

## **Capacity factors of Brazilian hydroelectric power plants:**

### **Implications for cost effectiveness**

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#### **Abstract**

Hydroelectric power plants account for more than 85 percent of the electricity produced in Brazil. The net social benefits of hydro depend on initial investment and the timing of cash flows based on a plant's Capacity Factor--CF (and valuation of non-monetary impacts over time). The inter-temporal timing issue also involves balancing the use of the energy stored in reservoirs and the likelihood of future replenishment in the presence of climate variability. The purpose of this study is to present the facts regarding CFs for hydroelectric plants in Brazil: by region and plant size (large, small, and micro). The study also describes how the planning for expansion has been affected by ecological and social concerns. Plants with large reservoirs are not feasible under new environmental regulations, probably resulting in greater dependence on fossil fuels in the future—leading to a different set of negative environmental impacts. In addition, comparisons with wind are presented, since these two alternative technologies currently represent the most cost-effective renewable energy

options for countries like Brazil in the medium term—until solar energy (with its own hourly CF issues) becomes more cost effective. The study concludes with an examination of the consequences for future capacity expansion plans in Brazil.

**Keywords:** Hydroelectric, Wind, Capacity Factor, Brazil

## 1. Introduction

With the growth of electricity demand in the developing world, discussions of the environmental consequences that stem from its use and production take on a sense of urgency. This study examines the production of electricity from renewable energy sources, primarily hydroelectric. Although the vast majority of developed countries utilize fossil fuels (and are adding renewables to their energy portfolios), there is still significant potential for utilizing water resources for electricity generation, particularly in South America, Asia, and Africa. The installed capacity of hydropower is expected to double by 2050 (IEA, 2012), much of it in developing countries due to high electricity demand growth and available environmental resources.

Here, we analyze the effectiveness of Brazilian electricity generation plants, utilizing the Capacity Factor (CF) of Hydroelectric as a key metric for evaluating their cost-effectiveness. The effectiveness (or efficacy) of a power plant can be defined by its design (installed power) and operating features:

$$CF = (E * 100) / (P * H)$$

CF: capacity factor (%)

E: Energy produced in a certain time interval (kWh)

P: installed power (KW)

H: number of hours in the same time interval (h)

The capacity factor is the ratio of energy that is actually produced divided by the total energy that would be produced if the plant operated all the time—with no need for plant maintenance or output reductions (due to low water flows--drought).

As is shown in the next section, the CF plays a significant role in determining the economic efficiency of investing in capital-intensive dams. The study presents CFs for hydroelectric plants of different sizes: large (HPP—Hydro Power Plants with installed capacity over 30 MW), small (SHPP—Small Hydro Power Plants with installed capacity between 1MW and 30MW) and mini ( Mini Hydro Power Plants—MHPP with installed capacity under 1MW) to identify links between CFs and scale, age, and geographic region. To facilitate comparisons, the CFs of thermal (Thermo Power Plants - TPP) and wind plants (Wind Power Plants—WPP) are also introduced. Policy-makers need to incorporate these CFs into the planning process to ensure least cost expansion plans that take into account the full opportunity costs of the alternative energy sources.<sup>1</sup>

Under regular operating conditions, any electric generating plant has a CF less than 100%. This situation occurs for many reasons: required maintenance, accidents, low levels of demand in certain time periods, incremental production costs that exceed prices in the electricity market, transmission constraints, fuel shortages, or environmental restrictions. In the case

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<sup>1</sup> For a comprehensive examination of micro-hydro power plants in the Amazon region, see Blanco, Secretan and Mesquita (2008). These authors present a case study of how a micro-hydro system can be cost-effective for small isolated communities. The focus of the present article is on the larger dams.

of hydro or wind plants, the main determinant of their CFs is the absence of the natural resources that drive the turbines. Given the high capital costs associated with both wind and hydro, weather and meteorological/hydrological conditions significantly affect economic performance. In addition, there is a significant public opposition to the environmental impacts of hydro on social and environmental grounds.

The debate over the impacts of hydroelectric power plants occurs in the policy arena and in academic literature. Non-governmental organizations such as Greenpeace and the World Wildlife Fund (Movimento Gota D'água, 2011, Amazon Watch, 2012, Sant'Ana, 2012) have presented the case against electricity from hydro sources. In addition, social movements and celebrities highlight concerns over dams related to affected populations and ecological impacts<sup>1</sup>. Within the academic community, a sampling of those arguing the case against hydroelectric power plants (HPPs) include several examples (McCully 2001, Bermann 2002, Cernea 2004, McCormick 2006, Fearnside 2009, and Sant'Ana 2012).

These opponents present challenges to policy makers in countries with a high share of electricity from hydropower; if planners expect to continue high dependence on HHP for energy security, they need to balance perceived benefits against the direct production costs and negative social and environmental impacts. The timing of cash flows based on a plant's CF (and valuation of non-monetary impacts) determines the net benefits of hydro. The timing issue becomes even more complex considering the delicate balance between the use of the energy stored in the reservoirs and the likelihood of future replenishment in the presence of climate variability. The purpose of this paper is to present the

facts regarding CFs for hydroelectric plants in Brazil: by region and size (HPP, SHPP and MHPP,). In addition, comparisons with wind are presented, since these two alternative technologies currently represent the most cost-effective renewable energy options for countries like Brazil in the medium term—until solar energy (with its own hourly CF issues) becomes more cost effective (Jannuzzi and de Melo, 2013).

## 2. The Brazilian case

Currently, Brazil is the largest nation with a high dependence on hydroelectric power. Table 1 presents a ranking from 2010; the statistics exclude the exports from Paraguay to Brazil (from its share in the power plant of Itaipu Binational, usually of the order of 36 TWh yearly).

**Table 1- Most Significant Producers of Hydroelectricity**

<b>Country</b>	<b>Hydroelectricity production (TWh) 2010</b>	<b>Share from hydroelectricity (%)</b>
<b>China</b>	<b>694</b>	<b>14,8</b>
<b>Brazil</b>	<b>403</b>	<b>80,2</b>
<b>Canada</b>	<b>376</b>	<b>62,0</b>
<b>USA</b>	<b>328</b>	<b>7,6</b>
<b>Russia</b>	<b>165</b>	<b>15,7</b>
<b>India</b>	<b>132</b>	<b>13,1</b>
<b>Norway</b>	<b>122</b>	<b>95,3</b>
<b>Japan</b>	<b>85</b>	<b>7,8</b>
<b>Venezuela</b>	<b>84</b>	<b>68,0</b>
<b>Sweden</b>	<b>67</b>	<b>42,2</b>

**Source: (IEA, 2012)**

The share of production differs from the share of installed power capacity, since some capacity may only be utilized during peak periods or it is unavailable during certain time periods. Non-availability reflects planned maintenance, unplanned outages, or because long or short term climatic conditions limit availability (in the case of hydroelectric facilities, wind, and solar). One of the arguments often cited by opponents concerns the sensitivity of the hydroelectric option to hydrological uncertainties: these reduce availability, and thus the capacity factor for HPP. Given the high capital investment for each unit of capacity, a low CF represents a potentially significant reduction in the cost-effectiveness of hydroelectric plants. Brazil is an important case in point, since the nation has significant undeveloped hydro potential: planned additions will depend on correctly incorporating CFs into benefit-cost analyzes. An empirical study of Portuguese hydroelectric dams (Barros and Peypoch, 2007) emphasized the heterogeneity of both production and capacity. That point certainly applies to Brazil as well, as later sections will show. At present, Brazil arguably has the greatest hydrological dependence among all nations in adequacy of supply capacity; the other major producer, Norway, has a much more regular water flow regime due to ice melting during summer in the northern hemisphere.

