Water-Energy-Land Nexus – Modelling Long-term Scenarios for Brazil

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***Abstract*—This paper analyses the water-energy-land nexus in Brazil. Recent drought saw more than 1% of the nation's economy lost and resulted in unprecedented widespread water scarcity. Four power generation scenarios were evaluated for 2050 regarding their impacts on water and land resources. This analysis reveals that the mutual dependencies of water, energy and land are gaining in importance and cannot be managed effectively without cross-sectoral integration. The findings suggest that a diversification of electricity generation technologies with the expansion of photovoltaic and wind power can help limiting additional land and water requirements for future power supply.**

Keywords-Brazil; electricity planning; water-energy-land nexus;

I. INTRODUCTION

Commercial pressure on land is growing, as more food needs to be produced for the growing world population and biomass cultivation for biofuel production is increasing concurrently. If current water consumption patterns continue, two-thirds of the world's population will be living in water-stressed countries in 2025 [1], while global energy demand increase is predicted to be 80% by 2050 [2]. Thus, efficient management of resources, which considers their linkages, is of great importance. For instance, land is required to grow both food and feedstock for biofuels production. On the other hand, energy is used in agriculture, such as for the production of fertilizer and the preparation of land. Energy production accounts for 15% of the world's total water withdrawals [3] and in turn, water supply and treatment require energy as well.

Extreme weather events, such as droughts, floods and storms can have a damaging impact on water use and energy production. A drought in China in 2011 limited hydro generation along the Yangtze River and contributed to a higher coal demand. Several provinces had to implement electricity rationing and energy efficiency measures [3].

In 2012, as consequences of a delayed monsoon, hydro generation in India decreased, while electricity demand for pumping groundwater increased at the same time [3]. Hydro generation is very sensitive to river runoff. For instance, a decrease in precipitation of 1% in the Colorado River basin leads to a decrease of 2 to 3% in stream flow. A 1% decrease in stream flow results in a reduction of power generation by 3%. The reason for this is that multiple generation plants are constructed in series [4].

Effects of climatic changes can be mixed; for example, Australia and New Zealand could face a reduced average water availability for hydraulic and thermal power plants, while some parts could benefit from an increased winter runoff [5]. In some areas affected by strongly declining river runoff, alternative sources of electricity may have to be considered to compensate for the reduced hydropower generation [6]. A noteworthy effect behind the background of a warming climate is that the efficiency of thermal power plants and transmission lines declines with warmer temperatures [7]. The magnitude of the effect depends on the cooling technology. Dry-cooling systems, commonly used in water restricted areas, are more affected than wet-cooling systems [8]. Greenhouse gas and aerosol emissions from energy use retroact on the climate.

Water scarcity in several countries worldwide has increased the awareness of the links between energy, water and land and the resulting potential for a more efficient resource use.

II. THE RESOURCE NEXUS

A. Resource Interfaces

Water use for power supply can be subdivided into fuel production and electricity generation. Water requirements in the different stages of fuel production are dependent on the fuel source as well as on extraction, transport and process technologies. The production of synthetic fuels from coal or natural gas is highly water intensive compared to their direct usage. For example, producing synthetic fuel from natural gas consumes about 192 L/GJ compared to 9 L/GJ for direct utilization [9]. Biofuels require the most water of all fuels, mainly for irrigation (Table 1). Transport from mines or fields to processing facilities and end-users can also require water. For instance, water is added to produce coal slurry that can be transported via pipelines.

Apart from water use for fuel extraction and processing, additional water demand arises at power stations for cooling systems. Three general types can be distinguished: once-through, closed-loop and dry cooling systems. In a once-through system, cooling water is directly discharged to the source after passing it through the heat exchanger. Closed-loop systems evaporate a portion of the cooling water in

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TABLE I. WATER CONSUMPTION OF FUEL PRODUCTION [9]

Fuels	Water Consumption (L/GJ)
Natural gas + transport	9
Natural gas + gas to liquid	192
Coal mining and washing	15
Coal + slurry pipeline	36
Coal + coal-to-liquid	219
Uranium mining + enrichment	41
Oil (primary-secondary)	313
Corn ethanol	5,481

cooling towers. The remaining water is recycled and re-circulated with additional water from the source [10]. Dry cooling systems use solely air for cooling, thus, minimizing water use [11].

