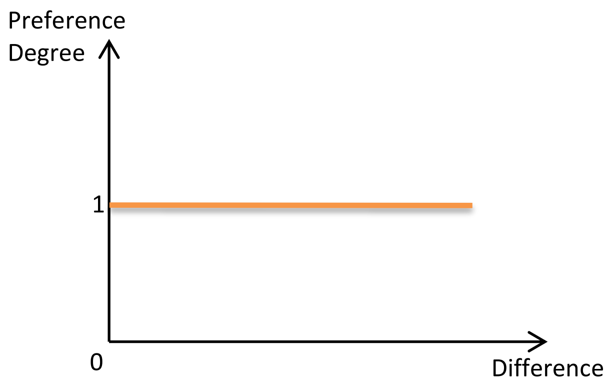

Figure 3.1 – Usual Preference Function

The function in Figure 3.1 means that if a_1 is higher than a_2 for criterion g_j, than a_1 is 100% preferred over a_2. For instance, let criterion g_j be 'Renewable Energy' and alternatives a_1 and a_2 be wind power and gas-fuelled CHP, respectively. Since wind is renewable and gas-fuelled CHP is not, than alternative a_1 is 100% preferred to alternative a_2.

However, if the criterion was 'GHG emissions' and the difference between the emissions from alternatives a_1 and a_2 was not high, then the decision-maker would not want to consider alternative a_1 100% preferred than a_2. This means that, small deviations might not be important – there would be an *indifference threshold* 'P' below which one alternative is not preferable to the other. Similarly, if the difference between the alternatives is in the middle of a certain range, the preference might be something between 0 and 100%. In these cases, a different preference function can be used (Figure 3.2). For additional information, Brans & Mareschal (2005) present a detailed analysis with other types of Preference Functions.

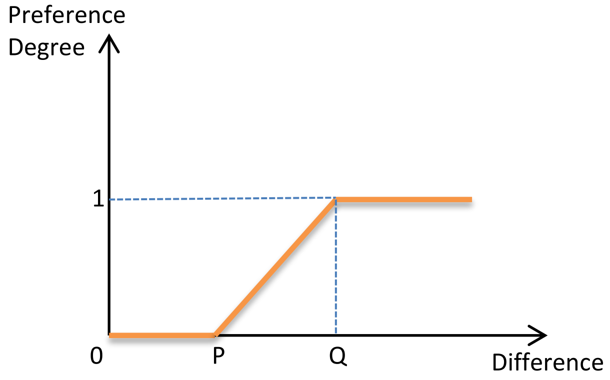

Figure 3.2 – Preference function example: V-Shape with indifference threshold

3.3.2 PROMETHEE Ranking

After determining the preference indices, the PROMETHEE Method aggregates them as follows:

$$\pi(a_1, a_2) = \sum_{j=1}^{k} P_j(a_1, a_2)\, w_j \qquad (3.1)$$

This equation gives the overall preference of a_1 over a_2, considering all the criteria. The closest this value is to 100%, the stronger is the global preference of a_1. Similarly, the preference of a_2 over a_1 is given by:

$$\pi(a_2, a_1) = \sum_{j=1}^{k} P_j(a_2, a_1)\, w_j \qquad (3.2)$$

These values are computed for each pair of the n alternatives being considered in the analysis. After that, the *outranking flows* can be computed according to equations (3.3) and (3.4):

$$\Phi^{+}(a_m) = \frac{1}{n-1}\sum_{l=1}^{n}\pi(a_m, a_l) \qquad (3.3)$$

$$\Phi^{-}(a_m) = \frac{1}{n-1}\sum_{l=1}^{n}\pi(a_l, a_m) \qquad (3.4)$$

For each alternative a_m the positive and the negative outranking flows (Φ^{+} and Φ^{-}, respectively) are calculated.

The positive outranking flow (Φ^{+}) represents how much the alternative is superior to the others, taking into account all the criteria. In other words, how this alternative *outranks* the others. Conversely, Φ^{-} characterizes the level to which this alternative is *outranked* by the other. Hence, with these values, a ranking of the alternatives can be calculated.

In this report the *complete ranking*, also known as PROMETHEE II is presented. Further information about the *partial ranking* (PROMETHEE I) can be found in (Brans & Mareschal, 1994).

The ranking is simply computed according to the value of the difference between positive and negative outranking flows of the alternatives:

$$\Phi(a_m) = \Phi^{+}(a_m) - \Phi^{-}(a_m) \qquad (3.5)$$

Roughly, the higher $\Phi(a_m)$ the better the alternative a_m.

3.3.3 Geometrical Analysis for Interactive Aid – GAIA Plan

From (3.5) – (3.5):

$$\Phi(a_m) = \frac{1}{n-1}\sum_{j=1}^{k}\sum_{l=1}^{n}\left[P_j(a_m,a_l) - P_j(a_l,a_m)\right]w_j \qquad (3.6)$$

And $\Phi_j(a_m)$ can be defined as:

$$\Phi_j(a_m) = \frac{1}{n-1}\sum_{l=1}^{n}\left[P_j(a_m,a_l) - P_j(a_l,a_m)\right] \qquad (3.7)$$

Hence, $\Phi_j(a_m)$ represents the outranking flow when only the criterion j is being considered ($w_j = 100\%$) and is defined as *the single criterion net flow*.

Since there are n alternatives and k criteria, all the flows can be represented in a matrix M($n \times k$):

Table 3.3 – Single criterion flows

Alternatives\Flows	$\Phi_1(.)$	$\Phi_2(.)$	…	$\Phi_k(.)$
$a_1(.)$	$\Phi_1(a_1)$	$\Phi_2(a_1)$	…	$\Phi_k(a_1)$
$a_2(.)$	$\Phi_1(a_2)$	$\Phi_2(a_2)$	…	$\Phi_k(a_2)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$a_n(.)$	$\Phi_1(a_n)$	$\Phi_2(a_n)$	…	$\Phi_k(a_n)$

Despite the same dimensions of Table 3.1 and Table 3.3, the latter is particularly more useful than the former. This is because it takes into account the relation between criteria and alternatives, as well as the preference degree for each and, additionally, its values are not dependent on units (dimensionless).

In order to visualize the relations between all the alternatives and criteria, the n alternatives could be plotted in a figure in which the number of dimensions would be the quantity of criteria (k). Since this representation is not possible for more than three criteria, a projection of the alternatives and the criteria vectors in a plan can allow the visualization of most of the relationship involved in this process.

Hence, the GAIA plan is defined as the plan for which most of the information is preserved after projecting the points that represent the alternatives and the vectors representing the criteria axes in the k-dimensional space. It is obtained by *Principal Component Analysis* as explained by Brans & Mareschal (1994) and the measure of how much of the information is preserved after projection is given by the parameter δ. Usually, values of δ higher than 80% are desired although those around 60% are already satisfactory (Brans & Mareschal, 2005).