The regulatory and commercial framework adopted in Brazil requires that any electricity sold have a physical guarantee associated with each unit of plant capacity. This requirement provides an important element for this study, since the "assured energy" is defined in terms of the commercial definition. Data from contracts provide us with a valuable source of information. To enable

comparisons with other types of renewable energy, the authors also investigate the assured energy of wind and thermal power plants in Brazil.

Decision-makers consider more than traditional financial measures of cost-effectiveness, given the role of stakeholders who are concerned with environmental and social impacts. For now, we will focus on direct financial comparisons, recognizing that placing monetary values on other impacts can be done at the next stage of project comparisons. The factor frequently (and mistakenly) used, as a measure of economic efficiency by opponents of HPPs is the Capacity Factor (CF). This index is better characterized as a measure of effectiveness: the extent to which the HPP is available. CF could be viewed as a measure of productivity, represented by the ratio of output to inputs. Efficiency is related to productivity, but it involves comparing how close the facility comes to meeting some predetermined standard.

CF is defined as the ratio of the energy generated within a time interval divided by the power capacity installed at the plant. In the case of HPPs, energy produced depends on the water in the reservoirs. Thus, this indicator will depend on hydrological conditions and the production patterns of upstream dams. It depends on the water volume available to drive the turbines in the long run, the operation strategy for the related system of dams, and the transmission system to which it is connected (ultimately adjusting for technical losses based on distance to customer loads). Given the capital intensity of HPP, delays in the certification and licensing process increase the net present value of investment costs (particularly when some construction outlays have already occurred).

The choice of renewable vs. nonrenewable energy depends on national priorities balancing economic, social, and ecological objectives. Proposed new

HPPs are evaluated by energy policy-makers, by the independent operator of the electric system, and as well by environmental agencies; these institutions jointly establish the conditions for granting licenses. These groups consider the trade-offs based on the volume stored in the reservoir, meeting safety and reliability standards, and mitigating environmental and social impacts. For thermal power plants (TPP), effectiveness, measured by the CF, also includes the certainty of fuel supply, operating conditions, environmental restrictions, and equipment reliability. Wind farms depend for their effectiveness on the correct location of the particular project and associated engineering and operational features of the equipment. Thus each technology has its peculiarities that influence the CF and efficiency (effectiveness) of each plant

### **3. The Brazilian Electric System.**

As has been noted, the Brazilian electricity system is characterized by the dominance of hydroelectric generation. The plants operate within an interconnected system that is among the largest in the world, with dimensions similar to the European continent. This system consists of 64,000 miles of transmission lines, with planned additions of over 30,000 miles by 2021 (EPE, 2012). Table 2 shows the composition of the installed generation capacity in Brazil as of January 2013 (ANEEL, 2013).

**Table 2- Capacity of Brazilian plants (January 2013)**

Power Plants	Capacity ( MW)	Share %
Hydropower HPP	79.905,28	65,99
Small Hydro Power Plants SHPP (<30MW)	4.496,32	3,71

Wind Power Plants WPP	1.888,38	1,56
Thermal Power Plants TPP	32.777,00	27,07
Nuclear Power Plants NPP	2.007,00	1,66
Solar Photovoltaic Power Plants SPPP	7,58	0,01
Total	121.081,56	100

**Source: ANEEL (2013)**

Renewables account for approximately 70% of capacity, while thermal power plants (including nuclear) account for the remaining 30%. However, even in hydrologically unfavorable years, like 2012, actual production has been from mainly hydroelectric plants. The disproportionate role in output stems from dispatching HHP when water is available in reservoirs: it is uneconomic to dispatch power plants that use costly fossil fuels (involving direct costs and indirect costs due to greenhouse gas (GHG) emissions). Table 3 shows the output shares by technology for total production of 513.81 TWh in 2012.

**Table 3 - % Electricity Production by technology– Brazil 2012**

Plants	% production 2012
HPP /SHPP	85,9
WPP	0,6
TPP	10,4
NPP	3,1

**Source: ONS ( 2013)**

#### **4. Physical Warranty: a peculiarity of the Brazilian system**

The Brazilian electricity system has, as one of its basic premises, that all customers (distribution companies and large purchasers) must have signed contracts in advance of their consumption needs. The distribution utilities are included in this requirement, since they represent the set of customers with regulated tariffs. Thus, generators can only sell an energy for which there is statistical certainty for the generating unit's availability. This "certainty" may not be simple to achieve, since the HPPs have hydrological risks that affect future performance. Similarly, thermal plants in operation typically present a different reality than the design specifications for equipment: production systems fail or supply chains are broken. Wind plants, which are still very recent in Brazil, have not yet an appropriate historical record to enable analysts to predict availability with some degree of precision.

To further complicate this situation, considering a series of hydroelectric dams on the same river, it is necessary that operational decisions are made centrally to avoid a non-optimization of natural resources. Not all countries follow this centralization, for example in the U.S. often decisions are based on other integrated uses of water resources (for fisheries or irrigation) rather than solely on energy optimization. To address these uncertainties, the Brazilian regulatory model established that power plants could sell only the energy for which there is a Physical Warranty - PW, which provides greater contractual certainty.

The Physical Warranty (PW) depends on the production technology. For operating purposes, the PW of a HPP could be independent of its actual production in the short term, but highly dependent on its ability to provide

electricity to the system from a long-term perspective. In this case, the mathematical modelling of operational decisions has a time horizon of 5 years, which makes sense because if a potential supply crisis is identified, it takes time to construct infrastructure to mitigate the crisis. Of course, associating this perspective involves a criterion of risk consistent with the water basin associated with the plant. For a thermal power plant (TPP) this PW is associated with installed capacity, reflecting the highest Capacity Factor for this technology. This figure is then reduced by the expected failure rates due to outages and interruptions for scheduled maintenance. Actual utilization of TPP is less than availability, since these plants are primarily used as back up or peaking units. The contracts for fuel supply represent another factor determining the Physical Warranty in these cases. Wind farms do not yet have a database capturing long-term climatic patterns, so the PW is estimated from studies by the Energy Research Company-EPE<sup>3</sup>, based on short-term measurements. This PW estimation should be updated periodically, although required procedures have not yet been implemented.