Water withdrawal and consumption parameters for generation technologies indicate the reduced water withdrawal of closed-loop compared to once-through systems (Table 2). Consumption, on the other hand, is higher through the evaporation in cooling towers. Hydropower has the highest water consumption of 17 m^3/MWh due to evaporation losses from the increased reservoir surface. However, hydropower, as opposed to thermoelectric generation technologies, does not have additional water requirements for fuel production.

Land use for power generation results from fuel production, with fuels being extracted, processed, transported and stored. Particularly high land requirements can result from biomass cultivation on agricultural land. Land use associated with electricity generation results from power stations as well as transmission and distribution lines. Different conceptions of the term "land use" are common. Occupied land is defined as the area engaged during a period of time [12]. Transformed land is the area altered from a reference state, which can be broken up into direct and indirect transformations. Direct transformations comprise only immediate effects of a process, while indirect transformations cover secondary effects, such as additional land use for materials used in a process [13]. The level of impact on the land is neither considered in land transformation nor in occupation [13].

Water supply and wastewater treatment require energy. The overall energy intensity of freshwater supply is dependent on the depth of the water source, the preexisting and required water quality as well as the distance and height between source and customer [14]. Energy requirements for wastewater treatment are subject to the treatment processes and the desired reduction in contamination levels.

TABLE II. WATER USE OF ELECTRICITY GENERATION [11]

Technology	Cooling System	Consumption (m^3/MWh)	Withdrawal (m^3/MWh)
Photovoltaic		<0.01	-
Wind		0.00	-
Hydropower		17.00	0
Biomass	Closed-loop	2.09	3.32
Nuclear	Closed-loop	2.54	4.17
	Once-through	1.02	167.88
Natural gas (comb cycle)	Closed-loop	0.78	0.97
	Once-through	0.38	43.08
Natural gas (steam)	Closed-loop	3.13	4.55
Coal	Closed-loop	2.60	3.80
	Once-through	0.95	137.60

B. *Assessing the Nexus*

The aim of a nexus assessment is to map key linkages and to assess available options in terms of their impact on resources. Results can support decision making, as potentially conflicting policies of different sectors can be avoided by understanding their implications for the whole nexus [15].

Statistics of weather and climate events are changing, but regulations, building codes and rules of thumb are based on experiences, thus assuming a stationary climate system [16]. Modelling tools are needed to assess long-term interactions and feedbacks between resources against the background of a changing climate [17].

III. CASE STUDY BRAZIL

A. *Background*

Brazil has high renewable water resources of 43,157 cubic meters per capita per year [18]; however, water resources are unevenly distributed. In the North, the Amazon River basin accounts for over 80% of available water in Brazil, while 84% of the population lives in the Southeast, Northeast and South, where less water is available. The mismatch became particularly noticeable in 2012, as severe droughts in the Northeast were accompanied by simultaneous floods in Amazonia [19]. A recent drought in the Southeast led to water rationing in São Paulo, because of critical low reservoir levels.

Population growth and economic development has increased water and energy demand in Brazil. Electricity consumption has increased by 4% annually from 2004 to 2013. Electricity supply in Brazil is highly dependent on hydropower, accounting for 69% to 84% of annual electricity production between 2004 and 2013 (Fig. 1).

Recent droughts and the high dependency of electricity supply on hydropower raise concerns about energy and water security in the future. This study aims to assess the effects of future electricity generation on land and water

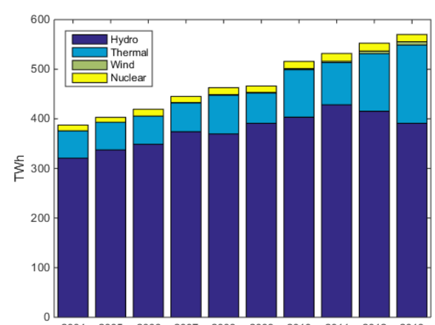

Figure 1. Power supply mix of Brazil 2004 - 2013 excluding self-production (data source: [20]).

resources in Brazil against the background of changing water availability. Furthermore, energy demand for water supply and wastewater treatment is estimated to identify potentials for energy savings.

