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Low Hydrology Scenario
for the Brazilian Power Sector 2016–2030

Impact of Climate on Greenhouse Gas Emissions

Executive Summary

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1st Edition

PREPARED BY PSR CONSULTORIA FOR THE WORLD BANK

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Summary

DEIXAR UMA PÁGINA EM BRANCO PARA INCLUIR DISCLAIMER, DIREITOS AUTORAIS E INFORMAÇÕES DE ISBN

PREFACE

Publication of the study “Low Hydrology Scenario for the Brazilian Power Sector 2016-2030 - the Impact of Climate on Greenhouse Gas Emissions” represents a milestone in cooperation between the World Bank and the Ministry of Environment, in the studies that provided the technical basis for the elaboration of Brazil´s Intended Nationally Determined Contribution (iNDC), and in the context of the Paris Agreement negotiations.

For a precise analysis of greenhouse gas emissions scenarios covering the period 2020-2025 to reflect Brazil´s determined contribution or, more importantly, the longer period 2020-2030 mirroring the Brazilian indicative contribution up to 2030, it was essential to analyze the low hydrology scenario in the light of the potential impact of climate change on it over the longer term. It was also important to examine the options to mitigate probable adverse effects. These options might involve the increased use of thermoelectric plants in the power matrix, with a consequent increase in the country´s GHG emissions. Low hydrology could therefore make it difficult for Brazil to implement its ambitious iNDC, announced at the UN General Assembly in New York in September 2015 in the run-up to the Paris Agreement.

The main source of electricity generation in Brazil is hydroelectricity, which accounts for 64.7% of installed capacity, and is responsible for supplying over 80% of the country´s electricity in hydrologically normal years, and 60% in unfavorable years. The supply of renewable energy from hydropower sources, together with biofuels - especially sugarcane by-products - accounts for around 42% of the Brazilian energy matrix. This percentage qualifies Brazil as a low-emission energy source country, particularly when compared to the world average (13%) or that of the OECD countries (7%). It is clear that no discussion of a long-term Brazilian emissions scenario would be feasible without a detailed technical study of a low hydrology scenario for the electricity sector.

With the immediate and effective assistance from the World Bank within the framework of the *Partnership for Market Readiness (PMR)*, it was possible to enlist the support of PSR, a distinguished consulting firm with extensive experience in the study of the Brazilian electric power sector. As a result, we benefited from first-class technical support that enabled Brazil´s iNDC (known as NDC after the Paris Agreement entered into force in November 2016) to be recognized nationally and internationally as one of the most ambitious contributions for achieving the Agreement´s objectives: to limit the increase in the average global temperature by a maximum of 2 degrees Celsius in relation to the pre-industrial era, and to make efforts to ensure that temperatures increase by no more than 1.5 degrees Celsius. We hope that this innovative study, now edited and also available in English, will help practitioners and others in the water, energy and agriculture sectors in Brazil and elsewhere to be increasingly aware of the risk associated with climate change, in particular with regard to its impact on emissions in these sectors.

The Ministry of Environment is proud to have contributed to this study and wishes to record its thanks and appreciation to our partner, the World Bank, for the excellent work which led to the publication of the study.

By engaging in the responsible technical debate on the future of Brazil's greenhouse gas emissions, and consolidating Brazil´s leading role in combating global climate change - especially by working hard towards a low gas emissions future - we hope to continue making a creative and practical contribution to building a better future for all.

EVERTON LUCERO
Secretary for Climate Change and Forests
Ministry of the Environment

ACKNOWLEDGEMENTS

This report, under the direction of Christophe de Gouvello, senior energy specialist and coordinator of the World Bank's climate change agenda, together with Thadeu Abicalil, senior water and sanitation specialist, was prepared at the request of the Secretariat for Climate Change and Forests (SEMCF) of Brazil´s Ministry of the Environment by a PSR Consultoria team comprising Rafael Kelman (coordinator), Pedro Avila, Bernardo Bezerra and Ana Carolina Deveza. Jose Domingos Gonzalez Miguez and Adriano Santhiago de Oliveiro coordinated SEMCF oversight. Special thanks are due to Newton Paciornik for his contribution to the technical review of the intermediate documents.

The World Bank and the Secretariat for Climate Change jointly organized a number of in-house seminars which provided an opportunity for Brazilian and other experts to discuss methodology and preliminary results.

Under the leadership of Antônio Barbalho, Director of the World Bank's Energy Sector for Latin America, the report received contributions from World Bank reviewers Erwin de Nys, senior water and sanitation specialist and program coordinator, Rikard Liden, senior specialist in hydroelectricity, and Thierry David, senior specialist in water resources management. Thanks are also due to the administrative support team at the World Bank office in Brasilia, in particular to Zélia Brandt de Oliveira and Victor Neves.

This work was carried out with the support of the Partnership for Market Readiness (PMR) program of the World Bank's Climate Change Cross-Cutting Solution Area involving three World Bank areas: the Energy Sector, the Water and Sanitation Sector and the Climate Change Area.

The authors are also grateful to the organizations and entities which generously shared their knowledge and impressions during the preparation of this study. Errors or omissions are the sole responsibility of the authors.

GENERAL OBJECTIVE AND METHODOLOGY

Hydropower is the main source of electricity in Brazil is hydroelectricity. In 2016 it represents 65% of the installed capacity and is responsible for the largest share of Brazil´s electricity market, supplying more than 80% of the country´s electricity in normal hydrological years and 60% in dry years. Environmental constraints related to the construction of new hydro power plants have had the following interrelated effects:

- A reduction of the energy storage capacity with respect to the electricity consumption due to the trend, over the last 20 years, of the construction of run-of-the-river plants, with limited and no ability to regulate water inflows;
- As a consequence, more thermal power plants were built in order to offset the seasonal and intermittent supply of hydroelectricity and that produced by renewable sources, such as wind power and sugar cane biomass;
- The trend of reducing the regulation of water inflows through hydropower plants with reservoirs also increases the vulnerability of the power system to climatic variations.

In parallel, early studies aimed at simulating the impact of climate change on hydrology in Brazil have pointed to the possibility of significant alteration of precipitations, which could reduce the availability of water inflows for hydropower generation in the next decades[1].

This study, prepared for the World Bank and the Ministry of Environment (MMA) in the context of the *Partnership for Market Readiness* (PMR) aims to provide some understanding of the consequences for the Brazilian power sector in a low hydrology scenario on horizon 2030. These consequences are important not only from the point of view of the power sector itself, but also in the context of the commitment recently made by Brazil to reduce emissions as part of the intended Nationally Determined Contributions (iNDC) presented by the government at COP21 and in the new Paris Agreement. Lower than average water inflows in recent years (2013-2014) forced more thermoelectric power plants into operation for longer periods of time, thus increasing the power sector related greenhouse gas emissions. Thus, a low hydrology scenario on horizon 2030 would contribute to the increase in Brazil´s emissions projected in this horizon in the iNDC, possibly reducing the effect of the mitigation efforts that have been implemented by the country in the electric power and other sectors.

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[1] A. Lucena et alii (2009): "The vulnerability of renewable energy to climate change in Brazil", Energy Policy, Volume 37, Issue 3, March 2009, Pages 879–889. More recently, a new, still unpublished study by the Strategic Affairs Secretariat (SAE) of the Presidency of the Republic of Brazil, conducted by researchers at the National Institute for Space Research (INPE), the Ceará Foundation for Meteorology and Water Management (FUNCENE) and the Federal University of Rio de Janeiro (COPPE-UFRJ), also points to higher risks of drier hydrology as a consequence of climate change.

Given the structure of the electricity sector matrix, it is clear that climate variations - induced or not by human activities - have an impact on Brazil´s emissions. Several studies, based on data produced by climate change simulation models, have explored the possible consequences of climate change caused by the generation of hydroelectricity in Brazil. These studies use a *down-scaling* approach that employs the results of global circulation models to generate results with higher spatial resolution. This approach can also be referred to as *top-down* (i.e. from global to local simulation). Despite the significant progress made in recent years in this area, including in Brazil with INPE´s ETA model, the results of the *down-scaling* approach still reveal substantial levels of variability and uncertainty. These results are hardly compatible with the degree of precision required by power sector studies and planning and modeling tools. For example, past series of inflows of certain basins (e.g. Sobradinho), reconstructed by *down-scaling*, indicate values that are at times significantly higher or significantly lower than the observed values, and the meaning of these variations may change when a global model is exchanged for another (e.g. the HadGEM model for the MIROC model). This scientific "gap", which still exists between global models and the fine spatial resolution of local parameters, particularly with regard to inflows at hydroelectric plants, makes it difficult for agents in the power sector to fully internalize the difference between the conventional "climate risk" and the new "climate change risk", which can in turn jeopardize future emissions projections.

In the light of the above, this study proposes a complementary approach of the *bottom-up* type, based on historical series of local observations of hydrological parameters, using, in particular, series of inflows of hydroelectric plants. We believe that this approach provides results that will assist power sector agents to more easily understand climate risk since it uses the same historical series, the same water parameters and the same modeling tools that they currently use. A key advantage is that this methodology enables the power sector to conduct sensitivity tests to climate variations, especially the dry hydrologies which could result from climate change but which would still be statistically coherent with the historical series familiar to the agents.