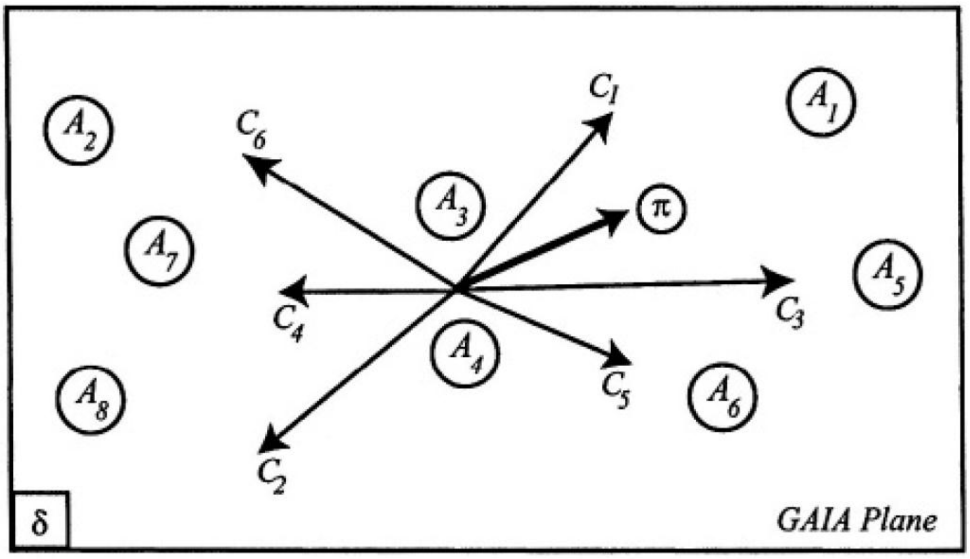

Figure 3.3 – The GAIA Plane. Source: (Brans & Mareschal, 2005)

The GAIA Plan provides a general overview of the alternatives and how they are related to each of the criteria and amongst each other. It holds the following properties (Brans & Mareschal, 2005, p.178):

- The closer one alternative is located to another, the more similar they are (in Figure 3.3, for instance, alternatives A_2, A_7 and A_8 are similar to each other and quite different from alternatives A_1, A_5 and A_6)
- Alternatives that are on the direction of a particular criterion are better regarding this criterion (alternative A_2 would be good regarding criterion C_6 and not very suitable for criterion C_5)
- The angle between two criterion axis are related to the correlation between those criteria:
    - angles close to 0^{o} indicate big correlation between criteria

  - angles around 180° show that the two criteria are conflicting
  - orthogonal angles illustrate that the criteria are not related to each other
- The size of the criterion axis indicates how discriminating this criterion is: the bigger the axis, the more discriminating the criterion

The vector π represented in Figure 3.3 is a way of considering the weights of the criteria. Since it takes into account all the outranking flows and the weights, it points to the direction of the best alternative according to the PROMETHEE calculations. In the example of Figure 3.3, the order of the alternatives, from the best to the worse, would be:

$$A_1 - A_5 - A_6 - A_3 - A_4 - A_7 - A_2 - A_8$$

It is also possible to notice that, if the weights change, the vector π would move in the GAIA Plan. For instance, if a certain criterion had a weight of 100%, the vector π would be coincident with the vector of this criterion.

Finally, the size of the vector π represents how strong PROMETHEE ranking results are. The longer the vector π, the stronger the decision power of the method.

PROMETHEE calculations and the generation of the GAIA Plan can easily be made through computer algorithms and some programs are available for that usage. One of them, developed by Professor Bertrand at the Université Libre de Bruxelles, is available at http://www.promethee-gaia.net/software.html. Another option is the D-Sight® Multi-Criteria software, which is used to calculate the values and GAIA Plan in this dissertation.

4 Sustainability Analysis of Distributed Generation Impacts

In a holistic view of the demand for electricity, one should take into account the entire context in which the development is to be made. Hawken et al. (2000) state that, when solving a problem, we should aim to solve many others at the same time. This statement can be applied to the scope of this dissertation meaning that a developing country that aims to establish economic growth and meet its future demand for electricity should choose energy policies considering the impacts it could have in creating jobs, establishing a sustainable industry, promoting equity, etc., while preserving natural resources and potential for future developments.

One of the aims of this approach is to try to establish a balanced set of DG alternatives that should be encouraged by policymakers in Brazil. This means that the solution sought should not be one *'that generates significant environmental harm, that generates social disquiet or that generates economic loss or spends public funds inefficiently'* (Dodds & Venables, 2005).

Hence, to each of the sustainability pillars (economic, environmental, social and technical) a set of areas where DG could have impacts is analysed. These areas, shown in Figure 4.1, were chosen considering the key development strategies specified in Brazilian Laws and reports, potential segments where DG is more likely to cause benefits or harms and technical aspects linked to the technologies.

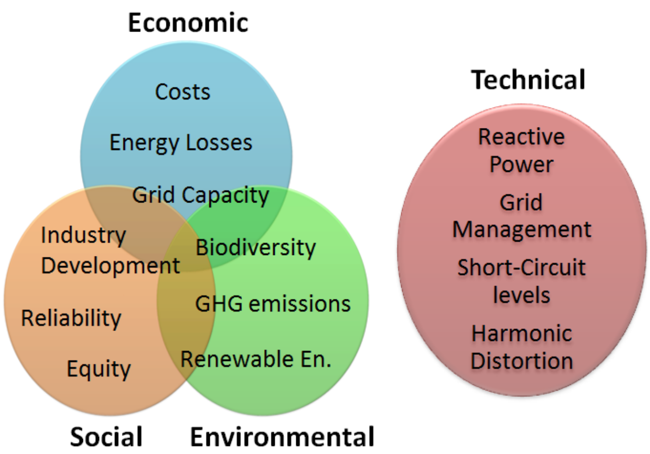

Figure 4.1 – Sustainability examination of possible impacts of DG

4.1 Economic Impacts

The economic impacts of DG are an important aspect that should be carefully taken into consideration, particularly in a developing country where access to electricity can bring health and education improvements that could later help the country maintain its development, reducing the importance of economic impacts and increasing the significance of social and environmental aspects.

In this survey the economic aspects were divided into three different points, namely: cost of electricity production, reduction of energy losses and improvement of grid capacity usage.

4.1.1 Costs

The first economic aspect to be taken into consideration in this report is the costs of electricity production. These costs are assessed according to the values provided by the Brazilian Electricity Regulatory Agency – ANEEL (Castro, 2010) and shown in Table 4.1.

Table 4.1 – Costs of Electricity generation per MWh for the five different technology options

Technology Options	Costs (in Brazilian Real per MWh)	Costs (in Great Britain Pounds per MWh)
Small Hydro	R$ 141.93	£ 54.05
Biomass	R$ 144.20	£ 54.91
Solar PV	R$ 550.00	£ 209.44
Wind	R$ 130.86	£ 49.83
CHP	R$ 200.00	£ 76.16

Since the PROMETHEE method used to compare the options does not get influenced by the units, obviously the currency used does not change the final result. Hence, the currency adopted is pounds and, with the intention of properly consider small changes in prices that are common to occur in the electricity market, the method was set to consider as 'indifferent' any difference in costs amongst the alternatives that is lower than £ 5.00.

Even considering the learning curves and costs reduction with the large spread of new technologies, Solar PV would still be considerably more expensive in the near future. For instance, a study conducted in Australia showed that the costs of solar rooftop panels by 2030 might still be up to four times more expensive than wind and biomass technologies (McLennan Magasanik Associates, 2009).

On the same lines, wind power costs are reducing rapidly in Brazil. At the beginning of PROINFA, the cost of wind energy was around 79 £/MWh, in 2009 it was already 57 £/MWh and the auction of wind energy prepared by the Government in 2010 lead to a price of only 49.83 £/MWh (Castro, 2010).

4.1.2 Energy Losses Reduction

One of the potential benefits of DG is to reduce losses in power capacity and in energy. In this sense, the current section will assess how better one technology is to reduce energy losses when compared to another. It does not use values of energy losses for each, but rather classifies them so that their ability to reduce losses can be compared, regarding energy. For assessment of power losses, the ‘Grid Capacity’ criterion is used.

If the electricity generated by certain type of DG matches the demand profile in the region where it is installed, all the energy generated will be consumed locally, reducing losses. Additionally, even if the demand is still higher than the sum of the DG in that region, the extra amount of energy that would have to be transported from the central station to the end-users (and then subjected to losses) would still be reduced.

For that reason, the alternatives score is made as a combination of the indices ‘demand following’ and ‘operating reserves delivering’ presented by Moya et al. (2008).