IV. METHODOLOGY

A. Model Description

A model was developed to assess the water-energy-land nexus from an electricity perspective based on bilateral interfaces as depicted in Fig. 2. The model aims to assess the long-term effects of electricity generation on the water-energy-land system. Scenarios are used to assess different generation technology compositions and to account for climatic changes and data uncertainties. The results of the assessment are presented as absolute values and relative to a reference value (Table 3).

The study area can be hierarchically subdivided into sub-areas, allowing the evaluation of results at different levels. Areal extent is recorded as figures, because entities are represented as knots. Horizontal exchange between entities is not designated with the exception of electricity, which can flow between sub-areas.

B. Energy for Water

Supply requirements (*WS)* of each water supply category *c* (e.g. agricultural, industrial and domestic) and the amount of treated wastewater is projected for each time step *i* and sub-area *a* with a specific growth rate *gr*.

$$WS_{c,a,i+1} = WS_{c,i} * (1 + gr_{c,a}) \quad (1)$$

Based on the supply requirements, the energy demand for each service (*PCW*) is calculated using area-specific energy requirements (*fp*).

$$PCW_{c,a,i} = WS_{c,a,i} * fp_{c,a} \quad (2)$$

Total energy requirements for water services results from the sum of all assessed categories and sub-areas. Energy requirements for pumping cooling water at power stations are not considered, as they are included in the overall efficiencies of the stations.

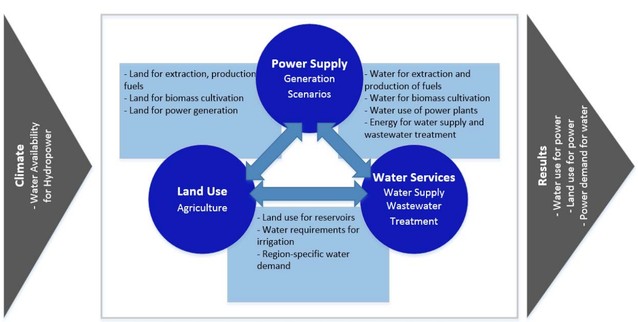

Figure 2. Schematic diagram of WEL model

TABLE III. MODEL OUTPUT AND REFERENCE VALUES.

Output Value	**Reference Value**
Water withdrawal for power generation	Total water withdrawal
Water consumption for power generation	Total water consumption
Land use for power generation	Total land demand
Power demand for water services	Total power demand

C. Power Supply

Power demand (*PC*) is comprised of the projected base demand and the calculated demand for water services (2). The total power supply requirement (*TPSR*) results from total power demand and percentage grid losses.

$$TPSR_i = PC_i / (1 - Leg_i) \quad (3)$$

Generation capacities of the five categories photovoltaic, hydro, wind, nuclear and thermoelectric generation are projected for each sub-area. Thermoelectric generation comprises oil, gas, coal and biomass as sub-categories. Power supply (*PS*) by technology *t* is calculated based on the installed capacity (*GC*), as well as area- and time-specific capacity factors (*fc*), which account for seasonal variations and long-term climatic changes. The time factor (*ft*) is defined by the chosen time step.

$$PS_{t,a,i} = GC_{t,a,i} * fc_{t,a,i} * ft \quad (4)$$

Predefined preferences specify the order in which the generation categories are used. First, photovoltaic, wind and nuclear capacity are used to supply power. In the second step, hydro capacity is utilized. In the last step, thermoelectric capacity supplies the remaining requirements. As thermoelectric capacity is used to match demand and supply, capacity is not used to its maximum load. Output is distributed between sub-areas subject to the installed capacity and the capacity factors are recorded to monitor utilization.

