7 The water–energy nexus of Brazil's hydropower

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Introduction: the heat is on

The water–energy nexus is a glaring example of resource interdependencies among the United Nations' (UN) Sustainable Development Goals (SDGs): water needs energy to reach final consumers, and energy supply needs water for cooling and other purposes. Pursuing the SDGs on water (SDG 6) and energy (SDG 7) in a silo-type of planning could accelerate risks of water stress and power outages. Attempts to increase resource productivity, in line with the overarching aim of this book and SDG 12, will need to take those interdependencies into account. Our contribution assesses the water use of hydropower in Brazil, i.e. the water dimension of the most relevant energy source in a large emerging economy.

Brazil has a track record in sustainability through hosting the two Earth Summits in 1992 and 2012 as well as through its success in generating renewable energy. The 2018 edition of the Yale Environmental Performance Index puts Brazil ahead of China and India, suggesting a remarkable focus on sustainability in previous years. A case in point is Brazil's high share in hydroelectricity. However, hydroelectricity becomes a risky and much-contested source of energy. The severe droughts in the Southeast of the country in 2014–2015, along with the prolonged drought since 2012 in the Northeast, have unveiled water availability issues that affect the electricity sector, among others, and raised concerns. The crucial importance of this relationship between water and energy is increasingly recognised for future development, but there is a lack of integrated methodological approaches and well-defined metrics. This chapter contributes to a more holistic understanding of the nexus and an Integrated Resource Policy by assessing water evaporation for electricity generation in Brazil. The methodology used for evaporation and water footprint estimation was based on work by Semertzidis (2019). In the broader sense, this contributes to understanding the water cycle, climate impacts, and how it will affect the use of both water and energy in the future. Accordingly, we also discuss the results of a novel scenario analysis for the future of Brazil. Finally, our contribution concludes on the usefulness of this case for the broader narrative of sustainable development and resource productivity.

The evidence base: droughts, energy, and the water cycle

In 2014–2015 Brazil (and more specifically, the Southeast and Midwest) faced its worst drought in 40 years, which resulted in decreased reservoir capacities and consequently hydropower consumption decrease. Inhabitants and the agriculture sector suffered due to the lack of water, while blackouts hit cities like Rio de Janeiro and São Paulo due to weak hydroelectricity generation and high demand for services (for example, use of air conditioning due to high temperatures). To partly alleviate the problem, the assistance of burning more fossil fuels were required since they are used as a back-up energy source in Brazil.

Brazil faced several droughts in the past years, and it is anticipated that this trend will continue and increase in intensity and frequency, mainly in the Northeast of Brazil due to climate change (World Bank 2013). Water availability, in general, is recognised as being an issue for Brazil. This alarming for the electricity sector, since the hydroelectric production in Brazil historically accounts for more than 70% of the country's electricity supply matrix, with a capacity of 91.348 GW in 2014. An additional 31.7 GW of capacity was expected to be installed, as of 2014, in the northern region to match with the country's growing economy (Westin et al. 2014). The primary strategy of the Brazilian government so far has been an expansion of energy supply via the construction of the large-scale hydropower plants in Santo Antonio (3,150 MW) and Jirau (3,300 MW) on Madeira River, and Belo Monte (11,233 MW) on Xingu River, all three being in the Amazon Basin (Andrade Guerra et al. 2015). So, would the water be available to fuel the hydroelectricity demand of the future?

The water system and a water budget analysis

This apparent relationship between water and electricity needs to be explored: while research investigates into energy demand, little has been done to understand water availability and the water cycle at the beginning of the delivery chain. Comparing it with the broader resource productivity debate, this gap is comparable to overlooking essential mining conditions. A concept to assess water more comprehensively and the interlinkages with energy is needed. The resource nexus (Bleischwitz et al. 2018) could, in theory, fit the role of such a concept/approach since it attempts to integrate important aspects of sustainable development. Water and energy interconnections, or the water–energy nexus (WEN), are part of the overall resource nexus thinking, and it is important that they are treated together rather than separately and as distinct resources with their ensuing issues. This way of thinking could help to identify critical tensions between the two resources, highlighting possible synergies, and in turn, providing solutions to pressing problems. A more integrated resource policy would, thus, seek to address water availability along the whole life cycle, beginning with withdrawal and supply onto multiple users and potential re-use.