Table 4.2 – Assessment of the potential for energy losses reduction for the five DG alternatives

Technology Option	Demand following	Operating Reserves	Energy Losses Reduction
Small Hydro	Very bad	Normal	Bad
Biomass	Very good	Very good	Very good
Solar PV	Very bad	Very bad	Very bad
Wind	Very bad	Very bad	Very bad
CHP	Very good	Very good	Very good

This ranking is compatible with that presented by Quezada et al. (2006) and also with the comparison between CHP and solar PV in losses reduction that can be drawn from Cao et al. (2006, pp.26-28).

It is important to highlight that energy losses might reduce with the insertion of some DG and reach a minimum for a certain amount. However, excessive levels of distributed generation penetration can increase losses to values that can be up to five times higher than the losses without any DG (Quezada et al., 2006).

4.1.3 Grid Capacity

This aspect is also related to the environmental impacts, since when one avoids expanding the electricity grid, the current assets are used better and less additional raw material is needed, as well as less land for transmission lines being required.

Technologies of power plants that can be dispatched can improve grid usage better than intermittent ones for which the time of electricity production cannot be controlled. In this sense, the thermal ones (CHP and Biomass) have the biggest potential for better use of the system (Jenkins et al., 2010). In addition, these alternatives are usually generating electricity at the same time as the load attached to them is higher.

Small hydro power plants are quite predictable and, in theory, can be dispatched (Xue et al., 2007). However, the location of the power plant is determined by where the natural resources are located and usually new distribution network have to be built in order to reach these places. On the other hand, the predictability of this source of electricity can help utilities and the system operator to manage the distribution/transmission grids better, improving their capacity.

Regarding wind energy, the intermittency of the technology and the need of new distribution lines can also make it not very attractive when it comes to grid capacity improvement.

Finally, solar PV systems have to be carefully analysed when assessing their ability to provide better usage of grids. Some advocates of the technology might state that they can be useful in alleviating the grid since their production follows basically the pattern of the national load (the load of the entire interconnected system altogether) – Figure 4.2.

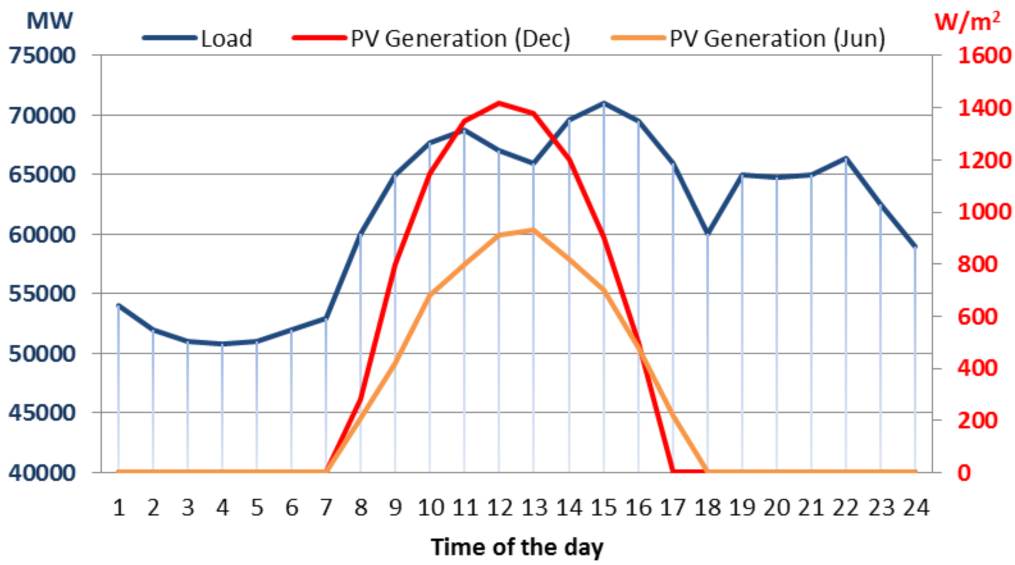

Figure 4.2 – National Load comparison with Solar PV potential electricity production. Sources: (Salamoni, 2004) and (ONS, 2010)

However, as analysed in section 2.1.4, the costs of the transmission system are considerably lower than those of the distribution grid. Hence, a comparison of electricity production and consumption should be made in the distribution grid where they are supposed to be installed, namely, feeders of residential end-users or small commercial ones. Figure 4.3 shows then that the improvement of grid capacity brought by Solar PV technology in Brazil would be very limited and mainly to the transmission system, not to the distribution one, since the production of electricity would not meet the peak of load demand. Instead, this kind of technology could lead to the necessity of expanding the system so that all the energy generated during the day could be transported to loads. In fact, problems of this kind are already being faced by some utilities in Germany (New Scientist, 2010).

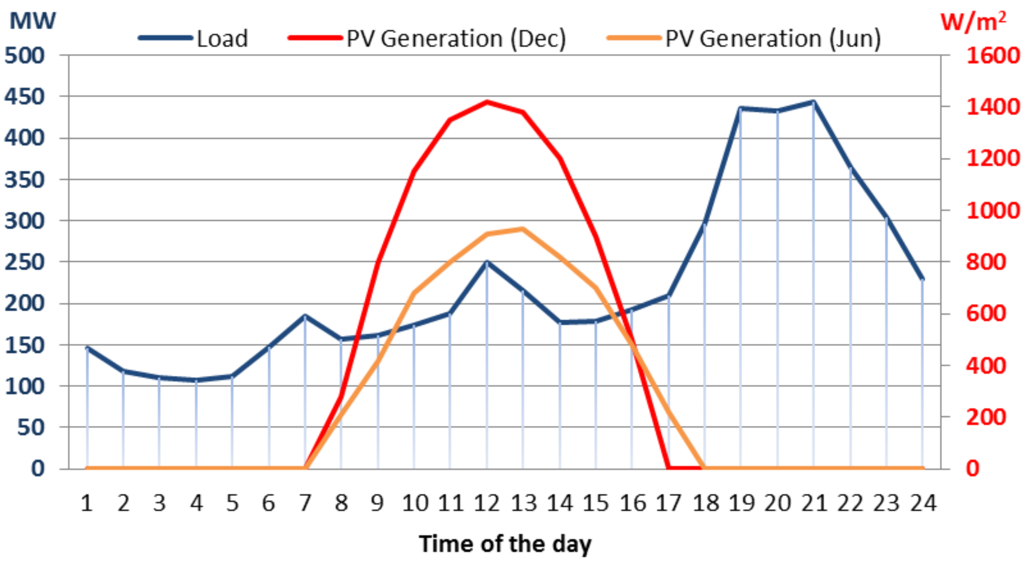

Figure 4.3 – Local residential feeder load comparison with Solar PV potential electricity production. Sources: (Salamoni, 2004) and (ANEEL, 2010)

In conclusion, the potential of the 5 different technologies to improve grid capacity can be 'ranked' as follows:

Table 4.3 – Potential for grid capacity improvement of the five DG alternatives

Technology Option	Potential for Grid Capacity Improvement
Small Hydro	Medium
Biomass	High
Solar PV	Low
Wind	Medium
CHP	High

4.2 Environmental Impacts

The environmental impacts of the five DG technologies are assessed through three indicators: greenhouse gases emissions, impacts on biodiversity and whether or not the source is renewable.

4.2.1 Greenhouse Gases Emissions

The emissions of Greenhouse Gases (GHG) are evaluated according to data found in different reports (DECC, 2011) (POST, 2006) (Lenzen, 2008). It is important to note that there are some variance on the total CO_2 equivalent emissions per KWh amongst the references due to different methods used and the assumptions made in each of them. With the aim of avoiding those discrepancies from changing the results of the present work, the PROMETHEE Preference Function was set to not consider the variance in GHG emissions if the difference from one technology to another is lower than 10 g of CO_2-e/KWh. The values obtained are shown in Table 4.4.