Thus, the PW is granted by the Regulator, with technical support from the ISO in order to provide the stamp of an external authority, thus facilitating confidence for energy traders. The PW of a plant can be changed periodically due to structural changes in its operating conditions (e.g. changes in environmental legislation that may reduce the output of the plant, due to the installation of energy-using scrubbers or seasonal operating restrictions). Changes may also occur due to poor operational performance, causing the regulator to change the stamp granted, until performance improves. The PW is usually expressed as an "assured energy" in  $MW_{avg}$ : the energy that would be

available at all hours of the year on average associated with a confidence level of 95%. Thus, the PW of a hydro plant is dependent on physical constraints for its production, but in long run it could be affected by operational dispatch. PW can be slightly less than CF due to transmission constraints that reflect the consequences of forecasting and investment errors.

## **5. Capacity Factor of Brazilian plants**

Given the need for an official definition for the assured energy for establishing contracts for each power plant, the electricity sector regulator—ANEEL—publishes on its website the PW values for plants in operation as well as for those that are still under construction. Since most of the new power supply in Brazil is based on contracts signed in an auctions process for future delivery (usually 3 to 5 years in advance), even plants not yet built receive a certificate (or warranty) of its regulatory PW.

For hydroelectric plants, this warranty is granted based on rainfall and stream flow statistics in its hydrological basin. Given Brazil's historical dependence on HPP, such data have been collected for decades, and capture flood and drought conditions in the different regions of Brazil. For TPP this permission is granted on the expected efficiency of the equipment and the availability of fuel contracts. For wind, the PW is based on fairly limited data, raising questions regarding the predictive power of the statistical models supported by relatively short periods for which measurements are available.

The statistics presented in Table 4 represent the information available at the ANEEL website (2012), grouped by generation technology and by geographic region. The hydro projects are grouped by size ( HPP, SHPP and

MHPP as defined in previous section). The thermal power plants (TPPs) were not grouped by size since the CF is more dependent on technology, plant age, and the fuel availability than its size.

With a few exceptions, the WPPs all have installed capacity below 30 MW, since there are tariff incentives for the production of energy from plants of this size. Thus, this categorization is somewhat arbitrary, but it captures the way data are reported. The nuclear plants in Brazil were not included in this study because there are only two plants (with one in construction since the 80's); it is unlikely that their number will increase. Solar plants represent an insignificant portion of Brazilian installed capacity to date, so they are not included in the study.

The average capacity factor calculated for each type of generation and region used the definition presented in the previous section. Before presenting the CFs for the different technologies in the five regions, we need to address some data issues. For five hydroelectric plants located in complexes involving several hydroelectric projects, the regulatory documentation indicated installed capacity, but no assured energy. This treatment could be explained by the fact that these plants only act as "firming" reservoirs, where the electricity that is actually produced comes from a plant located downstream: the CF is being effectively considered in the subsequent plant. Its capacity for energy production is therefore restricted to periods of exceptional hydraulic confluence, typically operating only on the peak of the system.

On the other hand, Itaipu (the largest hydroelectric facility in Brazil) was constructed as a bi-national project with the Republic of Paraguay, which despite having commercial rights on 50% of electricity produced there, has an

agreement with Brazil, which purchases almost all of its share. Since the assured energy is defined in regulatory terms to allow Furnas (the Brazilian owner of Itaipu) to sell this energy in Brazilian markets, the Itaipu CF is calculated as greater than 100% (which is correct from the regulatory “accounting” standpoint). For comparison purposes, Table 5 shows the change that would occur in the calculation of  $CF_{avg}$ , if Itaipu and firming reservoirs had been included in overall statistics. The small difference (less than 3%) between the figures indicates that this exclusion will not affect our analysis.

**Table 4- Official Capacity Factors by type and region (Brazil)**

<b>Region</b>	<b>Type</b>	<b>Number of Power plants in study</b>	<b>CF<sub>average</sub></b>
<b>Brazil</b>	<b>HPP</b>	<b>145</b>	<b>55,98</b>
S		32	50,54
SE		67	55,30
WC		23	59,79
N		11	60,95
NE		12	62,65
<b>Brazil</b>	<b>SHPP</b>	<b>352</b>	<b>61,43</b>
S		122	61,66
SE		122	56,74
WC		77	68,65
N		16	62,25
NE		15	59,84

<b>Brazil</b>	<b>MHPP</b>	<b>59</b>	<b>62,80</b>
S		29	65,94
SE		26	62,02
WC		3	35,67
N		1	73,5
NE		-	-
<b>Brazil</b>	<b>TPP</b>	<b>121</b>	<b>54,14</b>
S		16	61,53
SE		40	48,03
WC		23	50,54
N		2	54,92
NE		40	59,33
<b>Brazil</b>	<b>WPP</b>	<b>301</b>	<b>42,88</b>
S		64	38,09
SE		2	25,19
WC		-	-
N		-	-
NE		235	44,33

Source: ANEEL (2012)

**Table 5 Statistics excluding and including Itaipu and hydroelectric complexes**

<b>Itaipu &amp; Hydro Complexes</b>	<b>Type</b>	<b>Number of power plants in the study</b>	<b>CF<sub>average</sub> (%)</b>
Excluded	HPP	145	55,98
Not Excluded		151	54,57

The patterns by region and technology will be discussed in the next section. Suffice it to note that the patterns do not reveal wide variation across regions or generating technologies. The total power capacity installed for each technology included in this study is shown in Table 6. Also shown in the same table is the total of production capacity of each technology effectively in operation as of January 2013. Units that already have their "assured energy" legally designated but that are not yet operating (mainly HPP and WPP) explain the differences between the plants included in this study and the set in operation shown in Table 6. Some plants also have problems related to connection difficulties due to delays in transmission construction (mostly affecting WPPs).

The differences noted in MHPPs can be attributed to a lack of registration with the regulator for marketing purposes, since many of these plants are dedicated to self-consumption. The same point applies to TPP where the set of plants studied in this article is lower than the set actually in operation; there are several TPPs for self-production, not integrated to the grid.