Using this approach, we propose to develop future hydrology scenarios by using probability distribution indicators of the Natural Affluent Energy (ENA) entering the National Interconnected System (SIN). This methodology leads to the construction of a reference scenario and assumes that future flows will repeat those of the past ('stationary inflow hypothesis'). This reasoning leads to the use of the Monte Carlo Method, according to which 200 series of synthetic inflows are generated for the 195 hydropower plants of the National System Operator (ONS) using stochastic models that ensure the statistical "similarity" of these synthetic series with observed historical inflows, retaining parameters such as mean, standard deviation, temporal and spatial correlations, and extreme values observed in the historical record. This method helps addressing the uncertainty inherent to climatic variations, as it presents probability distributions of the results rather than single values.

Furthermore, the study uses statistical criteria to define a dry hydrology subset for the period 2015-2030, and analyzes the consequences of this "dry" scenario in terms of electricity and greenhouse gas emissions.

To produce energy and emissions results linked to these hydrological scenarios, the study uses the same approaches, assumptions and tools currently used by the energy sector stakeholders such as the Energy Research Agency (EPE), the Ministry of Mines and Energy (MME) and the National System Operator (ONS), with some premises adjusted by PSR, such as delays of certain projects or data related to the end of the period under study. Demand scenarios and supply expansion plans were thus constructed both for the reference scenario, using the same assumptions of the Ten Year Energy Plan (PDE), and for the low-hydrology scenario. The optimization of system operation is done using the PSR proprietary model SDDP model, considering the ONS operating procedures for the SIN. The SDDP operative simulation model produces as a result the energy generated by each plant of the system each month, according to demand levels (e.g. peak and off-peak).

Based on this generation (MWh) and its emission factor unit (tCO_2/ MWh) of the power stations, the amount of carbon dioxide (tCO_2) emitted by the SIN each month is calculated for each hydrological scenario. Each plant´s emission factor (tCO_2 / MWh) is determined based on its efficiency (fuel consumption per MWh generated), using data published by the MME when available, fuel type and fuel emission factor (tCO_2 per fuel unit). The emission factors of the National System Operator (ONS) were calculated based on standard values published by the Ministry of Science, Technology and Innovation (MCTI).

The study then compares these results of the *bottom-up* approach with the results of the *top-down* approach, using inflow projections for the same river basins used in the down-scaling work in the Brazil 2040 study undertaken by the Strategic Affairs Secretariat (SAE) of the Presidency of the Republic. This study, conducted by researchers at the National Institute for Space Research (INPE), the Foundation Ceará Foundation for Meteorology and Water Management (FUNCENE) and COPPE-UFRJ, considered the evolution scenarios of GHG concentrations of the RCPs 8.5 and 4.5 of the 5th Report of the Intergovernmental Panel Report on Climate Change (IPCC). Based on these climate change scenario data, new energy and emission results were produced using the same power sector simulation tools used in the *bottom-up* approach.

The study also explores the power sector´s emissions mitigation alternatives that could allow the increased emissions observed in the *bottom-up* dry hydrology scenario approach to be offset.[2]

The main conclusions of the study are:

- In case of low-hydrology, the availability of hydropower generation is reduced, requiring dispatching more thermal power plants and thus increasing GHG emissions.
- Annual emissions during a dry year (around 60MtCO2) can be four time higher than in a wet year (around 15MtCO2).
- Under the Low-Hydrology scenario considered in this study, the cumulated GHG emissions of the national power system for 2016-2030 period are around twice higher than under the Reference scenario.
- The average marginal operating cost would be around twice higher under the Low-Hydrology scenario between 2017 and 2027 (above R$200/MWh) compared to the Reference scenario (around R$100/MWh).

With respect to year 2025, the year for which Brazil has set its emissions reductions target in its INDC:

- the median value of the contribution of hydropower (in energy) would decrease about 5% under the Low-Hydrology scenario compared to the Reference scenario (from 70% to 65%),
- the average value of annual emissions of the national integrated power system would increase 30% in comparison to the Reference scenario (from 31.8 MtCO2 to 41.3MtCO2).

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[2] In addition, a preliminary and exploratory work was conducted to start analyzing the potential impact of increasing competition between the different water uses, in particular in terms of water withdrawals from river basins, mainly for irrigation, in case of a low-hydrology. The results of this preliminary study are presented in a separate Appendix, which can be made available upon request : "Appendix 1: Impact of irrigation growth on GHG emissions of the power sector in case of low-hydrology in Brazil (2015-2030) – A Preliminary Analysis"

Under an Alternative scenario, energy conservation measures and increased dissemination of renewable could compensate both the increases of the MOC and the emissions observed in the Low-Hydrology scenario.

2 EXPANSION OF ELECTRICITY SUPPLY AND DEMAND

For Chapter 2 of the study, PSR developed a supply and demand expansion plan for the period 2015-2030 (reference case). The expansion plan involves extending the generation and transmission infrastructure used by the National System Operator (ONS) to cover energy planning activities over the next five years, as well adopting the assumptions contained in the Energy Research Company´s (EPE) Ten Year Plan.

The process began by defining the macroeconomic hypotheses for the system´s predicted load, including future estimated electricity losses. This was followed by an evaluation of the energy supply (existing projects) and the preparation of a long-term expansion plan, to include reserves.

Water inflow scenarios were generated to determine the Natural Affluent Energy (ENA) that could be harnessed by the available hydroelectric plants.

The next step was to conduct an energy simulation of SIN through a proprietary hydrothermal stochastic dispatch model called SDDP (*Stochastic Dual Dynamic Programming*). The main steps of this method are shown in Figure 1.

Among the large number of results produced by the SDDP model, those of particular interest to our study are power plant generation, operating costs, GHG emissions and marginal production costs. The results vary according to month and hydrological scenario.

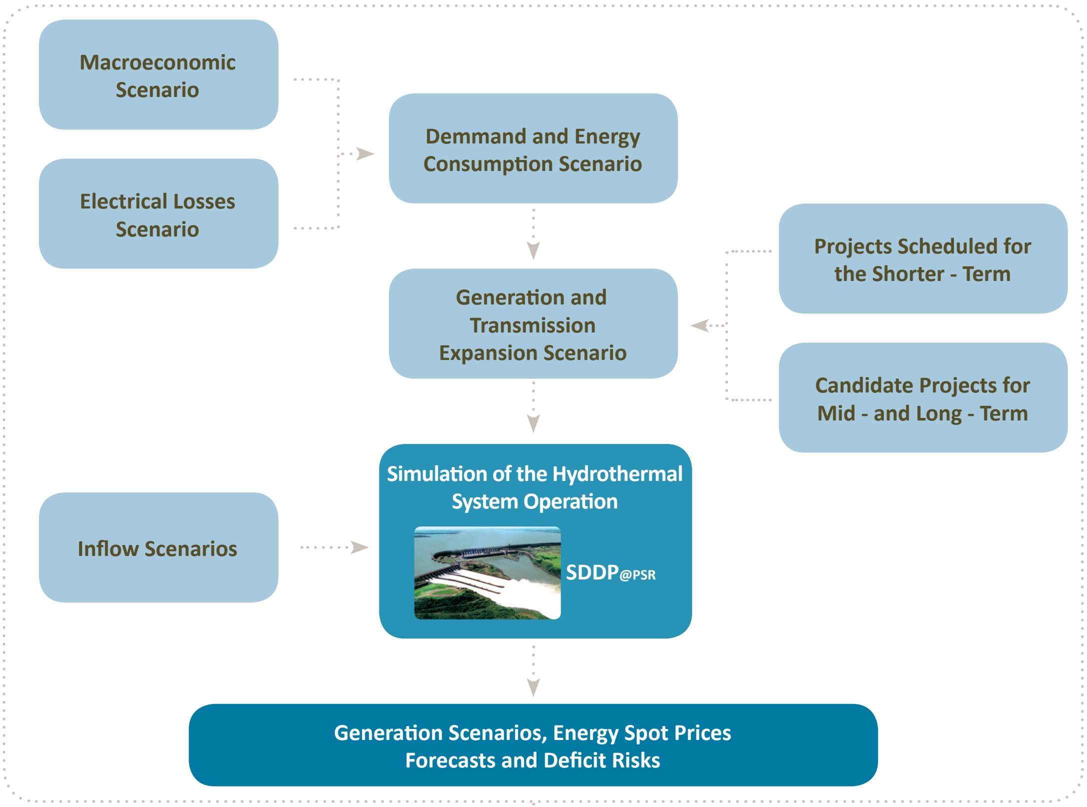


FIGURE 1 - **Overview of the methodology**

For the demand scenarios, we used short- and medium-term simulations (2015-2019) based on the ONS Monthly Operation Plan (PMO) for January 2015, and PSR assessments of construction/commissioning schedules of new electricity generating projects facing some kind of construction constraints.

For long-term simulations (2019+), the expansion is based on a mix of hydro, natural gas thermal plants and wind farms, using the following assumptions: (i) the Belo Monte hydroelectric dam complex to begin operations in October 2016; (ii) the Angra 3 nuclear plant to go into service in January 2019; (iii) all the hydroelectric plants contracted for in the auctions up to 2019 to start operating six months after the specified contract date (a usual occurrence for hydroelectric plants contracted in auctions).

Delays in the commissioning of new wind farms and gas thermal plants have not been taken into account in the study because the effects of delays are generally offset by certain contractual advantages (e.g. electricity purchased by distributors in anticipation of demand growth, which is almost always overestimated).

Power supplied by the system is in accordance with regulatory supply criteria: (i) distributors purchase contract additives at auction to counteract future demand uncertainties, and (ii) the amount of contracted reserve energy meets the reliability criteria established by the National Energy Policy Council (CNPE).

The development of hydrological inflow scenarios is a key point of the methodology, because it defines the sensitivity of the system to climatic variations, and therefore the need for thermoelectric dispatch to balance the SIN and hence the emissions of the system.