(2)

D. Water for Electricity

Withdrawal and consumption factors by unit of electricity produced are allocated to each generation category. All factors are partitioned into usages for fuel extraction, fuel processing and electricity generation on site. Water withdrawal (*WW*) for each technology and sub-area, as well as consumption, are calculated based on the energy supplied by the technology (*PS*) and the technology-specific water withdrawal factor (*fww*).

$$WW_{t,a,i} = PS_{t,a,i} * fww_t \quad (5)$$

E. Land for Electricity

Land use (*LU*) by generation technology and sub-area is, similar to water use, calculated based on technology-specific land use factors (*flu*) and the energy supplied by each category.

$$LU_{t,a,i} = PS_{t,a,i} * flu_t \quad (6)$$

Resulting land use for power generation is correlated to the projected total land use.

F. Model Limitations

The approach of prioritizing generation technologies is a simplification of complex electricity trading markets. Reasonable results can only be provided if the amount of fluctuating generation capacity, such as PV or wind, does not endanger grid stability. The study area is considered isolated, as no trade with neighboring countries is implemented and within the study area, a perfectly interconnected power transmission grid is assumed.

Land use parameters per unit of electricity produced are used to estimate land demand for power generation, thus making it sensitive to load factors. For example, if a power plant is out of use, no land will be allocated to the plant, although facilities and infrastructures are still in place. This can result in an underestimation of land use, if a whole generation category, such as thermoelectric generation, has a very low utilization rate. However, this would indicate a mismatch between power supply requirement and installed generation capacity.

Water and land resources are not limited, allowing the creation of infeasible scenarios through overuse of resources. Nevertheless, the comparison of supply mix scenarios in terms of their impacts on water and land resources is still possible.

V. Case Study: Scenarios

In this case study, Brazil was divided into five sub-areas: Northeast, North, Southeast, South and Central West. Official projections for future generation capacities were available up to 2023 [21]. For the period from 2023 to 2050, four generation scenarios were created to compare impacts on water and land use: scenario GenH assumes the full exploitation of the hydro potential; scenario GenW emphasizes on wind and photovoltaic generation; scenario GenB focusses on thermoelectric generation capacity with a growing proportion of biomass as well as the expansion of nuclear capacity; scenario GenM represents a balanced mix of the other three scenarios.

Four climate scenarios were used to assess the impact of decreasing capacity factors of hydropower due to climate change. CfC is the base case scenario assuming constant capacity factors. Scenario CfD assumes a fast decline in the Southeast and Central West – the regions heavily affected by the recent droughts. Scenarios CfA2 and CfB2 are derived from [22] representing the effects of climate scenarios IPCC SRES A2 and B2, respectively.

There is little data available about water usage of Brazilian power plants. Water withdrawal and consumption factors used in this study are based on available data in literature, which are predominantly obtained from power stations outside Brazil. Several datasets are used to account for uncertainties associated with data from other countries. Scenarios WuL, WuH and WuA1 are based on [14] covering the full range of available data with lower (WuL), upper (WuH) and average (WuA1) values. Scenario WuA2 is identical to WuA1 with the exception of the biomass factors, which are taken from [23]. Finally, WuG solely assesses electricity generation without water use for extraction and processing of fuels [11]. Land use of power supply was estimated using three datasets covering land transformation (LuF) [12], direct land requirements (LuG) [13] and land use intensity (LuM) [24].

VI. Results

A. Electricity Demand for Water Services

Electricity demand for water services in Brazil was 26 TWh in 2013, accounting for 5.7% of total electricity demand. The results indicate that this share will decrease to 4.9% in 2035. In 2050, electricity demand for water services is projected to be 69 TWh. About 62% of electricity demand for water services trace back to domestic water supply.

Energy requirements are particularly high in the densely populated Northeast and Southeast at 7.2 and 5.1 TWh, respectively (2013). The only exception is Central West, where the main energy use is for agricultural water supply.