**Table 6 Total Power Installed Capacity of the plants studied.**

Type	Power (MW)
HPP excluding Itaipu & complexes with multiple plants	90.463,8
HPP including Itaipu & complexes with multiples plants	100.088,2
SHPP	4.394,2
MHPP	41,38
TPP	13.307,4
WPP	7.719,60

## **6. Analysis of Capacity Factor Patterns and Effects**

### **6.1 Location**

In terms of location, the majority of hydroelectric plants in all its variants (HPPs, SHPPs and MHPPs) are concentrated in the Southeast (SE) and South (S); not surprisingly, these facilities are in the more developed regions where natural resources were initially exploited. On the other hand it is known that in the North, only the basins of the Amazon and Tocantins-Araguaia are inventoried with hydroelectric new projects totaling 87,800 MW with an estimated 34,000 MW more (EPE, 2008). In the Northeast (NE), the remaining potential, yet to be fully explored, is significantly lower than the North (N) (where the NE has approximately 6,500 MW inventoried and 2,200 MW estimated).

The N region has very few connections with the grid. With the planned expansion of new hydro plants in this region, it is expected that in a dozen of years the interconnections will completely link up the Brazilian regions. This, in turn, may encourage the inclusion of new investments in SHPP, still nascent in the North. It should be noted that the capacity factors of the hydroelectric facilities in the South and Southeast are slightly lower than those reported for the N, NE and WC, although this conclusion cannot be extended to the MHPP due the small number of plants in terms of produced power.

Thus, it is evident that the average capacity factor of HPPs in Brazil is expected to grow over time, given the greater number of plants planned for the N region, where the CF are typically higher than those found in S and SE. However, this pattern could be affected by environmental constraints for large reservoirs in the future. Note that most of the new projects are run of river power

plants due to the environmental restrictions; otherwise, the CFs in north region would be even greater. This fact has a huge impact in the need for additional generation, once there are no more reserves for drought years. The reserves are lower every year, as the growth of new generation focuses only on run of river hydro projects. The Independent Operator in Brazil recently declared that the reserves compared with the load, which accounted for 6,2 times in 2001 is forecast to be only 3,3 times in 2021 (Arteiro, 2013). Policy-makers will need to identify technologies (and determine how to finance them) for additional generation capacity.

Regarding TPPs, facilities are concentrated in the SE (the most industrialized and developed region) and the NE, where (during the last decade) the government undertook incentives for regional development. One of the characteristics of this effort was the installation of a large number of new TPPs in the region, historically fragile in terms of energy security. The S still has a concentration of TPP, but with less intensity compared to the SE and NE.

However in the NE region, where new generation projects have been more intensive, transmission infrastructure has not expanded as much. Since the purchase of energy from TPPs (as well as any other facilities) is done through auctions (which do not adequately specify locational elements), the criterion of regional allocation has not been followed. In some cases, new generation facilities that are ready to produce face the problem of inadequate connection options to the grid. In some cases, production was postponed for periods beyond one year. ANEEL then has to determine the income associated with the lost production; since the plants were ready but transmission was not, to incentivize

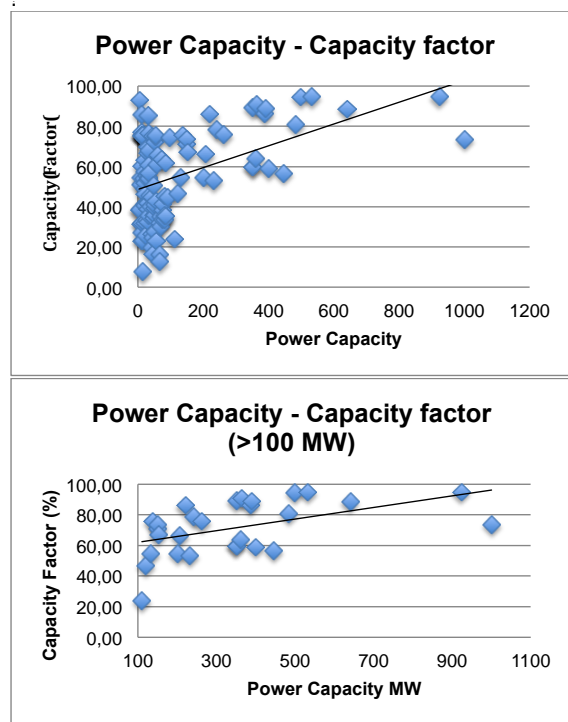
investment in generation, lost revenue will be covered by customers through higher tariffs.

Ultimately, the prioritization of the deployment of these plants occurs simply because of regional incentives. Several analysts and the independent system operator (Montenegro, 2012) are asking for new rules that are aimed at giving greater regional competitiveness to TPPs, especially biomass facilities. This measure could increase energy security, minimize the energy exchanges between regions, and postpone investments in new transmission lines required by the location of TPPs that are far away from the load. The WPPs have a clear dominance in regions S and NE where the physical characteristics of wind speed are paramount. It is not expected that this concentration will change in the medium and long term.

## **6.2 Scale Factor**

We investigated the correlations between the size of the plants (measured by the power) and the capacity factor, in an attempt to verify the presence of a scaling factor. For thermal plants we identified a weak correlation ( $r^2 = 0.43$ ), which is slightly more evident ( $r^2 = 0.49$ ) when we use only the thermal large (above 100 MW). Figure 2 shows these results.

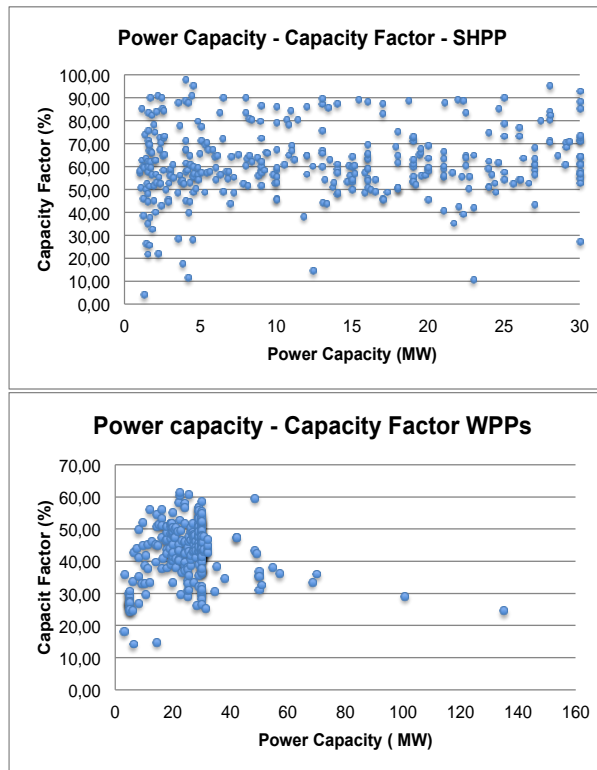
**Figure 2. Correlation Power capacity vs. Capacity factor in TPPs**



For wind plants and small hydro power plants, we did not find a significant correlation between the size of the unit studied (Power Capacity) and its capacity factor: we obtained weak correlation factors found (respectively  $r^2 = 0.08$  and  $r^2 = 0.11$ ). The results are shown in Figure 3.