3 OPTIMIZATION OF THE HYDROTHERMAL SYSTEM OPERATION

Brazil´s National Interconnected System is heavily dependent on hydrology, which makes the optimization of hydrothermal dispatch for a single future scenario a risky strategy. If a "wet" scenario is used, optimization will involve heavier use of hydropower. However, in the event of a real-life "dry" hydrologic scenario, the system will reach a low water storage level, possibly even leading to rationing (high-risk operation planning). On the other hand, deciding based on a dry scenario means less hydropower and higher costs due to the high thermal dispatch. If in real life the hydrologic scenario is "wet", reservoirs could reach a situation of excessive storage, possibly leading to spillage (highly conservative operation planning). Figure 2 gives an idea of the operational outcomes of decisions on hydrothermal dispatch.

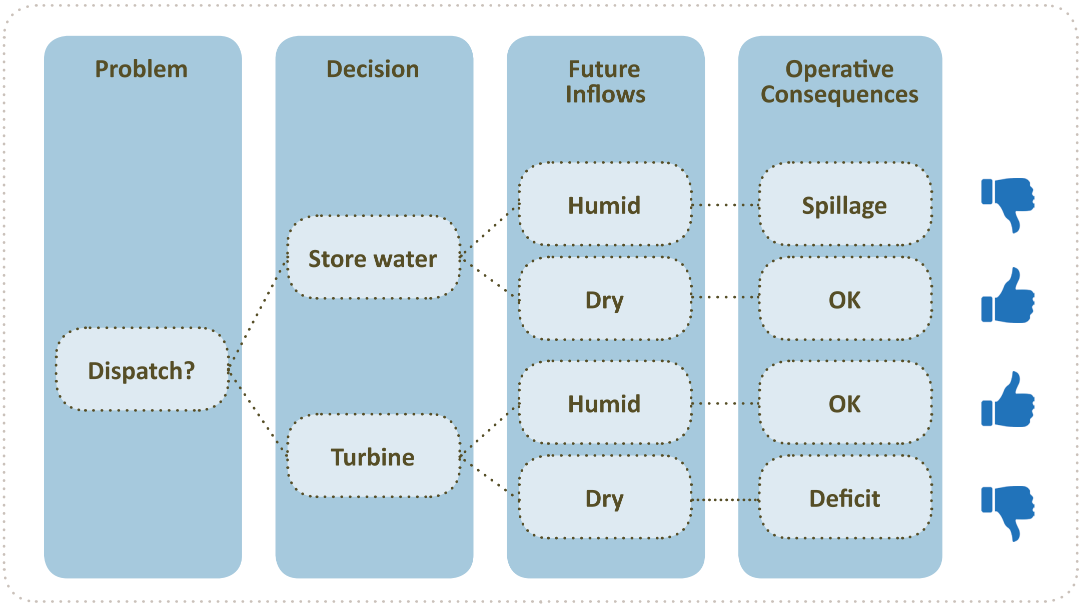


FIGURE 2 - Operational outcomes of hydrothermal dispatch decisions

It follows that an optimization model under uncertainty - specifically a stochastic model for hydrothermal dispatch - is more appropriate. This approach is based on the generation of synthetic flow series of future inflows in the 195 ONS hydroelectric plants for the planning horizon (2015-2030). For nearly four decades, synthetic hydrology has been used for the probabilistic evaluation of the energy supply in the Brazilian power sector. It is assumed that the process is stationary, which means that these series follow the same probability distribution of the historical series of past inflows, i.e. the *synthetic series* are generated by the periodic autoregressive model PAR (p) and retain the historical parameters since 1931 (mean, standard deviation, temporal and spatial correlations). The main reason is that the *historical series* is only one of the possible outcomes of a stochastic process, as if nature had randomly picked the time series according to some set of probabilistic laws, with a random component producing a different but equally probable series. This reasoning leads to the use of the Monte Carlo Method, according to which the PAR (p) model is used to generate *200 synthetic series* of inflows for each hydro plant. The optimization of the system operation for the 2015-2030 horizon is then done using the SDDP model, considering ONS operating procedures for the National Interconnected System (SIN).

Figure 3 shows the process used.

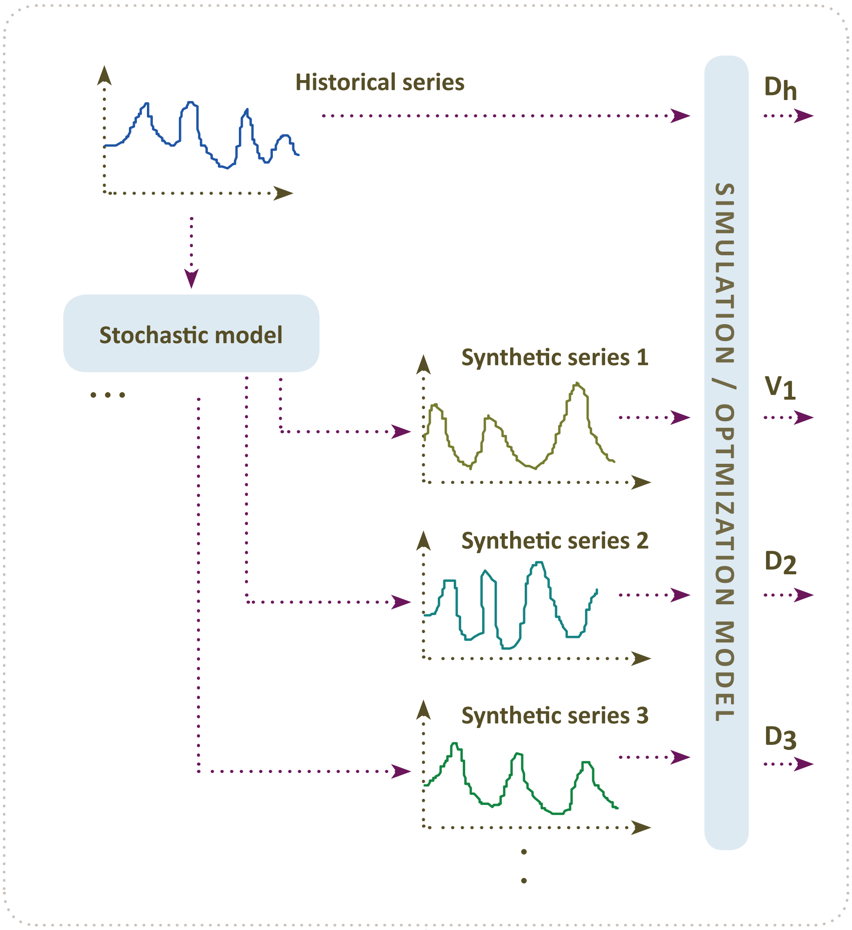


FIGURE 3 - **Modeling synthetic inflows using stochastic model**

Figure 4 shows 200 scenarios of ENA produced by the PAR (p) model for the first month of the planning horizon (January 2015) conditioned to the first year (TWh).

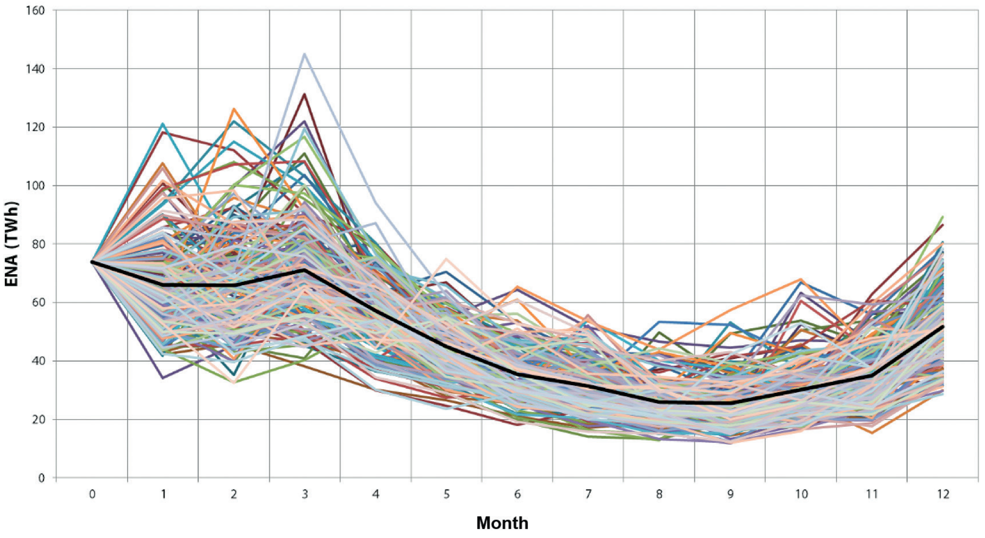


FIGURE 4 - Variability of ENAs generated by hydrological scenarios of the PAR (p) model

Figure 5 illustrates the ENA probability distribution of the entire system in the period 2015-2030, i.e. the sum of ENAs during the 192-month period, with values ranging from 11,000 to 14,000 TWh, with the average value being 12,378 TWh.