Table 4.4 – CO2-e emissions per KWh for different sources of electricity. Sources: (Lenzen, 2008) (DECC, 2011) (POST, 2006)

Technology Option	Emissions (g of CO_2-e/KWh)
Small Hydro	15
Biomass	80
Solar PV	106
Wind	21
CHP	510

4.2.2 Impacts on Biodiversity

This criterion aims to take into consideration the aspects related to impacts on flooding areas, deforestation to build the power plant or to yield the source, water requirements, pollution (non-CO_2 emissions) and waste generation.

Table 4.5 was created to assess the impacts for each of the sub-aspects, assigning numbers according to the level of impact of the technology in the aspect (green=0, yellow=1 and red=2). Subsequently, the total impacts were calculated as the sum of the sub-aspects. The last column of the table is then used as an input for the PROMETHEE model.

Table 4.5 –Assessment of impacts on biodiversity for the five DG alternatives. Sources: (EPRI, 2010)

Technology Option	Flooding	Deforestation	Air Pollution	Water requirements	Waste generation	Total Impacts on Biodiversity
Small Hydro	2	1	0	1	0	**4**
Biomass	0	2	2	2	2	**8**
Solar PV	0	0	0	0	0	**0**
Wind	0	1	0	0	0	**1**
CHP	0	0	1	1	0	**2**

4.2.3 Renewable Energy

The aim of this section is to give extra weight to the technologies that use a renewable source of energy to produce electricity.

Hydropower plants, solar photovoltaic systems and wind power use renewable sources of energy to produce electricity – water flow, solar irradiation and wind (Bergerson & Lave, 2002). Nevertheless, a deeper discussion of Biomass and CHP is necessary:

- Biomass: when using biomass to produce electricity, particularly from plants, the carbon emitted in the atmosphere by the combustion of the biomass is again captured when new plants grow, making it a low-carbon technology. Additionally, other nutrients are also again captured by plants in the growth process. The source of energy is then renewable, as long as the ratio of biomass usage to produce electricity is not higher than the ratio of plants cultivation process. The UNFCCC provides a definition of when biomass can be considered renewable (UNFCCC, 2006)

- Cogeneration: although the efficiency of this kind of generation makes it more attractive than regular thermal plants and also more environmentally friendly (Jasmab et al., 2006, p.303), the source used to produce electricity considered in this study is non-renewable natural gas.

Table 4.6 – Renewable energy DG alternatives

Technology Option	Renewable Energy
Small Hydro	YES
Biomass	YES
Solar PV	YES
Wind	YES
CHP	NO

4.3 Social Impacts

The potential effects of the DG technology options in the social aspects of sustainable development are assessed in this study with three indicators: improvement in electricity reliability that can be provided by DG, impacts of the alternatives in generating industry development and potential influences of the technologies to promote equity. The justification for the choice of each criterion is explained within their own sections.

4.3.1 Electricity Reliability

In 2001, Brazil faced a power shortage in some of the most developed areas of the country due to lack of investments in generation and transmission. This led to an emergency rationing of electricity that affected all end-users, from industries to small residential consumers (Eletrobras, 2008). After the rationing, society became very concerned about the reliability of the electricity system.

Even blackouts that last for small periods of time can trigger the fear of another rationing and suspicion amongst people. Hence, the potential of the different DG technologies to avoid blackouts is another key sustainability aspect to be analysed. In this report, this potential is assessed by the availability of the different technologies, as stated by Jenkins et al. (2010, pp.136-41). The availability factors are shown in Table 4.7. They represent the contribution that each technology can give to the distribution network security and depend on the type of energy source and on the number of generation units[3].

Table 4.7 – Availability Factors for the different technology options

Technology Option	Availability Factor (%)
Small Hydro	36
Biomass	65
Solar PV	14
Wind	64
CHP	73

4.3.2 Industry Development

The potential of each of the technology options to promote industry development is hard to quantify by a single index. Hence, it is analysed in this report the impacts[4] of each technology in stimulating development of national industry, that could create jobs, drive local economic growth and improve quality of life. The results are shown in Table 4.8 and the rationale is explained below.

[3] The values presented in Table 4.7 are chosen for three units of each technology. This number of units was chosen arbitrarily and is the same for all technology options since the aim of this research is to compare the options rather than analyse their absolute performance.
[4] While the aim of the study was to minimize impacts on biodiversity (section 4.2.2), in this criterion the purpose is to maximize the impacts.

Table 4.8 – Potential impacts on Industry Development for the DG alternatives

Technology Option	Industry Development
Small Hydro	Very High
Biomass	High
Solar PV	Very Low
Wind	High
CHP	Medium

Since Brazil has hydropower as its main source of electricity, the national industry of turbines and motors/generators for hydropower plants is traditional, well-established and very competitive with other countries (ANEEL, 2005, pp.51-53). Besides, other parts of the supply chain for small hydro, such as transformers and cables, are produced nationally (ABINEE, 2011), creating jobs and helping accelerate the sustainable growth of the country's economy. For those reasons, Small Hydro is classified for this criterion as having a 'very high' impact on industry development.

Biomass and CHP power industries use generation technologies that can be supplied by national industry and policies that eventually encourage the employment of Biomass and CHP in Brazil, and will also help improve the expansion of this industry (Procknor, 2007) (MME, 2007). Since the technology to generate electricity from biomass and CHP is quite similar, they would have the same impacts on the industry. However, electricity from biomass in Brazil comes basically from sugar cane bagasse, which makes it correlated with the production of biofuels (ethanol). Hence, policies that encourage biomass will positively affect the production of biofuels, enhancing their impacts on industry development.

The Wind turbines industry has been growing rapidly in Brazil since the beginning of PROINFA in 2003 and the requirement of this programme that at least 60% of the equipment and services used in the wind power plants must be from national origin (Freitas Jr., 2011). So, their impacts on industry development are 'high' but still not as those caused by the hydropower plants.

The Solar PV industry is however very incipient in Brazil. In fact, China is a leading country in solar panels manufacture,[5] representing more than 55% of the total world production and their industry is developing rapidly. Conversely, the Chinese internal market of photovoltaic modules represents less than 5% of the global market (EPIA, 2011). In Brazil this industry is basically inexistent (Gorgulho, 2011) and competition with well-established Chinese markets would be hard. Additionally, despite the fact that Brazil's power electronics industry could compete with others to provide the inverters needed (Controle & Instrumentação, 2001), most of the value chain of the entire solar industry would still be produced outside the country.

It can be argued that a regulation to encourage photovoltaic energy now in Brazil would start the PV industry and, in the future, it could be competitive. This is a reasonable concern; however, one should take into account that other countries' regulation towards this technology were already established years ago (REN21, 2010) and the *'first movers advantage'* defined by Ashford (2000) was already taken by their industry and the Chinese ones that took benefits from the new market.

4.3.3 Equity

When assessing the whole framework in which DG is located, social aspects have an important role. In this research, with the purpose of evaluating the potential of each technology to provide *'justice through participation'* (Fenner et al., 2006) the criterion 'equity' was chosen.

Issues related to inter-generational equity and the ability of DG to provide opportunities to future generations were, to a certain extent, examined in section 4.3.2. Hence, this section aims to evaluate the intra-generational aspects to try and establish which technology options would be more suitable to promote justice and reduce the current spread between rich and poor people in Brazil. This is made by investigating what portion of the society would benefit from possible policies and upon whom the burden to support the policies would lie.

[5] The analysis in this report is focused on solar panels, since they represent on average more than 60% of the total costs of the value chain associated with Solar PV industry (EPIA, 2011).

Costs of rooftop solar panels installation are estimated to be around £13,000.00 for a 3kW system (Castro, 2011, pp.14 - ANNEX). These costs are extremely high, particularly if considering that the average monthly income in Brazil is around £560.00[6]. Consequently, solar PV will be installed primarily by wealthy people and, if there is a policy to subsidize it (such as feed-in tariff or net metering) the costs of these systems will be prorated amongst all electricity consumers. In this scenario, the less wealthy ones (who cannot afford to install a solar panel) will be paying more for electricity so that the photovoltaic systems installed by high classes could be subsidized. Hence, Solar PV was categorized in the present study as having 'very bad' impacts in promoting social equity.