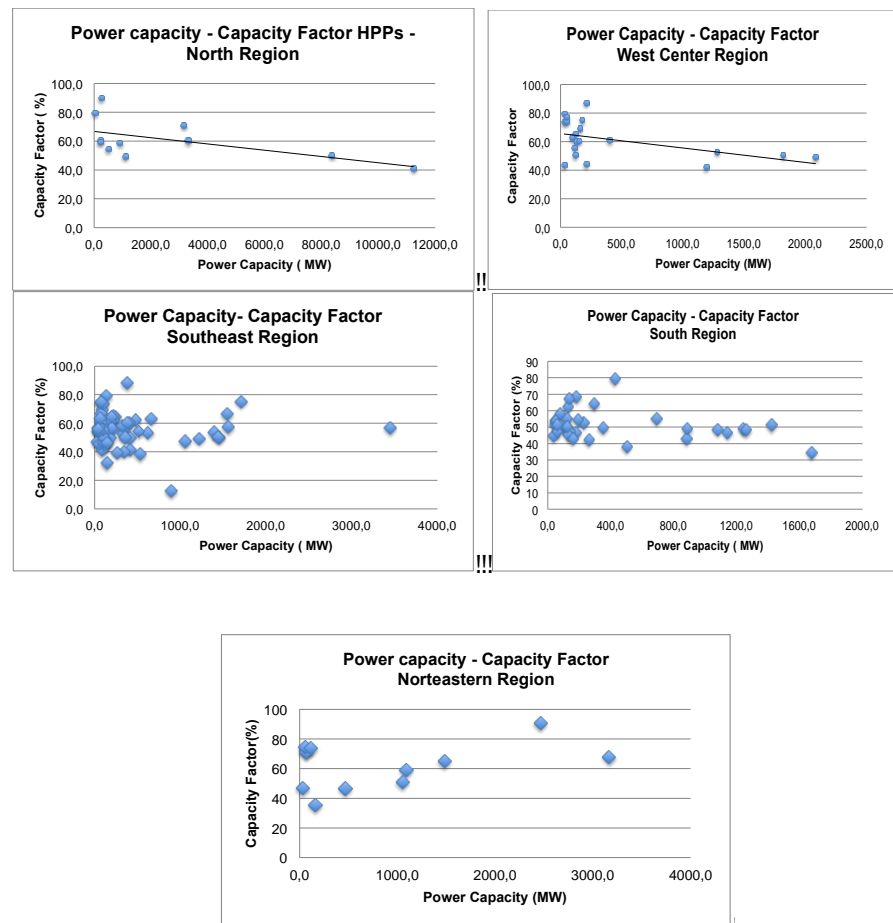
For large hydro's there is no evidence of correlation between the size of plant (measured by power) and the Capacity factor ( $r^2 = -0,10$ ), however when we made regional analysis, there is a improvement in this valuation, especially in N and WC regions (respectively  $r^2 = -0,58$  and  $r^2 = -0,48$ ). The correlation in the SE remained weak ( $r^2 = -0,02$ ). Finally, in the Northeastern and South, the correlation fits an intermediate position (respectively  $r^2 = 0,34$  and  $r^2 = -0,31$ ). All the regions, except the NE with its negative correlation coefficient, show a tendency of a lower CF for large dams. The figure 4 shows the regional data set.

**Figure 3 Correlation Power capacity vs Capacity factor in SHPPs and WPPs**



Consider the evidence: in N and WC regions the plants have  $CF_{avg}$  greater than those found in other regions (especially S and SE). Environmental resistance is likely to cause a tendency to reduce the growth of “possible” assured energy. That will cause more dispatch of thermal (TPP) in drought years. Ironically, this observation implies that protecting the environment associated with minor flooded areas requires the use the TPP more often, with the associated burning of fossil fuels.

**Figure 4 - Correlation of HPP Power capacity vs Capacity factor in different regions**



This point is corroborated by the fact that the SE region has the weakest correlation studied, probably because most of the dams in this region were constructed in the 60's and 70's, when there were few environmental restrictions. Thus, Brazil is using and is planning to use natural resources (water flows) to obtain less electricity than is technically possible. In periods accompanied by an unfavorable rainy season, the additional dispatch from TPP could be very costly. For instance, the additional cost for TPPs for security reasons in an unfavorable year (like 2012 or forecast for 2013) is approximately \$2 billion/year (Canal Energia, 2013). Also, the emissions of GHGs increase with greater TPP operation. As indicated in Brazilian statistics, emissions more than doubled from

29,2 kg/CO<sub>2</sub> in 2011 to 64,2 kg/CO<sub>2</sub> in 2012 (MCTI, 2012). The economic benefits of giving such priority to ecological systems warrant greater attention by both researchers and policy-makers.

### 6.3 GHG emissions

Since it is difficult to monetize environmental impacts, we analysed efficient plants using a MW/mile<sup>2</sup> index (power deflated by inundated area); for instance, consider Xingó (130 MW / mi<sup>2</sup>) and Itaipu (26,8 MW /mi<sup>2</sup>). Although one cannot say that there is unanimity in this opinion, the literature indicates,, that emissions of HPPs are significantly lower than TPPs (Santos, 2000 and 2008; Tremblay, 2005; Rosa, 2006; Kosnick, 2008; Barros, 2011; Saidur, 2011 and Sale, 2012). Also, the Methodologies established by the CDM-UNFCCC board, for eligibility for carbon credits projects determined that a HPP project must have a power density index greater than 10,4 MW/mi<sup>2</sup> (UNFCCC, 2012). Alternatively, the unit can be a run of river plant project. In addition, for a HPP from refurbished power, only the added capacity receives carbon credits.

**Table 8 GHG emissions in selected HPP and their equivalency in TPP emissions CT/year**

<b>Power plant</b>	<b>HPP</b>	<b>TPP Coal</b>	<b>TPP Diesel</b>	<b>TPP NG Simple cycle</b>	<b>TPP NG combined cycle</b>
<b>Tucuruí</b>	2.602.945	4.661.873	4.501.659	4.330.284	2.598.170
<b>Samuel</b>	535.407	237.492	229.330	220.599	1.323.360
<b>Xingó</b>	41.668	3.298.495	3.185.136	3.063.880	1.838.328
<b>Serra da Mesa</b>	895.373	1.401.860	1.353.683	1.302.149	781.289

<b>Três Marias</b>	540.335	435.401	420.438	404.432	242.659
<b>Miranda</b>	38.332	428.804	414.068	398.304	238.983
<b>Barra Bonita</b>	137.341	156.105	149.447	143.757	86.254
<b>Itaipu</b>	93.269	13.853.680	13.973.602	12.868.830	7.720.978
<b>Segredo</b>	23.497	1.385.368	1.337.757	1.286.830	772.098
<b>Sum</b>	4.908.166	25.857.739	24.969.088	24.018.532	14.411.119

**Source: Rosa, 2006**

Favorable results for HPP emissions are also reported by Tremblay (2005). Other authors present quite favorable evaluations of HPPs; they consider this type technology to have zero or relatively low emissions. (Kosnick, 2008, Saidur, 2011, Sale, 2012, and Ometto et al., 2013). These impacts should also include the downstream effects of dams. For a study of the Amazon region, see Manyari and Carvalho (2007).