The depletion of water is highly dependent on the regional and global climate conditions, and it is also site-specific. Hence, ideally, analysis of a hydroelectric system should be done on regional scales with some international and global connections. Also, the fact that the generation of electricity is highly time relevant, deems it important to use a maximum daily time step. Finally, each relevant power plant and water reservoir should be analysed individually. Research needs to quantify as accurately as possible the movement of water in, through and out of a specific volume of water, which makes it feasible to gain knowledge about the availability of water for future planning and decision-making. This type of analysis is achieved through a water budget (or balance). To do a water budget analysis and address the operation of a hydroelectric plant, it is essential to treat the process in a dynamic way since the main variables (precipitation, evaporation and river flow) are all dynamic in nature.

A landmark in recognising the impact of hydroelectricity on water resources was the 'Special Report on Renewable Energy Sources and Climate Change Mitigation' by the Intergovernmental Panel on Climate Change (IPCC) in 2012. The reason for the increased attention was the wide range of estimates on water consumption per unit of energy generated by hydropower plants, but also because these values were considerably more significant than those for all other technologies (Semertzidis et al. 2018). Torcellini et al. (2003) estimated it to be from 0 to 18,000 gallons per MWh (68.14 m^3/MWh). This wide range in values indicates the difficulty to estimate water use factors for hydroelectricity that could be universally applicable. The main consumption comes from evaporation from large reservoirs, which though can be multipurpose, storing water for agriculture, industrial or domestic use as well as for power production (Healy et al. 2015). Thus, water losses cannot only be attributed to power generation purposes alone. However, the vast majority of Brazilian hydropower reservoirs are solely used for electricity generation, which simplifies the problem in this particular case.

As of early 2019, the only existing analysis for all hydroelectric plants/reservoirs in Brazil is that by the Operator of the National Electricity System (ONS) in 2004. Since the climate is changing and evaporation is a dynamic process, the importance of estimating it anew was of great importance for our work. The results of the present study showed that the evaporation of some reservoirs estimated in this research was closely related to that by ONS. However, other reservoirs had a significant difference of even 300 mm per year, which shows the importance of having frequent evaporation estimations.

A model calculating evaporation and water consumption of hydropower, as well as performing a water budget analysis for individual reservoirs, states, and regions was created and used for 218 reservoirs. The model and the analysis were designed and delivered in such a way as to overcome spatial and temporal issues that inhibit water models to be meaningfully linked to energy models. The time step for evaporation and water consumption is hourly, and for the water budget analysis daily, while the spatial boundaries used are political, although hydrological boundaries were also used for the purpose of estimating future projections of river flows. The result is a novel assessment of Brazil's water budget for hydroelectricity and a tool for scenario analysis. Detailed future climatic scenarios for the reservoirs were created to perform a future scenario analysis of the main hydropower system of Brazil. The results and their meaning for Brazil, but also generally, are discussed to offer insight regarding policy implications for the future of hydropower.

Results of scenario analysis: high risks in the North and Northeast

The period chosen for the future projections analysis was 2015–2049. The main inputs for the water model are temperature, incoming short-wave radiation, wind speed, precipitation, and river flow.

Based on projections by IPCC and Marengo et al. (2011), the temperature in Brazil will rise within a range of 1 to about 4 °C until 2050. The exact increase is difficult to project, and so are the variations within the country itself and from season to season. Based on these projections, it was decided to create two different scenarios for evaporation estimation, using an increase of 2 °C and another of 3 °C until 2049, which lie in the middle of the projections above. At the same time, specific projections for incoming short-wave radiation and wind speed do not exist in literature. Based on a sensitivity analysis of evaporation, it was decided that the 2 °C scenario will be accompanied by an increase of 0.5 MJ/m^2 for incoming short-wave radiation and an increase of 0.5 m/s for wind speed. Additionally, the 3 °C scenario will be accompanied by an increase of 1 MJ/m^2 for incoming short-wave radiation and an increase of 1 m/s for wind speed. The first scenario will accompany the two different scenarios selected for precipitation.