B. Power Supply Mix

Power demand is projected to be 1,332 TWh in 2050. In scenario GenH, hydropower contributes 62% of total electricity supply by 2050, and 41% in all other scenarios (Fig. 3). The share of wind power reaches 38% in scenario GenW. Thermoelectric supply is 35% in scenario GenM and 39% in scenario GenW. The share of supply from biomass increases from 33% of thermoelectric supply in 2013 to 80% in 2050 in scenario GenB. In 2050, the mean annual capacity factors of hydropower throughout Brazil are projected to be 0.457 in scenario CfD, 0.449 in scenario CfA2 and 0.460 in scenario CfB2 based on 0.580 in 2013.

C. Water Use for Electricity Generation

Scenario GenW has the lowest water requirements, both in terms of withdrawal and consumption (Fig. 4). The highest water use results from scenario GenB at 126 billion

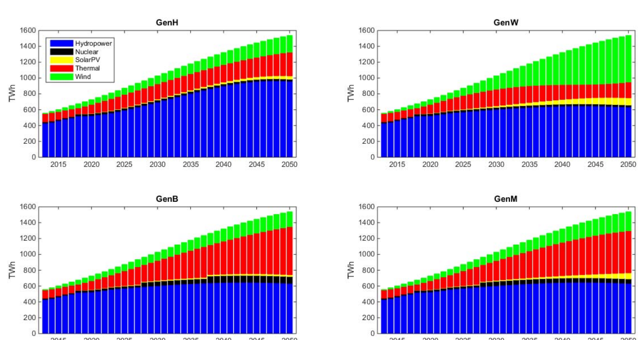

Figure 3. Power supply mix of the four scenarios generation scenarios.

cubic meters (bm^3) withdrawn and 193 bm^3 consumed by 2050 using water use factors WuA2. The scenario with the second highest water use is GenM.

The highest withdrawal and consumption rates result from water use factors WuH, whereby scenario GenB peaks at 201 bm^3 withdrawal and 323 bm^3 consumption by 2050. Results using WuL and WuH factors deviate up to 26% in withdrawal and up to 3% in consumption compared to results obtained with average factors (WuA1). The smaller water usage factor of biomass in WuA2 reduces withdrawal by 21–30% and consumption by 32–40% compared to WuA1. Considering solely water use at power stations (WuG), water consumption in scenario GenB is only 6% higher than in scenario GenW, whereas all other water usage factors result in 4 to 5 times higher consumption rates.

D. Land Use for Electricity Generation

Scenario GenB has the highest land requirements, as 315,260 km^2 are projected to be impacted by electricity generation by 2050, compared to 44,800 km^2 in 2013 using land use factors LuM (Fig. 5). Scenario GenM has the second and scenario GenH the third highest land requirements. The most land efficient generation mix is scenario GenW impacting 119,030 km^2.

Thermoelectric generation contributes the most to land use in all generation scenarios, with the exception of GenW, when using LuM factors. For example, in scenario GenH, thermoelectric generation supplies 19.5% of total power supply, but accounts for 46.1% of land use. In scenario GenW, thermoelectric generation (32.8%) has slightly lower requirements than wind generation (35.7%). Using LuF parameters, land requirements of thermoelectric generation account for 74.0% to 95.8% of total land use for power generation. The application of LuG factors leads to hydropower contributing the most to land use in scenarios GenH (62.5%) and GenW (48.6%), whereas thermoelectric generation is dominant in scenarios GenM (49.0%) and GenB (73.9%).

Subject to the land use factors, land requirements for power generation were estimated to 0.8% (LuF), 1.2% (LuM) and 2.0% (LuG) of total land use for agriculture

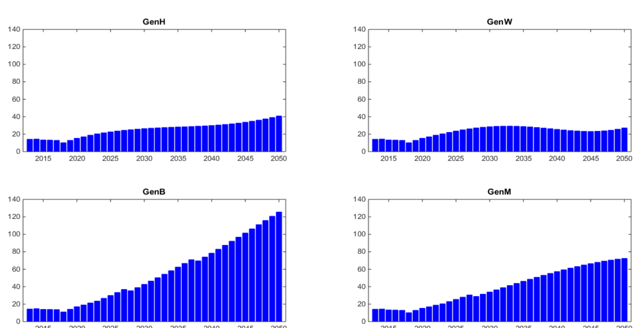

Figure 4. Annual water withdrawal for electricity generation (bm^3 of the four generation scenarios (water use WuA2, climate CfA2)