Conversely, the cost to install a 3kW[7] biomass system would be around £2,800.00 (Boccuzzi, 2008). These costs are roughly four times lower than the solar and, since the projects are usually in rural areas, funding from government bodies are more likely to be granted. In addition, policies that encourage this technology will also be promoting better life conditions and opportunities in rural areas, possibly decreasing migration of people into urban zones.

A similar analysis can be applied to small hydro projects, which are in rural regions and the necessary technology and know-how to build these plants is spread throughout the country.

Wind power plants need certain expertise that is not yet disseminated. Hence, the projects are usually made by big companies that are already established in the field. However, microwind turbines could eventually be an option for householders of middle class who could not afford solar panels but can contribute to dissemination of DG through more inexpensive technologies.

[6] http://www.brasil.gov.br/noticias/arquivos/2011/01/27/inflacao-impede-maior-crescimento-de-renda-do-trabalhador-brasileiro-diz-ibge

[7] Usually power plants that use biomass as a source have an installed capacity considerably higher than 3kW. So, a 3kW biomass system was used only in order to compare the prices with a solar system with the same power capacity.

Table 4.9 – Potential impacts on equity for the DG alternatives

Technology Option	Equity
Small Hydro	Very Good
Biomass	Very Good
Solar PV	Very Bad
Wind	Bad
CHP	Average

4.4 Technical Impacts

In addition to the three basic pillars of sustainable development (economic, social and environmental aspects), a complete analysis of DG options demands the examination of some key technical features, such as:

- the potential reactive power provision from each of the alternatives,
- their impacts on grid management,
- changes on short-circuit levels and system protection and
- increase of harmonic distortions.

4.4.1 Reactive Power Provision

Alternating current power systems have, apart from the active power that is transferred to the loads, a component of the total power called ‘reactive power’ that is related to establishing and maintaining the electric and magnetic fields in the power system (IEC, 2011). Additionally, reactive power control is important in the regulation of voltage levels.

The provision of reactive power is related to the type of generator and how it is coupled to the grid.

Table 4.10 – Reactive power provision from the five DG alternatives

Technology Option	Reactive Power Provision

Small Hydro	Yes
Biomass	Yes
Solar PV	Yes
Wind	No[8]
CHP	Yes

4.4.2 Grid Complexity and Management

Distribution grids were originally designed to work with current flows in one direction (from the central generation or substations to the loads). With the introduction of power plants along the network, current flows can now be in both directions. This means that the protection systems, voltage control regulations, power quality equipment, etc., might be affected and operate erroneously.

This item assesses the impacts of the five options considering their ability to solve problems of congestion, regulate voltage levels and perform islanded operation[9] (Table 4.11). The values are obtained from Braun (2007) taking into account the following considerations:

- Small hydro, Biomass and CHP uses synchronous generators[10]
- PV is always coupled to the grid with an electronic converter
- Wind energy is produced with induction generators[11]

[8] Some wind turbines' architectures (such as double-fed induction generation and full power converter wind turbines) can provide reactive power.
[9] The International Electrotechnical Commission (IEC, 2011) defines an Island in a power system as a *'portion of a power system that is disconnected from the remainder of the system, but remains energized'*. Usually the source of energy in this island is a Distributed Generation power plant.
[10] Although very small hydro power can use induction generators (Smith, 2001), this analysis is made considering that the generators used by small hydro are synchronous.
[11] Wind turbines can also use double-fed induction generation and be coupled to the grid with an electronic converter (Jenkins et al., 2010).

Table 4.11 – Assessment of the potential contribution of the five DG alternatives to grid complexity and management

Technology Option	Congestion Management	Voltage Quality	Islanded Operation	Total Potential Contribution
Small Hydro	4	0	3	**7**
Biomass	4	0	4	**8**
Solar PV	4	4	3	**11**
Wind	2	0	0	**2**
CHP	4	0	4	**8**

4.4.3 Impact on Short-Circuit Levels

Rotating machines connected to the grid without electronic converter (all the technology options in this study except for Solar PV and some wind plants) can increase the short-circuit level of the grid (Boutsika & Papathanassiou, 2008) (Brenna et al., 2009) and, hence, have the potential to raise the short circuit current to values higher than the supported by some grid components (Cazzato & Botton, 2009).

Solar PV systems are connected to the grid with static converters, which limit the short circuit current (Jenkins et al., 2010). In this case, the problem of potentially exceeding the rated current limits of medium and low voltage grid equipment is alleviated. Similarly, some of the variable speed wind turbines can be connected via converters, which would also minimize this problem.

As a result, technology options with rotating machines that are connected directly to the grid were categorized as having a 'high' impact on short circuit levels (Table 4.12). To solar PV, which is connected through converters, it was assigned a 'low' potential of increasing fault currents. Since wind turbines can be coupled to the grid with or without converters depending on the technology used, their impact on short circuit currents was written off as 'medium'.

Table 4.12 – Impacts on short circuit levels of the different technology options

Technology Option	Impacts on Short Circuit Levels
Small Hydro	High
Biomass	High
Solar PV	Low
Wind	Medium
CHP	High

Increase in short circuit currents might also cause problems to the distribution grid protection system. Distribution power system protection is formed by several different elements that are coordinated to each other to disconnect the smallest part of the grid in the shortest period of time. Hence, the short circuit current provided by several small scale power plants, according to the network topology, can be perceived by one of the elements of protection in the grid (such as a fuse) and not by another element to which the first one is coordinated (like a circuit-breaker). When that happens, the protection of the grid is jeopardized (Barker & De Mello, 2000). Other impacts of DG on grid protection and further explanations can be found in (Jenkins et al., 2010, pp.95-126).

4.4.4 Increase of Harmonic Distortion

Electrical systems are designed to work with voltage and current profiles that alternate in a sinusoidal profile with a determined frequency (usually 50 or 60Hz). When non-linear loads (such as electronic equipment) are connected to the grid, this sinusoidal shape can be distorted, causing alterations in the voltage or current profile, called Harmonic Distortions (Leonardo Energy, 2007). When a generator uses electronic devices to connect to the grid (such as inverters) the power plant can also cause harmonic distortion (IEEE, 2002).

However, harmonics caused by small scale generators connected directly to the distribution grid are more difficult to quantify since the levels of distortion can be affected by previous distortion on the grid produced by non-linear loads from consumers in that area (IEEE, 2010). For that reason, it was chosen to classify the alternatives by levels of influence in harmonic distortion (high, medium or low) rather than via numbers - Table 4.13.

Table 4.13 – Potential of Harmonic Distortion generation by the different technology options

Technology Option	Harmonic Distortion
Small Hydro	Low
Biomass	Low
Solar PV	High
Wind	Medium
CHP	Low

Alternatives that produce electricity using synchronous or asynchronous generators (small hydro, biomass and CHP) do not inject high levels of harmonic distortion in the grid and so are classified as having “low” impacts on voltage and current steady-state profiles (Joos et al., 2000).

Wind turbines, however, are connected through induction generators with electronic converters to control the speed. For this reason, it was categorized as producing harmonic currents in a ‘medium’ scale (Jenkins et al., 2010, pp.29-37).

Finally, solar photovoltaic panels can have “high” impacts on harmonic levels since they produce direct current electricity and are always connected to the grid through inverters that can distort voltage profiles more than the other generation technologies analysed (Salamoni, 2004).