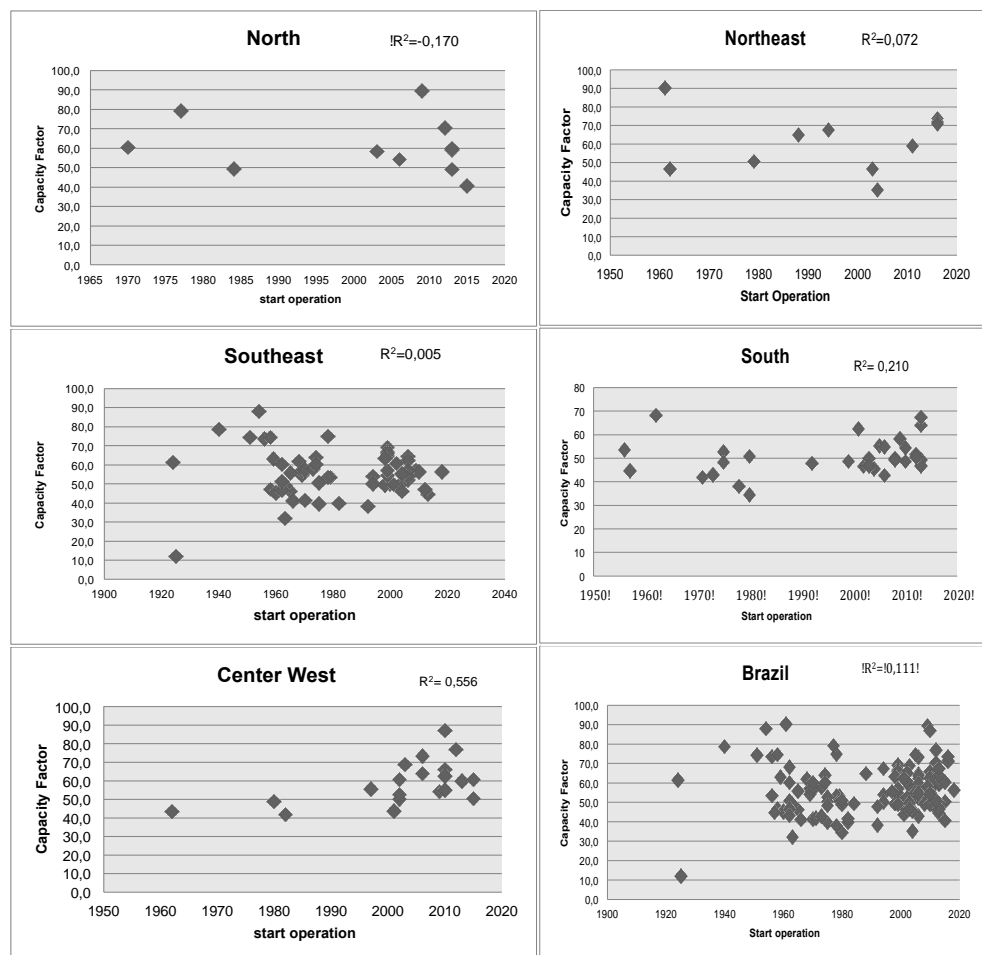
#### **6.4 Statistics**

There is minimal regional variation for the standard deviation of the CFs, when comparing one technology and a representative set for all Brazil. The smallest standard deviations were found in  $CF_{avg}$  from WPP. The figures show that almost all wind plants have their installed capacity between 20 and 30 MW (64.1% of observations) and about a quarter of the projects have exactly 30MW (24.9%). This concentration of size and standardization of power plants inevitably leads to smaller deviations from CF. It is worth noting that this phenomenon stems from incentives for renewable energy production, limited to wind power plants with 30MW or less. It is not uncommon to have enterprises

registered under different names and with different corporate constitutions, but with the same owners or investors, separated by a physical division (often only a fence) to achieve the benefits (subsidies) from such public policy incentives.

For the hydropower alternative, the study investigated whether the older projects had a higher CF due to a greater leniency for granting environmental licenses in the past. We could not find any correlation between the CF and the year in which operation of the HPP began<sup>4</sup>. Figure 5 shows the poor support for this hypothesis for different regions and for whole country as a whole.

**Figure 5- Correlation CF and year of starting operation of HPPs**



In addition, we investigated similarities among the different regions using the CF metric. For this we used the Student hypothesis test for two means.

We tested the hypothesis of similar patterns in relation to the capacity factor for different regions. When applying the Student t test for two means, the results indicated that only the South has a different pattern from the rest of the country. On the other hand, the pattern for the different regions and with the set of HPPs in Brazil can be considered homogeneous (with the hypothesis accepted with 95% confidence. Table 9 presents these results, showing that there are no significant differences among the CFs of hydros in Brazil--with the exception of the south.

**Table 9 – Matrix of hypothesis-testing results**

<b>Region</b>	<b>Brazil</b>	<b>S</b>	<b>SE</b>	<b>WC</b>	<b>NE</b>	<b>N</b>
<b>Brazil</b>	xx	Rejected	Accepted	Accepted	Accepted	Accepted
<b>S</b>	Rejected	xx	Rejected	Rejected	Rejected	Rejected
<b>SE</b>	Accepted	Rejected	xx	Accepted	Accepted	Accepted
<b>WC</b>	Accepted	Rejected	Accepted	xx	Accepted	Accepted
<b>NE</b>	Accepted	Rejected	Accepted	Accepted	xx	Accepted
<b>N</b>	Accepted	Rejected	Accepted	Accepted	Accepted	xx

The different pattern in South could be explained by small reservoirs. In this region there are few examples of large Hydros with Clean Development Projects CDM, that UN CDM Board accepted to allow carbon credits, justified by higher ratio power capacity/ flood area. For instance, see the details for the CERAN plants in Table 10: all of them were allowed to receive carbon credits.