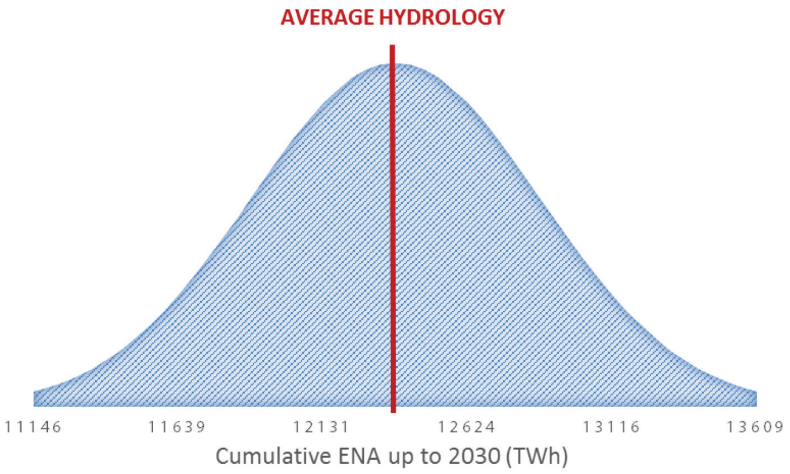


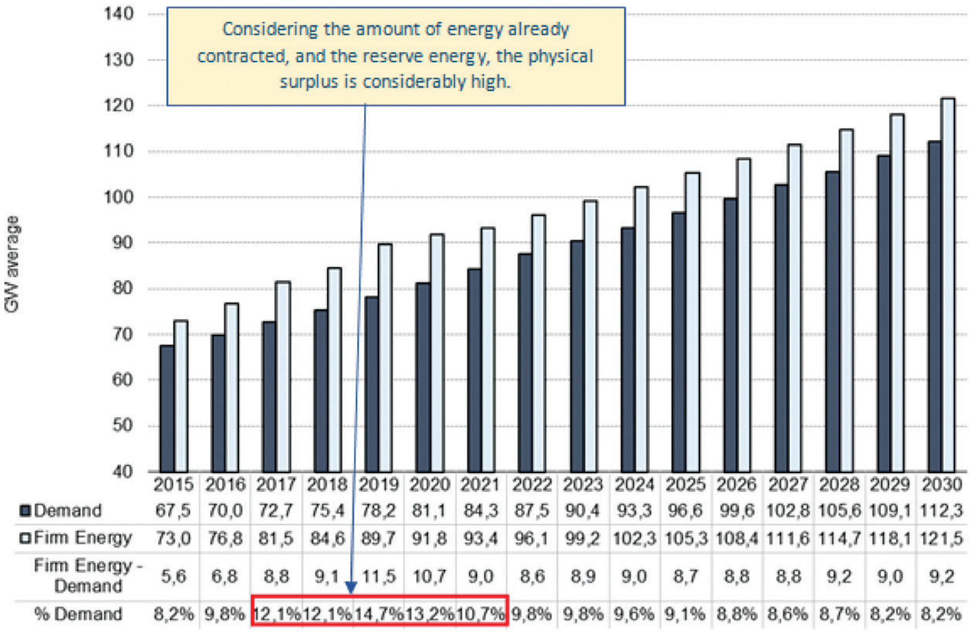
FIGURE 5 - Definition of average hydrology

Based on the execution made with SDDP, it is possible to relate each of the two hundred scenarios of Natural Affluent Energy (ENA) to output results such as Marginal Operating Cost (MOC) and GHG emissions. The values can then be presented over the entire period for the 200 hydrological scenarios. These results are shown below.

4 ANALYSIS OF THE REFERENCE CASE

In Chapter 3 we present the average results of the reference case, obtained from the simulation of the SIN operation, for the hydrology statistical series (without the abovementioned climate change assumptions).

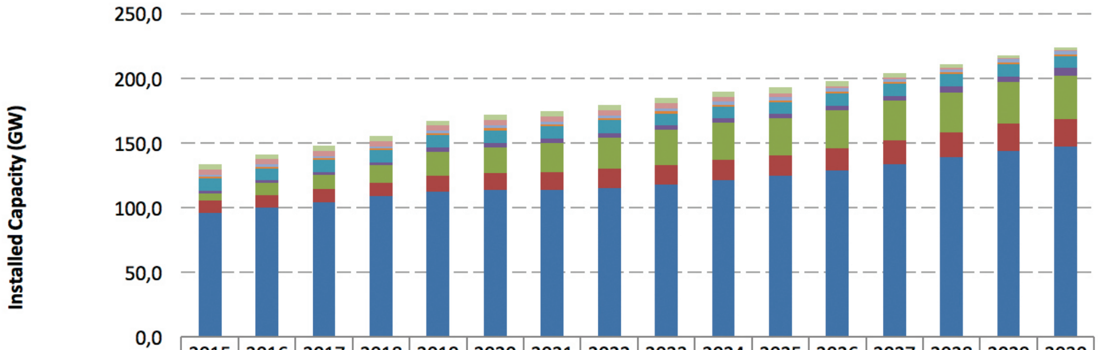
It can be seen that over-supply in the system in short and medium term horizon (up to 2019) increases as the result of the low demand growth forecast over the 2015-2019 horizon and the implementation of the major hydroelectric projects that have already been contracted. On the longer term horizon, the oversupply tends to remain at around 8-9% of demand (2% without reserve power).



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
■ Demand	67,5	70,0	72,7	75,4	78,2	81,1	84,3	87,5	90,4	93,3	96,6	99,6	102,8	105,6	109,1	112,3
□ Firm Energy	73,0	76,8	81,5	84,6	89,7	91,8	93,4	96,1	99,2	102,3	105,3	108,4	111,6	114,7	118,1	121,5
Firm Energy - Demand	5,6	6,8	8,8	9,1	11,5	10,7	9,0	8,6	8,9	9,0	8,7	8,8	8,8	9,2	9,0	9,2
% Demand	8,2%	9,8%	12,1%	12,1%	14,7%	13,2%	10,7%	9,8%	9,8%	9,6%	9,1%	8,8%	8,6%	8,7%	8,2%	8,2%

FIGURE 6 - Physical balance of average annual supply and demand with reserve energy

Figure 7 shows the supply of energy in terms of installed capacity, by different sources.



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
🟩 Others	3,7	3,7	3,7	3,7	3,7	3,7	3,7	3,7	3,7	3,7	4,3	4,1	3,6	3,1	2,4	1,9
🟥 Diesel/ fuel oil	4,4	4,1	4,1	4,1	4,1	4,1	4,1	4,1	4,1	3,7	3,0	1,5	1,3	0,9	0,9	0,9
🟦 National coal	1,4	1,5	1,5	1,5	1,7	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3
🟧 Imported coal	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4
🟦 Biomass	9,3	9,4	9,5	9,6	9,9	10,2	9,6	9,9	9,4	9,4	9,4	9,4	9,4	9,4	9,4	9,4
🟪 Nuclear	2,0	2,0	2,0	2,0	3,4	3,4	3,4	3,4	3,4	3,4	3,4	3,4	3,4	4,6	4,6	5,8
🟩 Wind	5,6	9,1	11,0	13,6	18,4	19,7	22,3	24,5	27,3	28,4	28,4	29,9	30,7	30,7	32,2	33,7
🟥 Natural Gas	9,5	10,1	10,6	10,6	11,8	13,1	14,0	14,9	15,3	15,8	16,1	17,2	18,8	19,6	20,8	21,4
🟦 Hydro	95,7	99,6	103,8	108,5	112,4	113,3	113,3	114,7	117,3	121,0	124,2	128,2	133,1	138,7	143,7	146,7

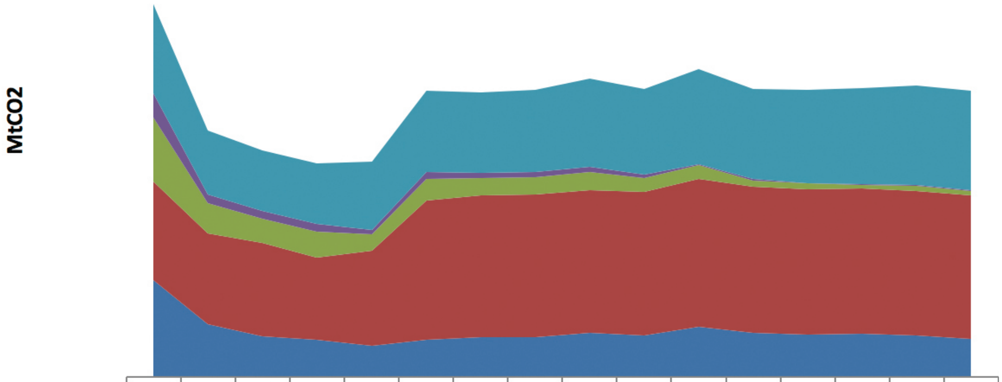
FIGURE 7 - Evolution of generating capacity by source (absolute values)

The Marginal Operating Costs (MOC) are higher for the initial years (around R$470/MWh for 2015 and R$225/MWh for 2016) as the result of the low inflows of 2013 and 2014 and structural problems. From 2017 onwards, the MOC are lower because behind-schedule plants and new contracted supply have been included in the simulation timeframe. From 2019 to 2023, the average MOC is 120R$/MWh, increasing to 140 R$ / MWh over the longer term.

Figure 8 shows the evolution of average annual emissions over the planning horizon. For 2017-2019, GHG emissions decline relative to 2015 due to more hydropower energy entering the grid and the expectation of improved hydrological conditions.

This is due to the fact that coming years are not expected to be as dry as the 2012-2015 period: the average projections resulting from the Monte Carlo simulations indicate an improvement of hydrology comparatively to previous years. In addition, new hydropower plants are planned to start generating in this period.

The decommissioning of oil-burning thermal plants reduces maximum annual emissions, but does not modify average values, given the low dispatch factors of these plants.