4.5 Weights of the Impacts

After gathering the data for all the criteria and analysing it under the Brazilian context to be able to apply the PROMETHEE Method, one has to assign weights to each of the impacts. This analysis was made according to the national policies for the rational utilization of energy sources established by Law 9478/1997 (BRAZIL, 1997), which include to:

1. Promote the development, creating jobs and enhancing energy resources
2. Protect the interests of consumers regarding price, quality and availability of products
3. Protect the environment and promote energy efficiency
4. Find the appropriate technology for energy supply considering different Brazilian regions
5. Encourage the use of renewable energy

The study also takes into account the reasons why the Regulator would promote the encouragement of DG, which also includes (Castro et al., 2011):

6. Postpone investments in grid expansion
7. Losses reduction

Since the costs of electricity generation would have impacts in several aspects of society, as well as in other criteria, it was assigned the biggest share of weights - 16%.

The first aspect cited by Law 9478/1997 makes reference to industry development and all the consequences that are analysed in Section 4.3.2 (Industry Development). Hence, a weight of 12% was assigned to this one. It can be argued that the weight of this aspect had to be more important than the costs, but a Sensitivity Analysis provided in Section 5.2 shows that an increase in the assigned weight of this criterion would not substantially affect the results.

Item 4 (appropriate technology) is also related to Reliability and Equity, social aspects that were weighted with 8%.

Items 3 and 5 make reference to the environmental impacts analysed in Section 4.2. Hence, for each of the three impacts in this area, 8% weight was assigned. A same weight was given to Grid Capacity and Energy Losses Reduction, since they are part of the criteria assumed by the Regulator (items 6 and 7).

For each of the four technical aspects, an equal share of the remaining 16% was assigned. This gives adequate weight for those impacts while acknowledging that they are engineering issues that can be solved more easily and in a shorter period of time.

Table 4.14 – Weights assigned to each of the criterion

Criterion	Weight
Costs	16%
Grid Capacity	8%
Energy Losses	8%
GHG Emissions	8%
Impacts on Biodiversity	8%
Renewable Energy	8%
Electricity Reliability	8%
Industry Development	12%
Equity	8%
Reactive Power Provision	4%
Grid Complexity and Management	4%
Impacts on Short Circuit Levels	4%
Increase of Harmonic Distortion	4%

The weights assumed in this section might be important when analysing the final results and the best technology options choice can be biased by these values. However, a Sensitivity Analysis was performed and is discussed in Section 5.2, with the purpose of making the conclusions presented in this dissertation more robust and less affected by subjective figures.

5 Results and Discussion

5.1 Choice of the DG technologies

PROMETHEE II ranking is shown in Figure 5.1. The total outranking flows were calculated according to eq. (3.1) for the five technology options and, as a result, the following rank is established:

1st. Small Hydro

2nd. Biomass

3rd. Wind energy

4th. CHP

5th. Solar PV

This means that, according to the set of criteria established in this analysis, the data relative to each criterion under Brazilian context and their weights, the best option of DG to be encouraged by policymakers would be Small Hydro. Biomass and Wind energy can also have strong positive impacts in the sustainable development of the electricity sector.

On the other hand, policies should not incentivize the increase of gas-fuelled CHP power plants and photovoltaic panels. The reasons for that include the fact that the impacts on many of the criterion investigated would be negative and, hence, the outcomes of those policies would not be favourable to Brazilian society.

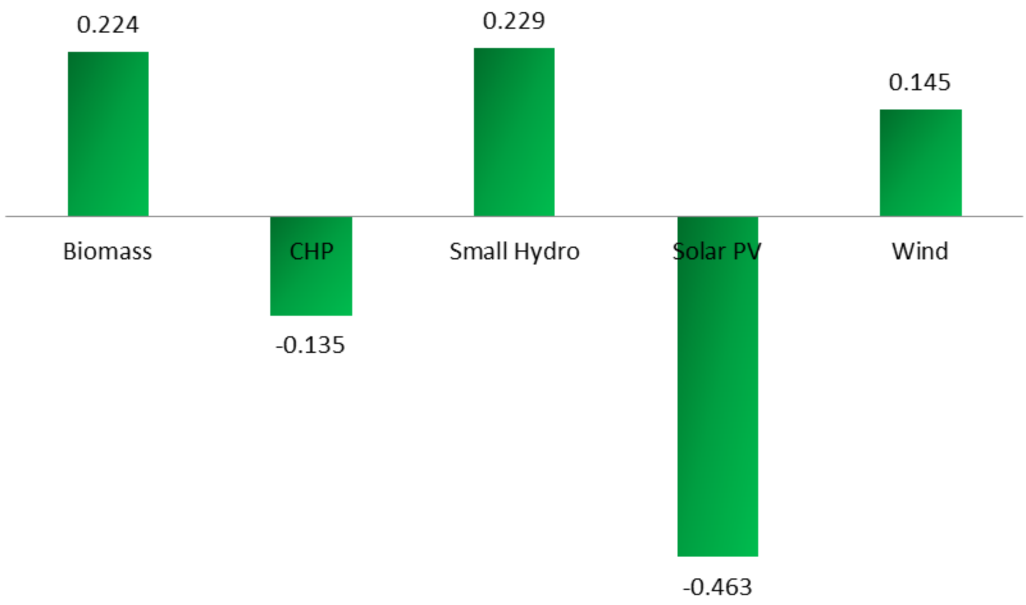

Figure 5.1 – Total outranking flows for the five DG technology options

The PROMETHEE ranking gives a summary of the results, but results presented in Figure 5.1 are not enough to provide a deep analysis of the reasons why solar PV should not be encouraged, while small hydro, biomass and wind should.

For that reason, the GAIA plan was drawn (Figure 5.2).

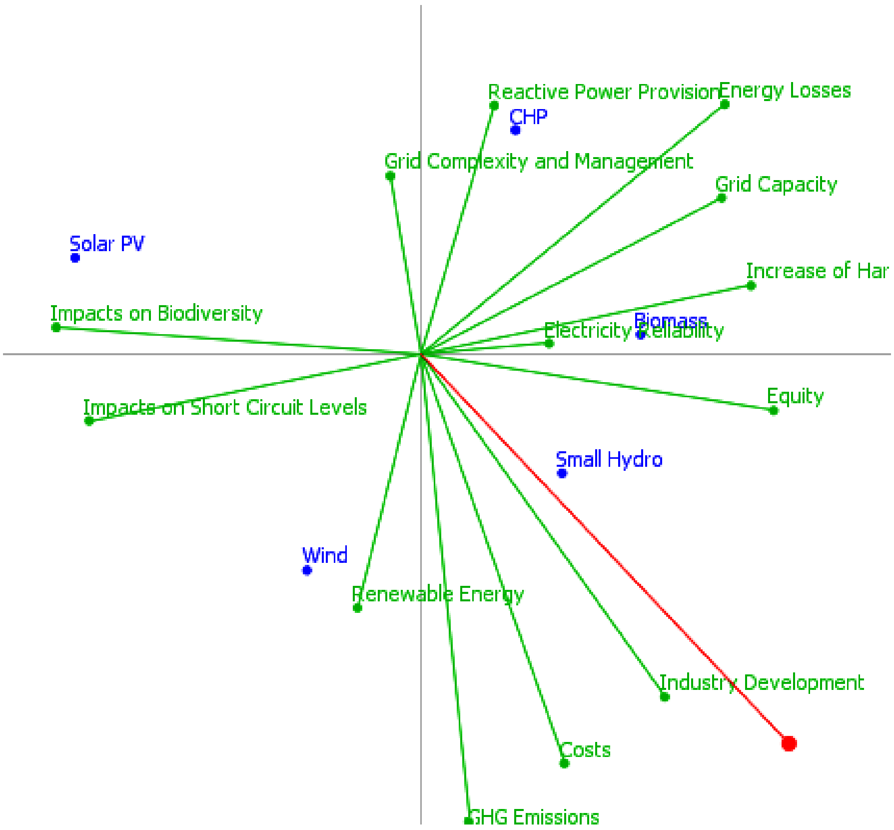

Figure 5.2 – GAIA plan showing the 5 technology options and their relative position to the 13 impacts

The δ parameter, defined in section 3.3.3, is 86.6%, indicating that the representation shown in Figure 5.2 preserves most of the information calculated in the PROMETHEE method.