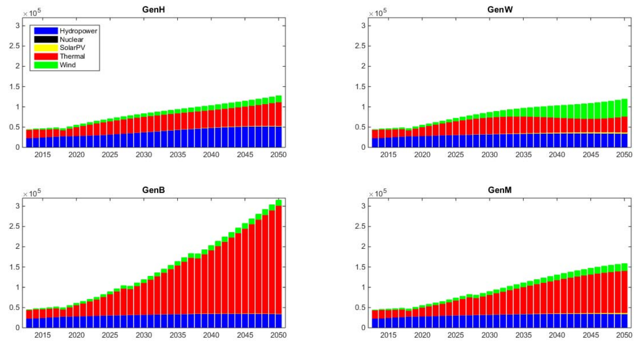

Figure 5. Land impacted by power generation (km^2) using land use factors LuM (climate scenario CfA2)

throughout Brazil in 2013. The South and the Southeast region use the most land for power generation compared to total agricultural area regardless of which factors are chosen. Additional land demand in the regions differs between generation scenarios. The expansion of wind power (scenario GenW) increases land use for power generation from 1.3 to 5.2% (LuM) in the Northeast by 2050. The Southeast and the Central West are especially affected by scenario GenB, which raises the shares to 14.1% and 16.7% (LuM) by 2050. In the North, hydropower expansion in scenario GenH is projected to increase land use for power generation to 3.1% by 2050 based on 0.9% (LuM) in 2013.

VII. Discussion and Conclusion

Electricity demand for water services was estimated to 5.7% of total electricity demand, displaying potentials for water and energy savings through water efficiency measures. In particular, overhauling the public supply network could be expedient, because domestic supply accounts for 62% of energy requirements for water services and about one-third of the supplied water is lost in the network [25].

Lower capacity factors of hydropower in the future could increases the attractiveness of other generation technologies. However, future projections of water stress and droughts in Brazil are inconsistent: ranging from little changes of the available water to a large increase of water stress in the South-East [26].

The increase of water use for power generation in this study is higher than the 35% increase in withdrawal and the doubling of consumption projected worldwide by the International Energy Agency for 2035 [3]. The main reason is the assumption of a greater economic growth in Brazil compared to the world's average, resulting in rapidly rising energy demands.

Solely considering the generation step to assess water use for power supply, as simulated with water use factors WuG, results in an underestimation of actual water requirements and a distortion of the results in favor of thermoelectric generation technologies due to high water requirements of fuel production.

Water use of biomass has a big impact on the final results, as can be observed by comparing the results from WuA1 to WuA2. Water requirements are difficult to estimate, not only because of region-specific irrigation schemes, but also because of multiple utilizations of biomass. For example, about 75% of electricity from biomass in Brazil was produced using sugarcane bagasse from ethanol production in 2013 [20]. Thus, water demand for irrigation needs to be allocated to both ethanol and electricity. The same applies to land use; for instance, when reservoirs serve multiple purposes, such as electricity generation, storage of drinking water and flood control.

Land use for power generation is projected to increase in all generation scenarios. Particularly high increases result from scenario GenB, in which land use is projected to increase sevenfold by 2050 based on 2013, mainly due to high land demands for biomass cultivation. The applied land use factors vary significantly, both in terms of absolute values and weighting of the different technologies, which reveals the great uncertainty associated with the parameters in literature and the need for further research, which also accounts for multiple resource utilizations. However, ranking the generation scenarios by both land and water use reveals the same order. The least water and land demands are associated with scenario GenW, independently of water and land use factors. Thus, in spite of discussed uncertainties, the conclusion can be drawn that investments in wind and photovoltaic power can limit additional water and land demands for future power supply in Brazil.

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