The projections for precipitation are more complicated than the ones about temperature, since climate models have uncertainties about the direction of change and detailed impacts, especially since the weather patterns in Brazil are so inconsistent due to the meteorological phenomena present in the region. Generally, the IPCC projected reduced precipitation in the North, with a potential increase over other parts of the country. Also, the Northeast will have decreases, according to Marengo et al. (2016). Finally, Reboita et al. (2014) projected trends of negative precipitation in the more northern region of the country of −1.5 to −2.5 mm/day and increases in the Southeast and South of ~1.5 mm/day in the period 2070–2100. These values are in agreement with Marengo et al. (2016). Since precipitation projections are difficult, it was decided to have four different scenarios of precipitation/river flows, of which two will be presented here. The first one is based on the GCM miroc5 (World Bank n.d.), which projects an extreme upward precipitation future of 1858 mm (from 1439 mm in the period 2010–2015) for the period 2016–2039 and 1865 mm for the period 2040–2049. The second one is based on the GCM ipsl_cm5a_mr (World Bank n.d.), which projects an extreme downward precipitation future of 1190 mm (from 1439 mm in the period 2010–2015) for the period 2016–2039 and 1225 mm for the period 2040–2049. The reason these two scenarios were selected is that they present extreme upward and downward precipitation.

The first two parts of Figure 7.1 show the annual progression of evaporation from 2015 through to 2049 for the two scenarios created. There is an increasing trend for evaporation for both scenarios, mainly due to temperature increases, along with incoming short-wave radiation and wind speed. The progression of the lines in both scenarios is similar, but the difference lies in the values themselves. Both scenarios share the same values for 2015, which is the base year, and then there is a 3–4 mm upward difference every year, except for the South that has 2–4 mm, from scenario one to scenario two. In the 35-year period, the increase of evaporation has been most prominent in the North with an overall increase of about 103 mm more for scenario two than scenario one. The least increase was in the South with 77 mm. Overall, for a 1 °C increase in temperature, a 0.5 MJ/m^2 increase in incoming short-wave radiation, and a 0.5 m/s increase in wind speed, the average difference between the two scenarios for the country was just over 90 mm in total.

The second two parts of Figure 7.1 show the monthly evaporation for the period 2015–2049 for scenarios one and two. The graphs for both scenarios are similar, with the difference lying in small increments throughout the year. Evaporation is rising for every month of the year, with September–February seeing the largest rise in both cases. The average rise per month of the year is from 3.38 mm per month in the South to 4.41 mm in the North, with the country's average being 3.9 mm. The North had increases from 3.7 mm in

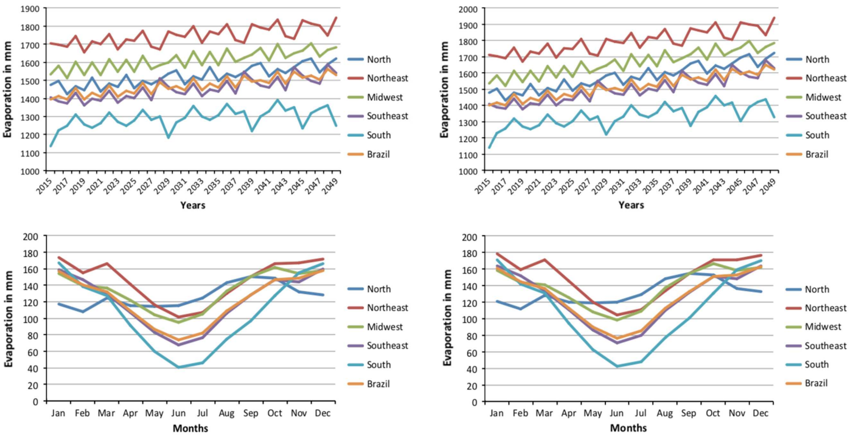

Figure 7.1 Annual evaporation results from scenario one (top left) and scenario two (top right), monthly evaporation results from scenarios one (bottom left) and scenario two (bottom right), for the period 2015–2049.
Source: Semertzidis (2019).