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
🟦 Natural gas	9,2	6,6	6,3	6,2	7,0	8,4	8,3	8,4	9,1	8,8	9,8	9,3	9,6	9,9	10,3	10,3
🟪 Diesel	2,4	0,9	0,8	0,8	0,5	0,7	0,5	0,6	0,6	0,3	0,1	0,1	0,1	0,1	0,1	0,1
🟩 Oil	6,7	3,1	2,5	2,7	1,6	2,3	1,8	1,8	1,8	1,4	1,4	0,7	0,6	0,4	0,5	0,5
🟥 National coal	10,1	9,3	9,6	8,5	9,9	14,4	14,6	14,7	14,8	14,9	15,3	15,1	15,0	15,0	14,9	14,8
🟦 Imported coal	10,0	5,5	4,2	3,9	3,2	3,8	4,1	4,1	4,5	4,3	5,1	4,5	4,4	4,5	4,3	3,9
TOTAL	38,4	25,4	23,4	22,0	22,2	29,5	29,4	29,6	30,8	29,7	31,8	29,7	29,7	29,8	30,1	29,6

FIGURE 8 - **Average annual emissions by source for the reference case**

Figure 9 shows the probability density function of the annual emissions in selected years. It should be noted that 2015 is an atypical year, since many of the thermal power plants will be connected for most of the time. The probability distribution is subject to this short-term situation. A reduction is expected in subsequent years due to the rebalancing of supply and demand which will lead to an average reduction in emissions. There is however a small increase between 2020 and 2030 caused by the anticipated increase of fossil fuel thermal generation in the energy matrix.

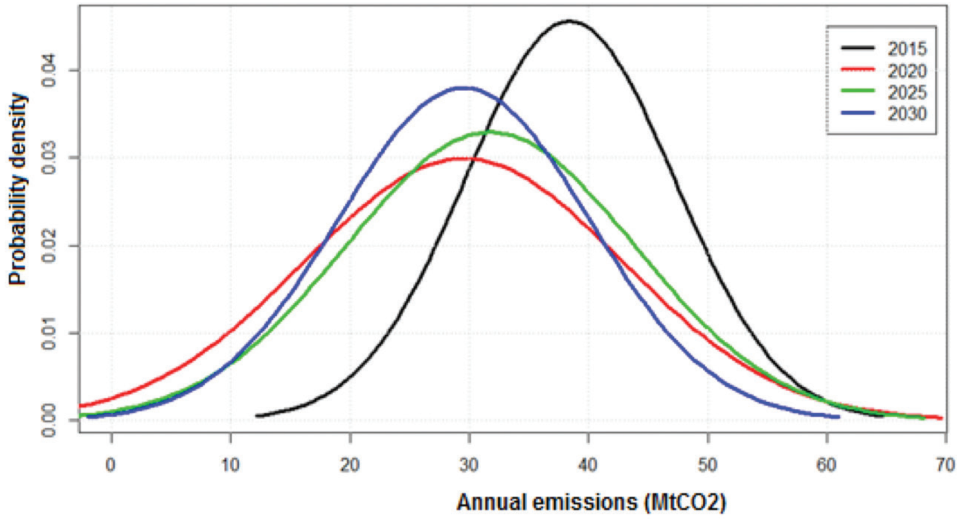


FIGURE 9 - **Probability density function of annual emissions for the reference case**

Although average emissions in 2030 are 30 million tCO_2, there is a 10% probability that they will be less than 17 million tCO_2, and a 10% probability that they will exceed 50 million tCO_2. As for cumulative emissions from 2015 to 2030, there is a 10% probability of an excess of 550 million tCO_2 (Figure 10).

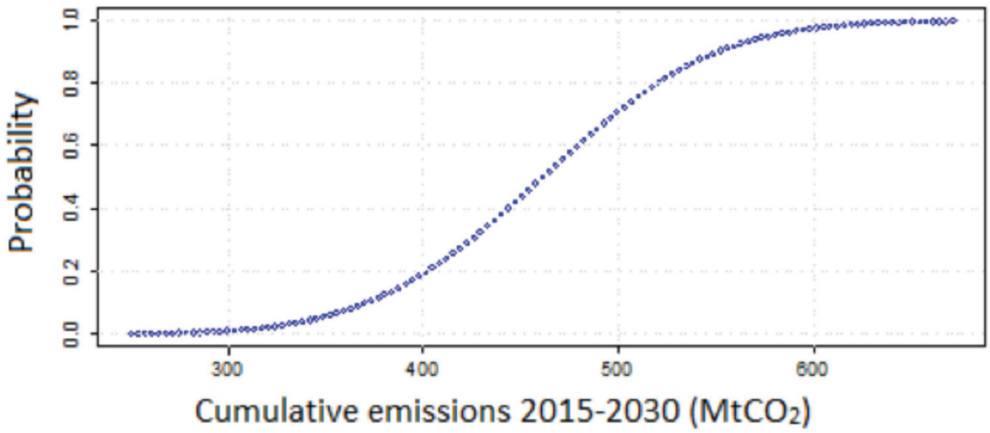


FIGURE 10 - Probability distribution of SIN emissions in 2015-2030 horizon for the Reference Case

5 ANALYSIS OF LOW HYDROLOGY

In Chapter 4 the term “dry hydrology” is formally presented, based on a statistical analysis of the synthetic series of Natural Affluent Energy (ENA) produced in the reference scenario. This is a *bottom-up* methodology based on the historic hydrological variability observed in the field, without considering climate change effects.

Using this approach, we assess the effects of low hydrology occurrence on the indicators associated with the operation of Brazil´s electric power sector, such as operating costs, increased output by thermal power plants and GHG emissions. This evaluation provides a clearer understanding of the *variability* of emissions in the Brazilian power sector due to hydrologic fluctuations.

Comparisons are made both for *annual* emissions and cumulative emissions between 2015-2030 (of greatest interest in terms of atmospheric CO_2 concentrations and, therefore, climate change).

5.1 Characterization of low hydrology

The “dry hydrology” hypothesis is defined as a set of scenarios where the cumulative ENA up to 2030 is among the 10% lowest values of the 200 scenarios generated to define the average values of the reference case[3], i.e. under 11750 TWh (also known as the p10 value). It is important to emphasize that the definition of low hydrology scenarios was based on values of cumulative ENA for the entire 2015-2030 horizon. It is possible of course that there are good hydrologic years within the series selected as “dry” years for the whole period, given that the analysis of the whole series showed that the cumulative ENA is low. This is due to the apathetic approach of the SIN to the existence of low water levels in the reservoirs.

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[3] While the definition of the 10% threshold is arbitrary, it is consistent with the threshold of 10% used in the power sector for defining the limit of acceptable risk. In addition, most of water rights issued in the country by state and federal water authorities are based on 90% guarantee.

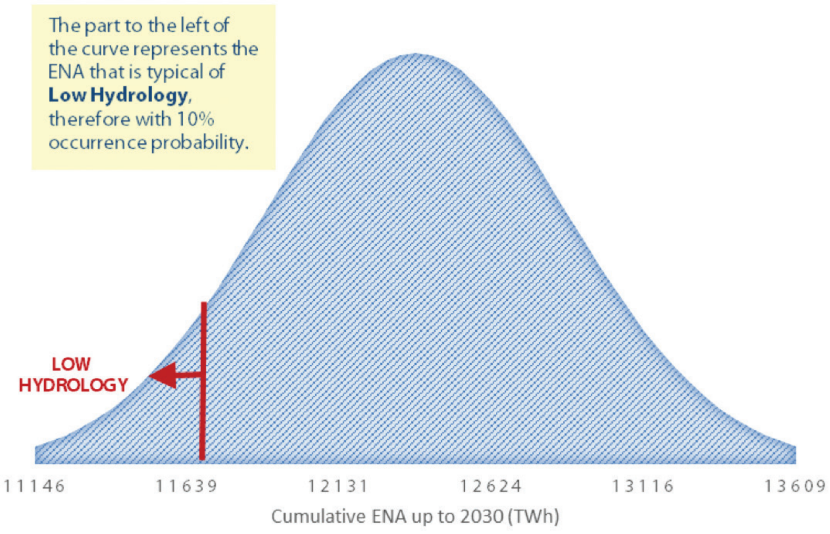


FIGURE 11 - **Definition of dry hydrology (1)**

Alternatively, Figure 12 shows the probability distribution of cumulative ENA with an indication of the subset of dry hydrology scenarios.

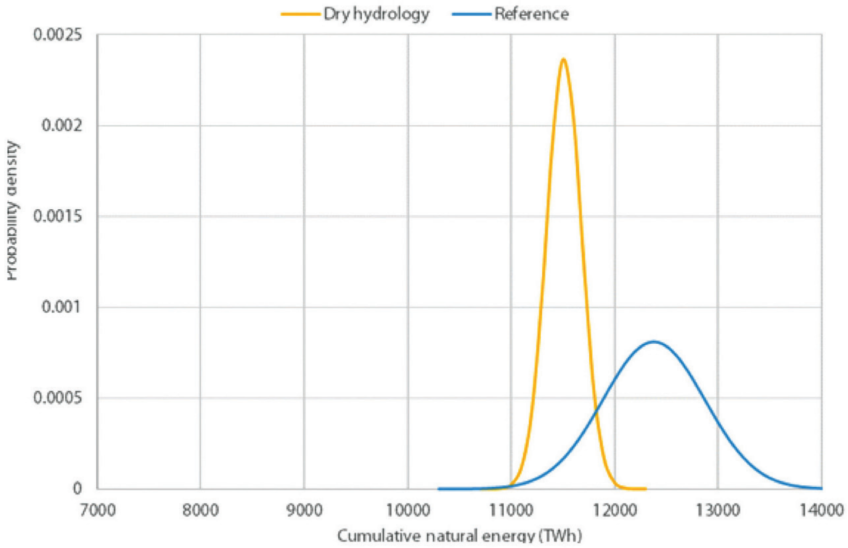


FIGURE 12 - **Definition of dry hydrology (2)**

The relationship between the expected value of the cumulative ENA of the dry hydrology subset, highlighted in yellow in Figure 12 (11510 TWh), and the expected value of the cumulative ENA for the entire sample of simulated series in the reference case (blue curve - 12378TWh), is 93%.