Regarding the relative position of the alternatives, it is possible to notice that Biomass and CHP are located close to each other, since the technologies are similar and, hence, their impacts might be related. On the other hand, the graph also shows that Small Hydro and Solar PV are opposite to each other, meaning that some of their characteristics might be conflicting.

The red stick means the projection of the weight vector in the GAIA plan, defined in section 3.3.3 as the vector π. In the case simulated, vector π is long compared to the other criterion axis. That means that the ranking given by this vector is robust and policymakers can efficiently rely on it when taking decisions. Figure 5.3 shows the projection of the alternatives in vector π to help facilitate the visualization of the results.

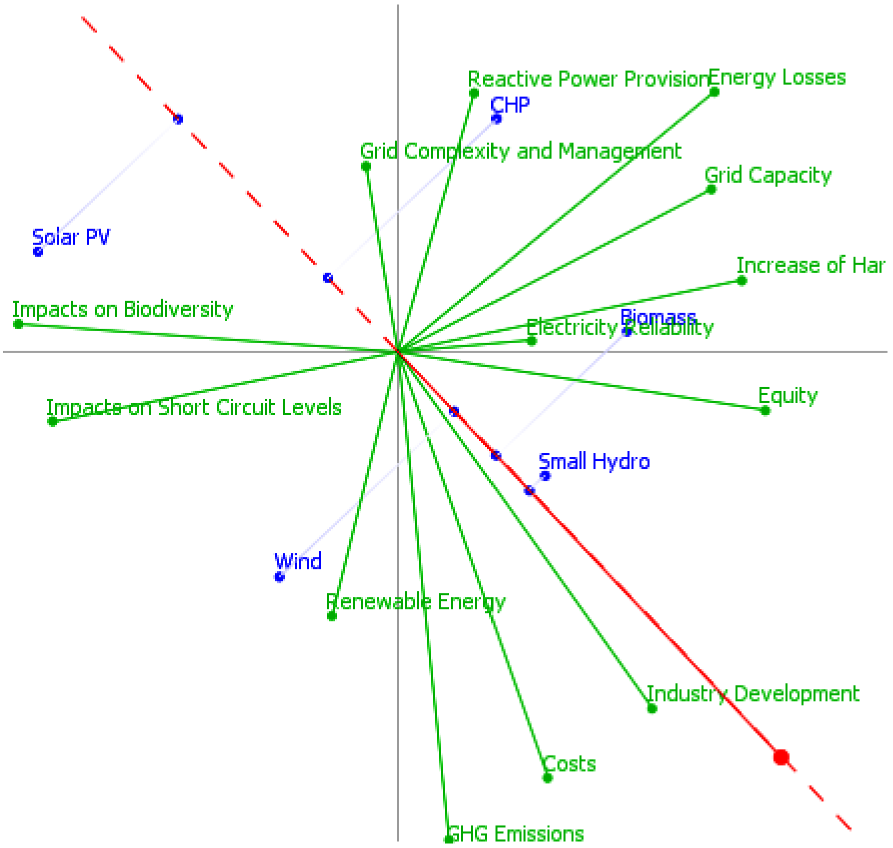

Figure 5.3 – GAIA plan with the projections of the alternatives in vector π.

Small Hydro is the further alternative in the direction of vector π, hence, it is the best alternative according to the method, followed by biomass and wind.

A view of *strong sustainability* (Neumayer, 2003) could lead the policymaker to perceive the solution from a different point-of-view, giving more importance to the 'impacts on biodiversity' axis. In this case solar PV would be the most suitable option and wind would be the second best. However, since the results from the holistic approach show that photovoltaic panels would not be a good solution for Brazil (it is actually the worst option according to PROMETHEE Ranking), a prudent solution would be to adopt policies that encourage wind energy, since it would still be a good solution overall and, when analyzing only the biodiversity criterion, it still is well categorized and would be in line with the 'strong sustainability' aspects.

Figure 5.4 shows the distribution of the alternatives considering only the impacts on biodiversity (vector π is coincident with the 'Impacts on Biodiversity' axis).

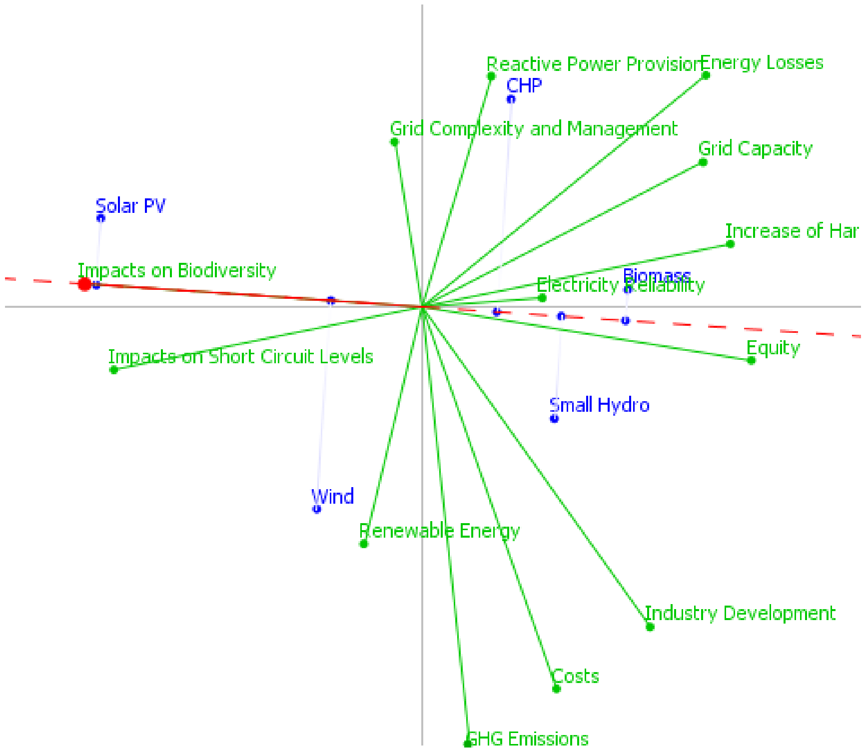

Figure 5.4 – Technology options choice considering only 'Impacts on Biodiversity'

Developed countries are strongly and increasingly encouraging the expansion of photovoltaic systems to generate electricity. In their context, this option can be justified, as discussed above. However, other countries can also adopt these policies only as 'followers', without analyzing the real need for that technology and without searching for their *appropriate technologies* (Darrow & Saxenian, 1993). In this sense, the present research shows that currently Brazil should not encourage the development of PV panels.

5.2 Sensitivity Analysis

The method used to evaluate the economic, environmental, social and technical impacts of each possible DG technology is robust since it uses real data, together with a deep examination of the effects of DG over the Brazilian context and compares them in a mathematical tool that is capable of dealing with different units, perspectives and circumstances. However, the weights assigned for each criterion depend on which aspects a country wants to emphasize, according to their state of development and particularities. For that reason, the weights chosen in this study, despite the reasoning that is used to choose them, can be questioned and could be different according to the country and to the time when the analysis is being done.

Consequently, in order improve the robustness of the results shown here, a sensitivity analysis for different weights was performed. The calculations were done with the software D-Sight® and, with the outputs, Figure 5.5 was drawn.