**Table 10 – Ratio of (power capacity/ flood area) in South projects of large HPP with UN CDM approval**

HPP	Capacity MW	MW/mi <sup>2</sup>
Monte Claro	130	238
Castro Alves	130	67
14 de julho	100	41
Brazilian Average		5,3

**Source: Ceran, 2013; EPE, 2012**

Furthermore, we also tested the hypothesis of similar CFs among the hydroelectric and thermoelectric plants, which was accepted with 95% confidence. This conclusion only is applicable to the Brazilian framework, since most of the thermal plants considered in the study have the role of supplying reserve energy for the interconnected system, when it has low stream flow or when the ISO has a strategy to preserve storage water in reservoirs.

#### **6.4 Wind Power Plants**

The WPPs are a major point of discussion in the definition of CF reference to Brazil. Since they represent the technology with the greatest reduction in investment costs, they are experiencing rapid market expansion. In addition, citizens have high expectations regarding their low environmental impact as an alternative to "replacement" of HPPs in the energy matrix Brazil.

A program to encourage energy from alternative sources, PROINFA, was created by law in 2002, but implemented only from 2005. The program remunerates the electricity from WPPs contracted under these incentive conditions to R\$ 292.25 / MWh, prices valid for year 2011 (Annual Plan PROINFA, 2012). To see the extent of the implicit subsidy, consider an auction

for new electricity supply, the WPPs in December 2012. These resulted in contract prices for delivery from 2017 quoted at about one-third this number: R\$ 87.94/ MWh (Acende Brasil, 2012).

The WPP participation in the expansion of the system is rapidly expanding. In January 2013, Brazil had 1.888,38 MW in operation, however the electricity regulator has already approved projects with an amount of 7.719,60 MW of assured energy. In addition, there exists a portfolio of plants able to participate in future auctions: about 600 projects whose total power exceeds 16.000 MW. Of these, 450 projects are located in the Northeast, totaling approximately 12.000 MW and 150 projects are in the South with approximately 4.300 MW (EPE, 2013).

It should be noted that whenever there are environmental issues associated with electricity generation, the opponents of traditional sources call for more renewable energy and environmentally friendly projects. WPP is the benchmark of the alternatives considered acceptable by the opponents of hydro. For these reasons it is noteworthy that in the 301 WPPS here studied, the officially designated  $CF_{avg}$  is of the order of 43%. However, the literature identifies a much lower number for CF metrics. For example, the US Department of Energy estimates that only by 2030, the expected CF will be approximately 46% for tall towers in *prime locations* (EIA, 2009). Donn (2011) has even lower numbers, on the order of 20%; the Wind Energy Center at the University of Massachusetts estimates a range of between 20-40% (2013).

In a recent comprehensive study, Boccard (2009) identified the performance of wind power  $CF_{avg}$  in different regions of the world: all of them were found to have lower performance than the ones expected in the Brazilian

WPPs. Table 11 reproduces the information contained in the article "Estimates Capacity factor of wind power vs. Realized values "(Boccard, 2009).

**Table 11 Average Capacity Factor of WPPs 2003-2007**

Country/ State	Capacity Factor %
European Community	20,8
Germany	18,3
Austria	20,1
Belgium	20,0
California (US)	22,4
Denmark	22,8
Spain	24,8
USA	25,7
Finland	21,8
France	22,3
Greece	29,3
Netherlands	21,5
Italy	19,1
Portugal	22,7
Poland	25,9
United Kingdom	26,1
Republic of Ireland	29,3
Switzerland	21,7

**Source: Boccard, 2009**

## 7. Economic sensitivity test

In order to understand the influence of CF on economical viability, we consider a specific example of a hypothetical hydro with 100 MW of total capacity. We varied the cost of investment from \$ 1.000/kW to \$1.500/kW and the CF from 0,30 to 0,60. The price of electricity was defined in \$ 45/MWh in line with the last hydro auctions in Brazil. In this study it was assumed that average inflation is 5% per year. After the fifth year (construction period) the price is adjusted annually by the cumulative inflation index.

The interest rate used in this study was 10 and 12% a year (nominal rates, for inflation around 5% a year). The NPV in this study was calculated for the first 15 years of operation, although the concession period is 30 years with a possible renewal for another 20 years. The results are shown in table 12.

As is easy to see, even for a high cost investment, hydros with CF greater than 40% are very competitive projects. The numbers indicates the reasonableness of Brazilian Planning that gives priority to hydroelectric projects.

**Table 12- NPV in \$ Millions- Hydro Option**

Investment \$ Millions	Interest rate (%)	CF 30 %	CF 35 %	CF 40%	CF 45%	CF 50 %	CF 55%	CF 60 %
100	10	22,4	38,1	53,8	69,5	85,2	100,9	116,6
	12	8,4	21,1	33,7	46,4	59	71,6	82,3
125	10	4,5	20,2	35,9	51,6	67,3	82,9	98,6
	12	(8,5)	4,2	16,8	29,5	42,1	54,8	67,4
150	10	(13,5)	2,2	17,9	33,6	49,3	65	80,7
	12	(25,3)	(12,7)	0,1	12,6	25,3	37,9	50,6

To value the option for WPP, we chose a hypothetical wind plant of 30 MW, with CF varying from 30% to 45% and with investment costs from \$ 1.500/kW to \$ 2.000/kW. In the same way, the price was referenced to real auctions, about \$50/MWh. We define that the construction period to be only 2 years, and only the first 15 years of operation were considered in financial valuation. All the assumptions about inflation, interest rates, and other considerations remain the same as used in the hydro analysis. The results are presented in Table 13.

**Table 13- NPV in \$ Millions- WPP option**

Investment \$ Millions	Interest rate (% year)	CF 30 %	CF 35 %	CF 40%	CF 45%
45	10	(3,0)	3,1	9,1	15,1
	12	(7,3)	(2,2)	2,9	8,0
50	10	(7,3)	(1,3)	4,7	10,7
	12	(11,6)	(6,4)	(1,3)	3,8
60	10	(16,0)	(10,0)	(4,0)	2,1
	12	(20,0)	(14,9)	(9,8)	(4,7)

The figures in this analysis indicate that the WPP solution is much more sensitive to investment cost and needs high CFs to be feasible, at least in terms of the prices that have emerged in recent Brazilian auctions.<sup>2</sup> These results

<sup>2</sup> The sensitivity of the cost effectiveness of wind to CF is implicit in the cost calculations performed by Ohunakin and Akinnawonu (2012) for Jos, Plateau State, Nigeria. They use 29% and 38.3% for capacity factors.