February to 5 mm in August, while the South from 1.75 mm in June to 4.6 mm in February. An interesting observation is that all regions have their minimum evaporation in June, except the North that has it in February. Also, the maximum evaporation occurs in December or January for the Northeast, Southeast and South, October for the Midwest, and September for the North.

More results: increasing water footprints

The first two parts of Figure 7.2 show the water footprint per region for the two different scenarios of precipitation (and river flows) for the period 2015–2049. The general trend in both scenarios is an increase in water footprint values for years with similar conditions. This is due to the steady increase in evaporation, which in turn increases the consumption of water. In the first scenarios, the North has the highest water footprint, whereas in the second scenario the Northeast has a higher one. Also, the Midwest's footprint is comparable to the Southeast's in both scenarios. The reason why this is happening is that these two regions share hydrographic regions and river flow is more important than precipitation above the reservoirs (Semertzidis 2019). The South has, in both scenarios, the lowest footprint.

The second two parts of Figure 7.2 show the monthly water footprint for the two scenarios for the 2015–2049 period. In general, the graphs have similar shaped lines. In both scenarios, water footprint values of all regions are closer in December–February, and the values of all regions are further apart during June–August. As was shown in the first two parts of Figure 7.2 as well, the North and the Northeast have the highest footprint values throughout the

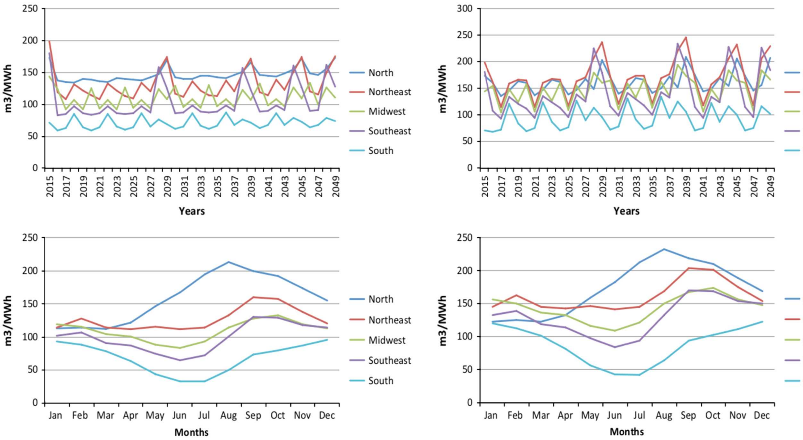

Figure 7.2 Annual water footprint results from scenario one (top left) and scenario two (top right), monthly evaporation results from scenarios one (bottom left) and scenario two (bottom right), for the period 2015–2049.
Source: Semertzidis (2019).

year, with the Midwest and the Southeast following, and the South having the lowest values all year round. The Northeast, the Midwest and the Southeast have their lowest footprint values in June, the South in June and July, and the North in March. On the other hand, the highest values occur in September for the Northeast and the Southeast, in October for the Midwest, in December for the South, and in August for the North.

Decreased water availability in the future could deem electricity production impossible to about 20% of certain months in the North, 30% in the Southeast, and 35% in the Northeast. Such months could potentially occur more frequently in the North and the Northeast. An integrated analysis with the IDA3 energy–water–land model developed by Spataru (2018), showed that Brazil as a whole would not face serious electricity supply issues if investments are targeted towards more regionally adapted hydropower, assisted by wind and solar as well as by better interconnections.