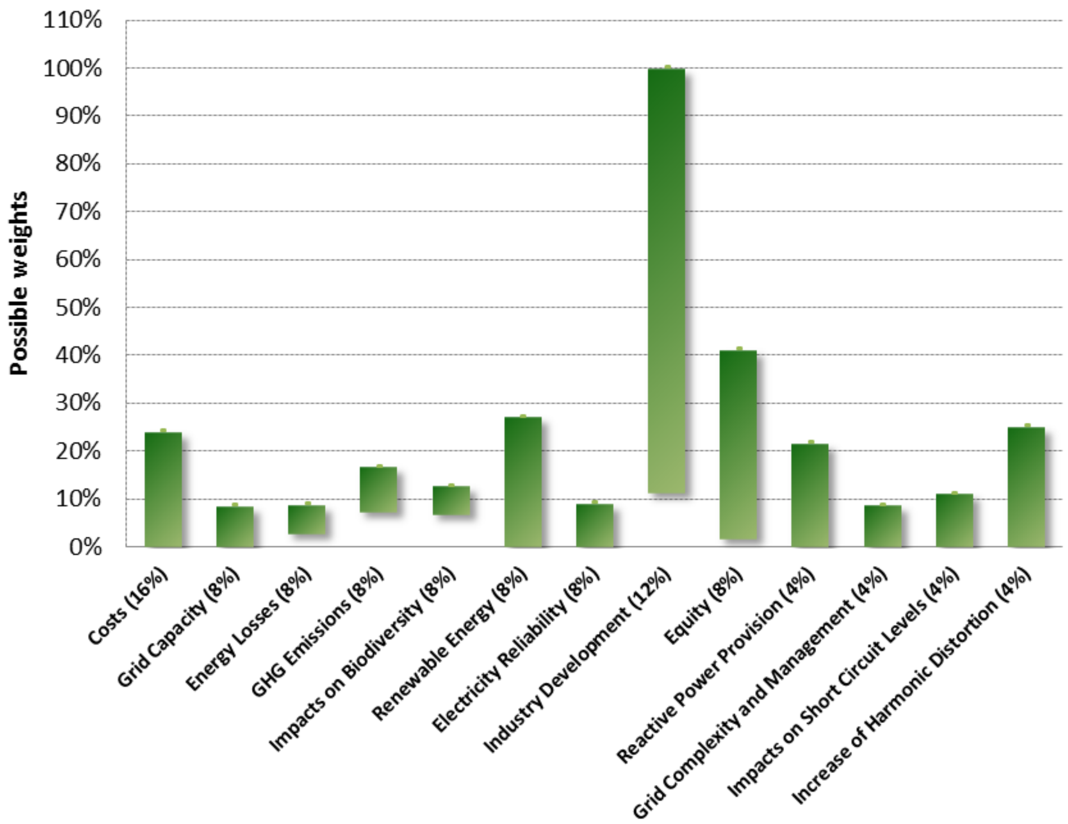

Figure 5.5 – Sensitivity analysis of the weights assigned to the 13 criteria

The numbers in parentheses after the name of each criterion show the original weight assigned for that criterion and the bars represent the weight range that could be assigned to the criterion without changing the final results – as long as the ratio between the weights assigned to the other criteria was kept unchanged.

An analysis of the graph shows that most of the criteria can have a small (or even zero) weight without affecting the final results. That means that, for instance, if costs were not taken into account (had zero weight) and all the ratios between the other weights were kept constant, then the results would still be the same. In other words, even when not considering costs, solar PV would still be the worse DG alternative for policymakers to encourage in Brazil and small hydro, biomass and wind would continue being the best options.

If an equal weight was assigned for all the criteria, then each one would be responsible for 7.69% (100%/13criteria). Figure 5.5 also shows that all the criteria (apart from 'Industry Development') can have a weight below this target, meaning that none of those criteria is, alone, crucial to obtain the results.

Special attention should be given to the ability of the alternatives to promote 'Industry Development'. If the weight of this criterion was below 11% than the results would change. In fact, when industry development is not considered, then Biomass becomes the best option, followed by wind. This also explains why some countries, such as the UK and Germany, make policies to encourage these two technologies very strongly. If their concern in industry development is not as high as that of a developing country, they are right to do that. In Brazil, however, and in other places where creating and maintaining new industries is crucial to sustain economic growth, the choices of DG technologies to be encouraged must be thoroughly investigated.

Another important aspect of this analysis is the upper limits of weights. We might start the investigation with the potential Impacts on Biodiversity of the technologies. According to Figure 5.5 if the relative importance of this criterion is higher than 13%, then the policies should encourage different technologies than those presented in the results. In fact, if this is the most important criteria of all (weighting a little bit more than 50%), than the best option would be wind, followed closely by photovoltaic panels. Of course this would be a scenario where all the other criteria, including costs, industry development and equity, would each be worth less than 10%. This may be the case in very developed countries, where society can afford to pay more for electricity in order to reduce environmental impacts, and issues regarding jobs and equity are already relatively solved.

5.3 Policy recommendations

Public Consultation no. 015/2010[12] promoted by the Brazilian Electricity Regulatory Agency (ANEEL) and the recent Public Hearing no. 045/2011[13] aim to promote the development of Distributed Generation with the following mechanisms:

- Net metering for very small power plants (up to 1MW) that uses renewable energy as a source or cogeneration
- Increase the discount on transmission and distribution tariffs for solar power plants from 50% to 80%

Nevertheless, the analysis presented in this dissertation shows that solar photovoltaic systems can have a negative impact on the sustainable development of the Brazilian electricity sector. Hence, the discount on tariffs for this source of electricity should remain equal to the other renewable sources or be eliminated.

In general, net metering systems could be encouraged for small hydro, biomass and wind sources. However, the impacts on grid capacity, complexity and management can be very different according to the distribution network and the technology involved. Hence, the utility should have the right to accept or not the connection of these generators to the grid.

[12] Available at http://www.aneel.gov.br/aplicacoes/consulta_publica/consulta.cfm?ano=2010&idArea=14

[13] Available at http://www.aneel.gov.br/aplicacoes/audiencia/dspListaDetalhe.cfm?attAnoAud=2011&attIdeFasAud=562&id_area=13&attAnoFasAud=2011

6 Conclusions and Further Work

According to Dodds & Venables (2005) one of the principles of sustainable development is to *'seek a balanced solution'*. To apply this concept at the development of DG in Brazil would mean that policies should try to encourage simultaneously three main technology options: small hydro, biomass and wind.

The present research demonstrates that, in a holistic approach, these choices are the best to address social, economic, environmental and technical aspects: they are more cost-effective, promote substantial industry development and equity, improve grid capacity, help reduce energy losses and increase systems reliability. However, the methodology used also shows that it is a matter of trade-offs and that the choices to encourage one or another technology might have impacts that are significantly different from each other.

Photovoltaic systems have been shown to be an inappropriate technology to the Brazilian electricity sector. Despite the fact that they can have positive impacts on grid management and the least environmental impacts, their benefits to grid capacity are very limited, the costs are high and social effects are negative. Therefore, current subsidies towards photovoltaic systems in the country should not be increased and a gradual reduction of those incentives is highly recommended.

To assert that Brazil should not spend public funds to subsidize solar PV goes against the inert mass called 'normal professionalism' defined by Chambers (1992) in which he argues that in our professional activities we *'value things more than people, numbers more than judgments, high technology more than low'*. This view, according to Chambers, is *'antithetical to the new views of development'*. Then, one of the barriers to convince policymakers that supporting solar PV in Brazil now is not a good idea will be to fight against the normal professionalism inert mass that makes them think that high-tech solar photovoltaic panels are intrinsically better than traditional well-established small hydro.

It is important to acknowledge that this analysis is performed mostly under local and national perspectives, trying to give DG a holistic approach that considers many social, economic, environmental and technical aspects within Brazilian context. However, further investigation could explore more the impacts of global issues towards national DG policies, such as: international treaties and pressure for the use of more environmentally friendly electricity technologies and reduction in GHG emissions targets; perspectives for changes in fossil fuel prices worldwide; potential benefits from international industry cooperation etc.

Further work could also include investigating thoroughly which aspects are only applicable to Brazil and what could be extrapolated to other countries in order to make the methodology suitable to assess appropriate DG technology options more broadly.

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