Using the SDDP simulation it was possible to correlate the Natural Inflow Energy (ENA) with the Marginal Operating Costs (MOC) of the power plants and the respective cumulative GHG emissions for the period under study, using 200 hydrological scenarios. These results are presented below. However, before proceeding to compare ENA, MOC and GHG emissions, it is worth comparing dry hydrology defined on the basis of a *bottom-up* approach, with hydrologic projections based on a *top-down* approach resulting from *downscaling* of global climate models.

5.2 Comparison of dry hydrology, defined on the basis of a *bottom-up* approach, with projections based on the *top-down* approach resulting from *downscaling* of global climate models

As already mentioned, in the *bottom-up* approach the simulation both of the reference case and the low hydrology case assumes that the hydrology is a stationary process (statistical characteristics of future series retain the same statistical characteristics of past series observed in the field).

In the *top-down* approach this assumption is discarded given the impacts resulting from a *downscaling* of the global climate model for the Brazilian river basins. This is therefore a scenario with hydrologic variability based on modeling climate change.

The scenarios used to assess the impacts of climate change were established in the *Fifth Assessment Report of the UN Intergovernmental Panel on Climate Change (IPCC)* and are linked to the atmospheric concentration of GHG. The IPCC Report adopted global climate change scenarios based on *Representative Concentration Pathways (RCP)*. For the simulations described here, we used the RCP 8.5 and RCP = 4.5 scenarios.

This climate change sensitivity analysis is part of a study prepared for the Strategic Affairs Secretariat (Presidency of the Republic) by the National Institute for Space Research (INPE), the Ceará Meteorology and Water Resources Foundation (FUNCEME) and PSR.

INPE was responsible for downscaling the results of the HadGEM and MIROC global circulation models for Brazil. Meanwhile, FUNCEME used the INPE outputs (rainfall and temperature series) and the SMAP rainfall-runoff model to generate flow series for the SIN hydroelectric plants. Finally, PSR, in partnership with COPPE, used these flow series to recalibrate the autoregressive inflow model of the different hydro plants and apply SDDP for the hydrothermal dispatch optimization.

We observed that for both global circulation models there is a substantial discontinuity in the comparison between the historical and projected flow series, with the projected flows being significantly lower than the historical flows. We noted an average flow reduction of between 44% and 57% for the HadGEM model and between 12% and 32% for the MIROC model. The simulation with the HadGEM model resulted in an ENA of 30% less than the historical ENA, while the MIROC model produced an ENA of 10% less.

Among the options for mitigating the effects of climate change in the SIN it is important for Brazil to review the existing impediments to the construction of regulatory storage reservoirs, when this is physically and environmentally feasible. These reservoirs are important assets for controlling hydrological variability and seasonality.

The figures below (Figures 13 and 14) compare for two natural flow gauging stations that are representative of Brazil´s hydrologic diversity (Sobradinho and Tucuruí) the historical natural inflows with those projected by INPE/FUNCEME based on a rainfall-runoff model combined with the HadGEM/ETA and MIROC/ETA climate models.

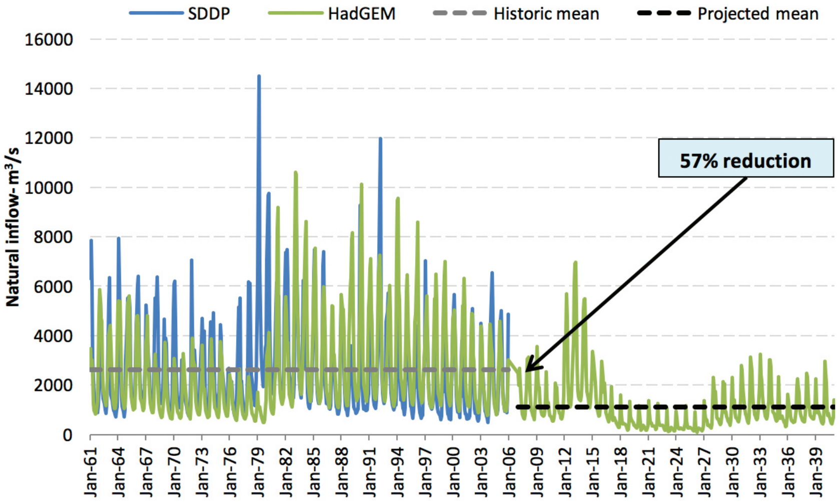


FIGURE 13 - **Natural inflow at Sobradinho HPP (HadGEM/Eta)**

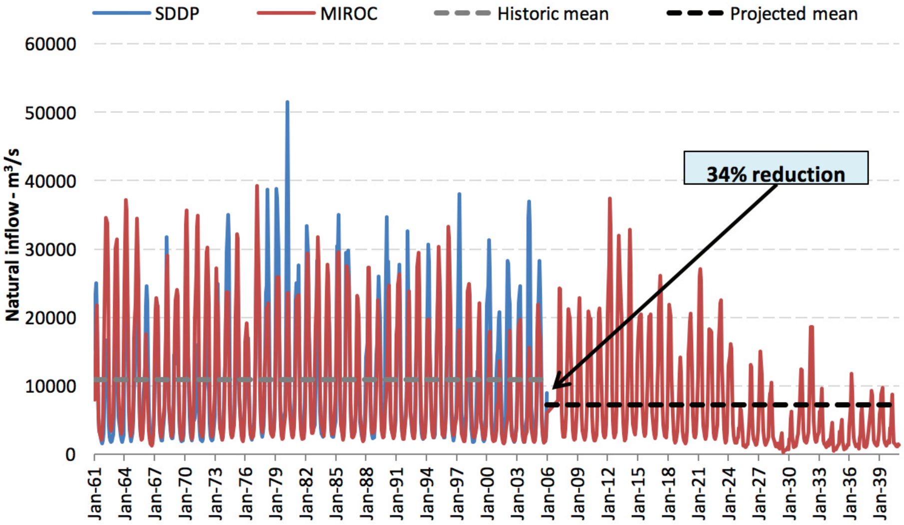


FIGURE 14 - **Natural inflow at Tucuruí HPP ((MIROC / Eta)**

It is however important to observe that the dry hydrology hypothesis defined in the *bottom-up* approach for the period 2015-2030 is still much wetter than the hydrologies for the same period that result from the currently available techniques for *down-scaling* global climate models (Figure 15) .

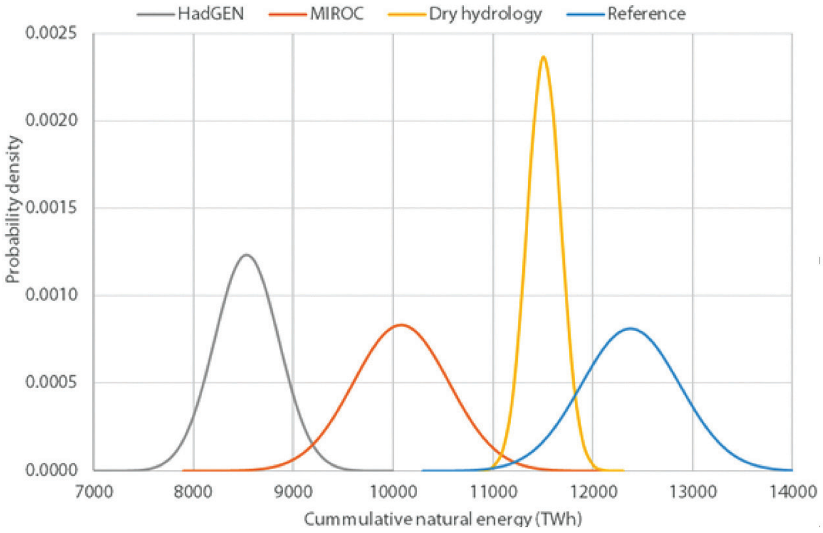


FIGURE 15 - **Probabilities distribution of the cumulative ENAs, 2015-2030**

The rationality of the dry hydrology hypothesis defined in the *bottom-up* approach appears to be consistent with the historical lows suffered by the SIN in 2014 and 2015, as can be seen in Figure 16 below: in every month from October 2014 to April 2015 new historically low water storage levels were recorded in the SIN reservoirs.