Discussion: regional disparities throughout Brazil

The results show the importance of evaporation for the water cycle when hydropower analyses need to be carried out. Seasonality is an important aspect that research and planning should take into account locations about future plants. We also stress that the evaporation rate is not going to increase uniformly throughout the year, making extremes through the seasons more prominent. As the situation stands, the South and Southeast of Brazil seem to have more sufficient reservoirs. Based on our evaporation assessment, the Northeast seems less suitable for hydropower plants. The North's and the Northeast's evaporation rates will likely increase more than in other regions, a factor that needs to be taken seriously into account for future planning.

The water footprint results showed that there is no 'normal' footprint value that can be used for all reservoirs. On the contrary, each reservoir should be assessed individually, which will allow more accurate comparisons with similar plants and their performance. One important finding was that the inundated area in relation to electricity produced is the key to designing an efficient reservoir/power plant. The South's footprint values are better compared to all other regions in Brazil, and they should be taken as the golden standard and something to strive for. The Southeast also normally performs well, but in times of droughts, water availability causes a large increase in footprint values, which also affects the country as a whole. The North and the Northeast do not have good water footprint values compared to other regions, which means that they suffer during times of reduced water availability, but also that the plants themselves were not built to be particularly efficient.

Future hydroelectricity plans should undergo a more strict water impact assessment. Furthermore, except in an extreme precipitation future, water footprint values for existing plants will most likely rise in all regions, which can magnify problems that some plants already have. From an energy perspective, this underlines the need for grid connections and seasonal back-up supply provisions. Hence it would be useful to assess whether an increase in capacity of some existing plants is possible. Alternatively, the water might be used for other purposes and investments in other electricity sources should be undertaken. Finally, once again, seasonality is important and extremes within the year will become more extreme. New capacity within the country should be sited in order to avoid as much as possible for too many reservoirs being affected at the same time.

An outlook for Brazil

The plans for hydropower have changed numerous times in the past in Brazil; the recent change in the government via the presidency of Jair Bolsonaro indicates less emphasis on environmental policy in general. However, energy security and water stress should be high on the agenda of any government, and hydropower will continue playing an important role. The two most prominent plans have been to either invest further into expansion in the North (Amazon), or more on smaller run-of-the-river plants all over the country. Both options have positives and negatives. Run-of-the-river plants cause significantly fewer environmental problems, but on the other hand, decrease the resilience of the whole system since they cannot withhold any water for times of need. Because of this, run-of-the-river plants are a direct contradiction to energy security. Constructing and operating a hydropower plant/reservoir needs to be done under strict regulations to protect the environment and human settlements. Plans need to be devised with adaptation in mind as well. Continuing with large reservoirs in the North of the country is also in direct contradiction with adaptation principles, because there is an overwhelming reliance on hydropower, with water being highly volatile due to climate change.

Furthermore, although most of the capacity factor values are within reason, what is striking is that the majority of the expansion, located in the North will have an average of 0.476, which is low compared to the rest of the country (Semertzidis 2019), and low compared to South American values. One of the biggest criticisms of the new Belo Monte power plant has faced is its low capacity factor of just over 0.4, meaning that the average capacity factor expected in the North is maintained below 0.5 (Semertzidis 2019). Future policy should thus have a regional angle on the water–energy nexus in the North and Northeast with innovation on the capacity factor.

Our analysis of the water–energy nexus calls for an overhaul of the electricity system of Brazil, with the involvement of experts and stakeholders. The country has a huge wind energy potential in the Northeast and the South, and one could further investigate into solar energy, useful forms of bioenergy and other nature-based solutions. An integrated resource policy with more resilient hydropower, complemented by upscaling wind and solar, could be a sustainable pathway for Brazil. It would need to be assisted by appropriate modelling analysis and participatory integrated resource planning, taking into account adaptation to decreased water availability. A regionally diversified capacity, in combination with better infrastructure, would mitigate risks for the country's future. Beyond electricity, other forms of water use such as agriculture and food, private households and industry will need more research too via advanced nexus assessments. Adapting to climate and social changes, while innovating on the productivity of water and electricity and its distribution are the keys for long-term resilience. We also wish to stress the importance of addressing water in the broader resource productivity debate.

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