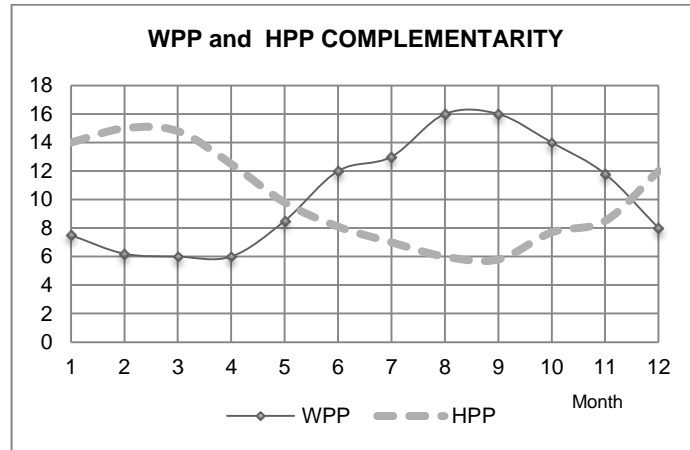
underscore the concern discussed in the previous section: given the limited experience in establishing likely CFs, developers of wind projects may have financial difficulties in the future. We shall see whether the WPPs already "sold" perform as officially predicted. As noted in previous sections, even if the CFs of wind plants are overestimates, they are lower than the similar parameter in HPPs, so the wind alternative is expected to be less profitable (depending on trends in investment costs) and more risky than the HPPs.

Joskow (2010) recently examined the issue regarding intermittent supply, arguing that when making a comparison between wind and other hourly intermittent sources of electricity, intermittent electricity may be computed to have comparable levelized costs as a dispatchable technology. The calculated levelized cost might then be utilized in a competitive bid to supply energy for long run; however, such a procedure is inappropriate. The technologies have different net incomes and potentially greater risks (calling for higher discount rates) due to the timing of production (and associated value of the output at different times of the day). On the other hand, one advantage of WPPs is their modularity and time-to-construction (although location and interconnection to transmission needs to be included in the analysis). Note that the intermittency for hydroelectric is more likely to be seasonal or drought-driven, while for WPPs, the intermittency is hourly or driven by local daily weather patterns.

Fortunately, in Brazil there exists a complementarity in the wind and hydrological regimes, so decision-makers could possibly reduce risk by using a Markowitz portfolio of assets as suggest by Ramos (2010). Figure 6 shows the schematic complementarity of WPP and HPP over time. This would be a favorable result. However this complementarity should be further investigated,

because characteristics of the wind regime still lack a strong statistical basis in Brazil (Denault et al., 2009).

**Figure 6- Complementary WPP and HPP over time (schematic)**



**Source: Ramos (2010)**

## 8. Policy Implications

This study addresses the concern that hydroelectric plants have substantially lower capacity factors than other technologies. It turns out that this concern is baseless, even when the thermal units are included in the mix. Although the TPPs have the potential for higher CF, sometimes up to their nameplate or nominal power, this has not been observed in Brazil. The main reasons are the secondary role of this technology used more often as "reserve power" (backup) instead a dispatch base load model or due to restrictions regarding fuel availability by contract, especially natural gas.

The effectiveness of HPPs, as measured by CFs in all the regions in Brazil, has statistically the same pattern, except the S region. The CFs of new projects are similar to those built when there were lower environmental hurdles and mitigation requirements.

For large power plants yet to be constructed, environmental restrictions are changing the projects to run-of-river option as the only possible alternative. So there is a reduction in water storage capacity during hydrologically unfavorable periods, as evidenced in the analysis of the correlation between size and CF; the relationship even could be negative, as shown by the HPPs in N region. The negative correlation indicates that, as much larger the HPP will be, as much lower will be their CF, compared with the situation without environmental restrictions related with the flood area. This outcome could be further exacerbated, since for large dams public opinion normally is concerned about environmental and social impacts of large construction projects and their subsequent operation. Thus, the new projects (with their effectiveness reduced) will result in an increase in the construction of new thermal plants (to meet reliability constraints), which brings its own set of environmental damages (fossil fuel emissions).

The wind technology in Brazil has shown very favorable conditions for its expansion: great potential under exploration and significantly falling prices for equipment. However, the industry lacks experience and reliable data for projects; this seems to have led to overestimations of expected CFs in comparison with international experience. There is evidence that the risk of wind power plants could be reduced by diversification assets strategy: in the future this complementarity could replace the back up of TPP, even in a partial way—leading to environmental benefits (reduced CO<sub>2</sub> emissions).<sup>3</sup>

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<sup>3</sup> Parthan, et. al. (2010) emphasize the importance of governance, careful analysis of business models, and capacity building when identifying and implementing projects that promote a low-carbon energy transition.

Note that the lack of CF variance for wind farms studied is affected by regulatory rules that set limits for plant sizes, otherwise the owners lose financial incentives: they utilize artificial boundaries to achieve an optimal regulatory (but not physical) configuration. Thus, the projects appear to have a uniformity that is somewhat artificial. This effect, probably a bad one, limits the use of real potential of wind farm site. Currently, all the new projects start with a precondition: it “*must be lower than 30MW . . .*”

This study counters the criticism of lack of hydropower effectiveness in production (measured by CFs) for Brazilian dams. It appears that the Brazilian government has a realistic basis for giving priority to the nation’s hydrological potential, while addressing social and environmental impacts. Although the Brazilian energy planners are aware of the convenience of hydropower in its supply matrix, there remains a serious lack of comparative evaluation of the environmental impacts of large reservoirs. After all, restrictions on reservoirs lead to the need for more thermal power plants as reserve capacity, with their associated environmental impacts, as well as effects on electricity prices.

Currently, the option to build hydropower with reservoirs is unavailable, so the new and large Northern HPPs projects will have their output limited. Finally, we conclude, that in the context of environmental decision-making, the thermal and wind options will remain even more important as complementary technologies to address adverse hydrological conditions in the hydropower network in Brazil.

Thus, as Berube and Villeneuve (2002) note, given the ethical principles of stewardship, participatory decision-making, prudence and control, fairness and justice, and optimality, the future of hydro in Brazil involves balancing citizen

concerns when choosing technologies. The issue of mitigating social and environmental impacts remains—which places a priority on research that can place reasonable monetary values on these impacts, so they can be incorporated into a comprehensive net present value analysis when policy-makers compare alternative projects and technologies.

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## **End Notes**

1. NGOs include the Movement of Impacted People for Dams (MAB). Celebrities include James Cameron, Arnold Schwarzenegger (Amazon Watch, 2011), and Susan Sarandon, to name a few.

2. For instance a plant could retain water in anticipation of higher prices in the future, damaging the dispatch of power plants located downstream.

3. EPE is the division of the Ministry of Energy in Brazil in charge of planning to address energy issues. For more on the role of sector regulator in promoting renewable energy, see [www.regulationbodyofknowledge.org](http://www.regulationbodyofknowledge.org).

4. For plants yet to be built, the year considered is the planned starting date for operation to begin.