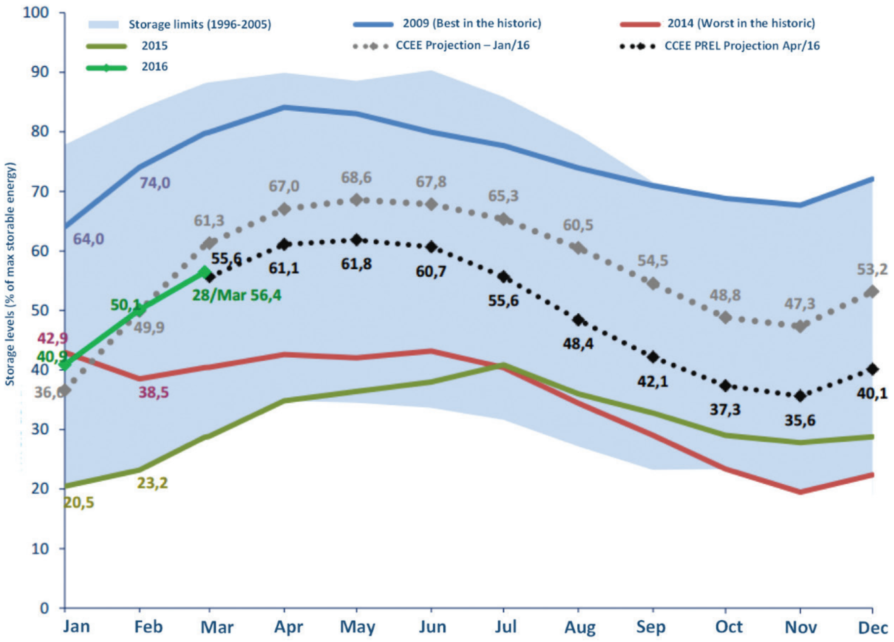


FIGURE 16 - **Projection of stored energy (Source: CCEE)**

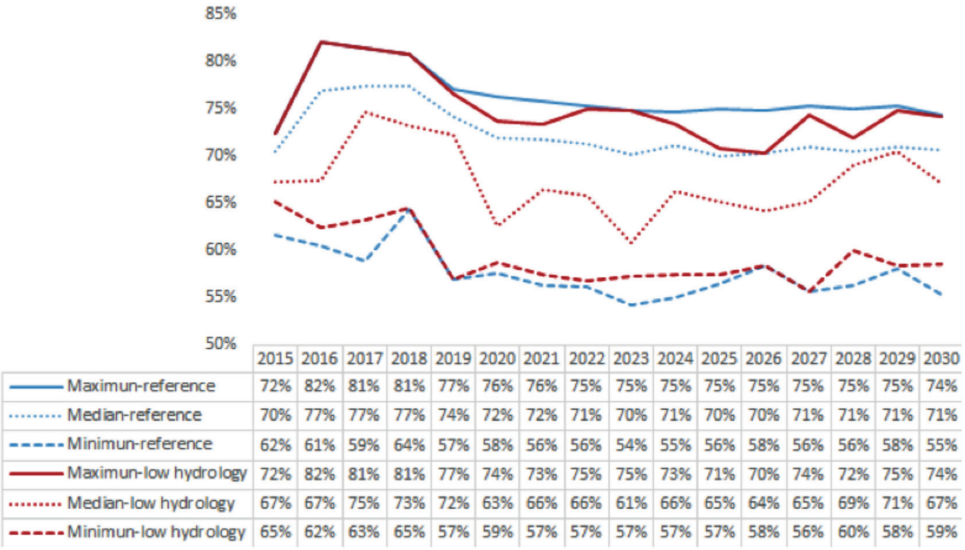
5.3 Marginal Operating Costs and emissions linked to low hydrology

The main results linked to dry hydrology of the *bottom-up* method are outlined below.

Table 1 compares the energy generated by source in the reference case and in the dry hydrology subset. The main differences are between the increased use of thermal plants burning imported coal, oil and diesel, and the decrease in hydroelectric generation (a relatively small decrease, but considerable in absolute terms). Figure 17.a details the annual evolution of the probability of hydropower share, which is reduced around 5% over the period. Total generation also decreases a little due to the higher energy deficit in the subset of dry hydrology scenarios.

SOURCE	REFERENCE SCENARIO	LOW HIDROLOGY SUBSET	RELATIVE DIFFERENCE
Imported coal	10	14	46.2%
National coal	22	23	6.9%
Oil	5	11	114.0%
Diesel	2	3	117.0%
Natural Gas	99	134	35.4%
Biomass	35	36	0.6%
Wind	128	129	0.1%
Solar	6	6	-0.1%
Nuclear	46	47	0.6%
Others	74	74	0.4%
Hydro	1035	981	-5.2%
TOTAL	**1463**	**1459**	**-0.3%**

TABLE 1 - **Comparison of average annual generation (GWM)**



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Maximun-reference	72%	82%	81%	81%	77%	76%	76%	75%	75%	75%	75%	75%	75%	75%	75%	74%
Median-reference	70%	77%	77%	77%	74%	72%	72%	71%	70%	71%	70%	70%	71%	71%	71%	71%
Minimun-reference	62%	61%	59%	64%	57%	58%	56%	56%	54%	55%	56%	58%	56%	56%	58%	55%
Maximun-low hydrology	72%	82%	81%	81%	77%	74%	73%	75%	75%	73%	71%	70%	74%	72%	75%	74%
Median-low hydrology	67%	67%	75%	73%	72%	63%	66%	66%	61%	66%	65%	64%	65%	69%	71%	67%
Minimun-low hydrology	65%	62%	63%	65%	57%	59%	57%	57%	57%	57%	57%	58%	56%	60%	58%	59%

FIGURE 17.a - **Hydropower share in the Reference and the Low-Hydrology scenarios**

New marginal operating cost values were calculated for each year of the low hydrology scenario. MOC are higher vthan in the reference scenario in 2015 (R$518/MWh compared to R$470/MWh) and 2016 (R$465/MWh compared to R$225/MWh), a result of the low inflows during the 2013/2014 wet season, and of a series of structural problems such as the friction factor of the HPPs. The MOC were much lower from 2017, caused by delayed plants and the new energy supply from the recent auctions appearing on the simulation horizon. In 2019-2023, prices varied between R$250 and R$320/MWh - significantly higher than those in the reference scenario (average of R$120/MWh). In the longer term horizon, the MOC continue to rise gradually (to R$300 MWh or more in 2026-2027) and then decline abruptly to around R$200/MWh by the end of the study horizon - also significantly higher than the reference case (R$140/MWh). The main driver of the final drop is the increase of the share of hydropower, because of the addition of new capacities (see figure 17.b).

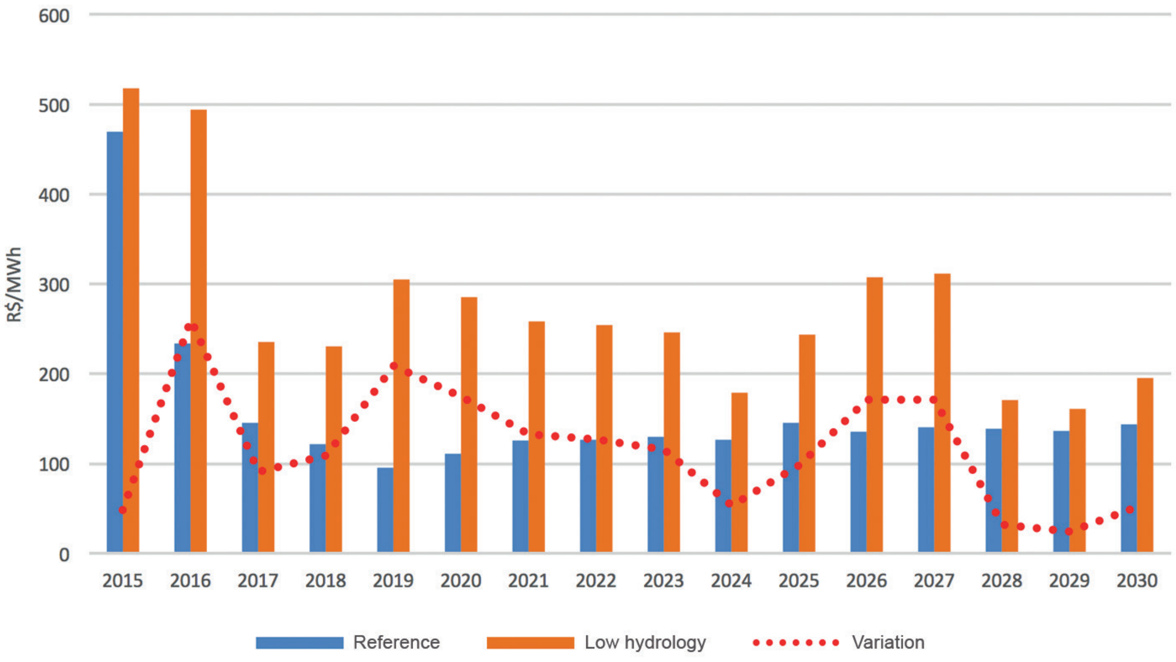


FIGURE 17.b - **Comparing MOCs for the Reference and the Low-Hydrology scenarios**

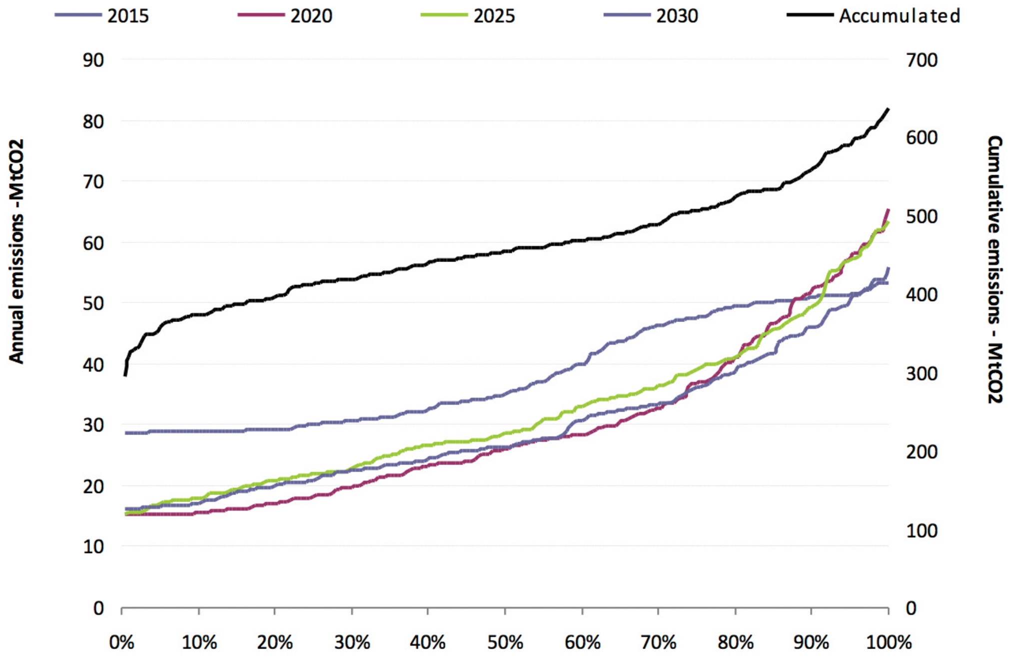


FIGURE 17.c - Probability distribution of annual emissions for the reference case

The emissions resulting from a low hydrology scenario based on the *bottom-up* approach were also calculated. Figure 17.c shows the emissions probability distribution for years 2015, 2020, 2025 and 2030 (left-hand scale), as well as the cumulative emissions over the entire study horizon (black curve, right-hand scale). Note that in the later years (2020, 2025 and 2030) the series with higher emissions (at right) present values that are around 4 times higher than those with lower emissions (at left). For example, for 2020 (in red) and 2015 (in green), whose distributions are presented in Figure 17 (values in left-hand scale), the highest annual emissions corresponding to a lower hydrology and greater dispatch of the thermal plants can exceed 60MtCO$_2$/year, while the lowest annual emissions corresponding to a wetter hydrology are around only 15MtCO$_2$/year.

Figures 18 and 19 show probability and probability density respectively for the SIN cumulative emissions on the 2015-2030 horizon for the dry hydrology subset compared to the reference case. Note the average cumulative increase of 150MtCO$_2$ (from around 460MtCO$_2$ to around 610MtCO$_2$). Also note that the standard deviation was considerably reduced (basically most of the thermal plants are activated in the event of a dry hydrology scenario).

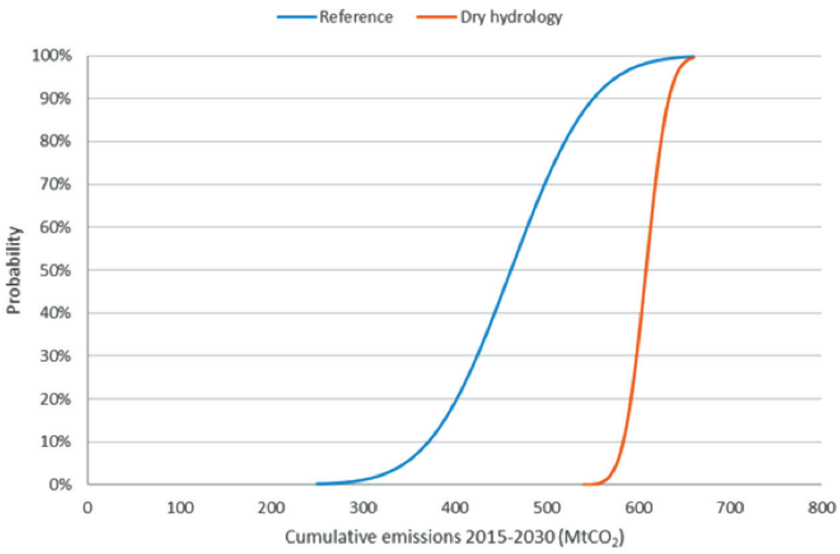


FIGURE 18 - Probability for SIN cumulative emissions for a dry hydrology scenario

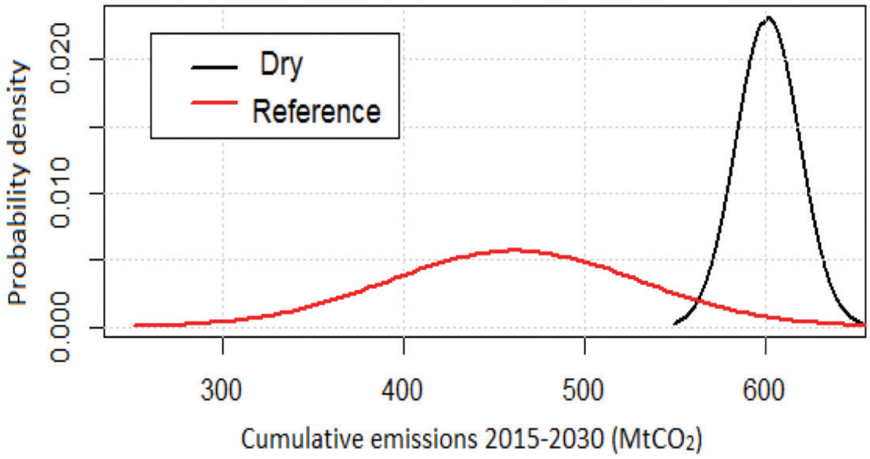


FIGURE 19 - Probability density function of cumulative emissions for a dry hydrology scenario

6 ALTERNATIVE CASE TO AVOID EMISSIONS INCREASE

In order to consider an alternative to offset increased GHG emissions during low hydrologic scenarios as described above, PSR established, in partnership with COPPE/UFRJ, an alternative expansion case involving the substitution of energy sources based on the burning of fossil fuels with renewable sources such as wind, solar and biomass, to meet the same reliability criteria. As well as substituting energy sources, this scenario envisaged an energy demand reduction that resulted from the deployment of more robust energy efficiency and distributed generation measures. The alternative case used the same macroeconomic and population growth assumptions.

Based on the set of new measures designed with COPPE and implemented, this alternative case showed a reduction of 15% in energy demand in 2030, compared to the reference case. In load terms this was an average reduction of 14 GW in the SIN.

According to Brazilian electricity sector regulations, the drop in demand in this scenario must trigger a corresponding reduction in supply. In this scenario, the reduction was achieved as the result of hydroelectric and natural gas thermal plants being cancelled as from 2020. The deployment of the alternative case based on the SDDP model resulted in a new MOC framework and, as expected, in a reduction of GHG emissions.

The probability distribution of GHG emissions shows annual emissions of under 30 million M tCO_2 - lower not only than the low hydrology case but also than the reference case. This is due to the fact that a specific "reverse" methodology was not developed. Under this approach, a target for a desired level of cumulative emissions would be set for the period (the cumulative emissions of the reference case), with the objective of reaching the same level in the low hydrology case through an optimized set of emission reduction measures. As seen, the alternative case outperformed the reverse methodology approach, by exceeding the goal of offsetting emissions growth.

When the cumulative emissions of both scenarios are compared, the average reduction is 20% compared to the reference case, which shows that rationalizing consumption and incorporating distributed generation have great potential for reducing GHG emissions in the SIN (Figure 20):as rationalizing the consumption reduces the demand and distributed generation (such as solar) displaces conventional generation, both contribute to dispatching less emitting powerplants, thus reducing emissions.

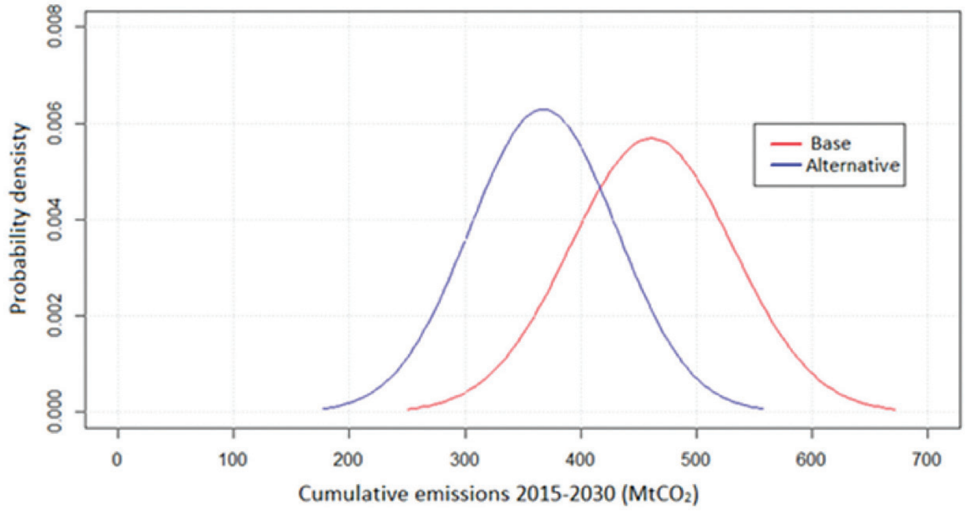


FIGURE 20 - **Probability distribution of cumulative emissions (2015-2030)**

In the alternative case, the MOC outcomes are higher for the years 2015 and 2016 as a result of low flows and structural problems in 2013 and 2014. However, these MOC are slightly less than in the reference case (around R$455/MWh compared to R$470/MWh in 2015 and R$115/MWh compared to R$225/MWh in 2016). From 2017, MOC values are reduced because the delayed plants and the newly contracted energy supply are included in the simulation horizon. In 2019-2023, average MOC amount to 80R$ / MWh, increasing over the longer term to 100 R$ / MWh, i.e. also less than the initial reference case (around R$140MWh over the long term).

Thus the alternative scenario would appear to be a "no regrets, no remorse" scenario that ensures an energy supply that is both cleaner and cheaper.