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Water-energy-emissions nexus – an integrated analysis applied to a case study

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ABSTRACT

Brazil has an electric system based on hydropower, especially in the State of Minas Gerais, in the Southeast Region. Competition for water use, water scarcity, economic growth, climate change and the lack of consistent and continuous energy planning are some of the problems related to planning and monitoring energy supply systems. Due to the lack of regional studies on expansion planning considering the water-energy-emissions nexus and its consequences, this work presents an integrated analysis of a case study on how changes in water supply and economic growth can impact hydropower and electricity generation in the State of Minas Gerais. The main results include the reduction in hydropower generation at the end of the study horizon (2019 – 2049) between (-16.8%) and (-7.8%) considering water restriction scenarios. The final electricity demand, in the reference scenario, increased by 40.8% and in alternative scenarios there was an increase between 63.6% and 89.5% when reductions in the rainfall regime were considered.

Keywords

Water-energy-emissions nexus;
Energy planning model;
Carbon emissions;
Power system;
Hydropower production;

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Abbreviations

ANA – *Agência Nacional de Águas* – Brazilian Water Agency
ANEEL – *Agência Nacional de Energia Elétrica* – Brazilian Electric Energy Agency
BEN – *Balanço Energético Nacional* – Brazilian Energetic Balance
CEMIG – *Companhia Energética de Minas Gerais* – Minas Gerais Energy Company
HGD – Hydro Gen Dry Scenario
HGP – Hydroelectric Generation Plants
HGVD – Hydro Gen Very Dry Scenario
HGW – Hydro Gen from WEAP Scenario
HPP – Hydroelectric Power Plant
IBGE – *Instituto Brasileiro de Geografia e Estatística* – Brazilian Institute of Geography and Statistics
IPCC – Intergovernmental Panel on Climate Change
LEAP – Low Emissions Analysis Platform
ONS – *Operador Nacional do Sistema Elétrico* – Brazilian Electricity Grid Operator
p.a – per annum
PVP – Photovoltaic Plant
SEI – Stockholm Environment Institute
SHP – Small Hydroelectric Plant
THP – Thermoelectric Plant
WEAP – Water Evaluation and Planning

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1. Introduction

The Brazilian power system is based on hydropower production, a very different situation in relation to several others countries where the participation of fossil fuels in electricity generation is dominant. According to the Brazilian Electricity Regulatory Agency (ANEEL) [1], there are three types of hydropower plants in the country:

- Hydroelectric Generating Plant (HGP): with up to 5 MW of installed capacity;
- Small Hydroelectric Power Plants (SHP): between 5 MW and 30 MW of installed capacity and reservoir area up to 13 km²;
- Hydroelectric Power Plant (HPP): between 5 MW and 50 MW of installed capacity as long as they are not classified as SHP, or with more than 50 MW of installed capacity.

In 2020, the hydropower plants were responsible for 60.7% of electricity generation in Brazil [2]. For instance, the scarcity of rains in 2021 caused a reduction in the level of the reservoirs of the main Brazilian hydroelectric power plants and the consequent reduction in the supply of hydroelectricity by 8.5%. This drop was offset by the increase in the supply of other sources, such as steam coal (+47.2%), natural gas (+46.2%), wind (+26.7%) and solar photovoltaic (+55.9 %) [2]. Therefore, achieving a stable and reliable electricity supply throughout the years has been a challenge for the power system operators, due to seasonal fluctuations and a significant change in the rainfall regime. Studies have shown the fragility and risks to which the socioeconomic and energy systems are susceptible. Firstly, those fragilities related to the irregularity of natural water distribution. Secondly, the persistence of drought [3].

Thus, despite relatively abundant water availability in Brazil, some concepts are changing, among them the outdated perception that this resource will never end. Protecting water resources means a permanent challenge for governments since their demand grows steadily in the development models considered by policymakers. The total amount of water withdrawn for human use increased by approximately 80% from 1997 to 2017. Additionally, projections show another increase of 30% by 2030 based on the year 2017 [4].

Brazil had a power crisis that led to compulsory consumption reductions in 2001, due to the lack of planning of the electricity sector during liberalization reforms in the power sector and due also to restrictions related to transmission capacity among regions. Several actions have been implemented since the crisis to increase power security, such as the construction of new transmission lines and increased interconnection between distant regions [5]. In 2014, a serious water supply crisis affected mainly the Southeast of the country, diminishing water availability for human consumption and impacting this region that has the highest population concentration [6]. The State of Minas Gerais is located in the Southeast region and it is of paramount importance for the Brazilian hydropower system due to the existence of large power plants in its territory.

In the following years, there was some increase in the rainfall precipitations, but at the end of 2017, the hydroelectric reservoir levels in the Southeast Region still reflected the drought crisis of 2014/2015. Figure 1 shows the hydroelectric and thermoelectric generation in Minas Gerais, according to the Brazilian Electricity Grid Operator (ONS) in the period between 2000 to 2018. A drop in hydropower generation can be observed from 2012 onwards due to the drought and in compensation the increase in the electricity generation by thermoelectric plants [7].

Figure 2 shows electricity imports and exports data from the State of Minas Gerais [8]. Traditionally, Minas Gerais is a net power exporter to other States, but from 2013 onwards, electricity imports have exceeded exports, as mainly consequence of the drop in hydropower production.

Considering this challenging scenario, this study aims to assess how changes in the water supply and economic growth could impact hydropower generation in Minas Gerais between 2019 and 2040 based on five different scenarios. More specifically, the results allow one to observe the behaviour of the electric production of the 22 largest hydroelectric power plants in the State of Minas Gerais in the horizon of 30 years; to identify opportunities for penetration or expansion of the supply from other energy sources that can contribute to electric generation; to identify the behaviour of greenhouse gas (GHG) emissions for the analysed scenarios.

The verification of the continuous loss of the capacity to export electric energy by the State of Minas Gerais shows probable future consequences for the planning of the electric operation in the country, given the role of the State in this context. Thus, the originality of this work lies in the planning of the expansion of electric generation, which considers the state dimension of the

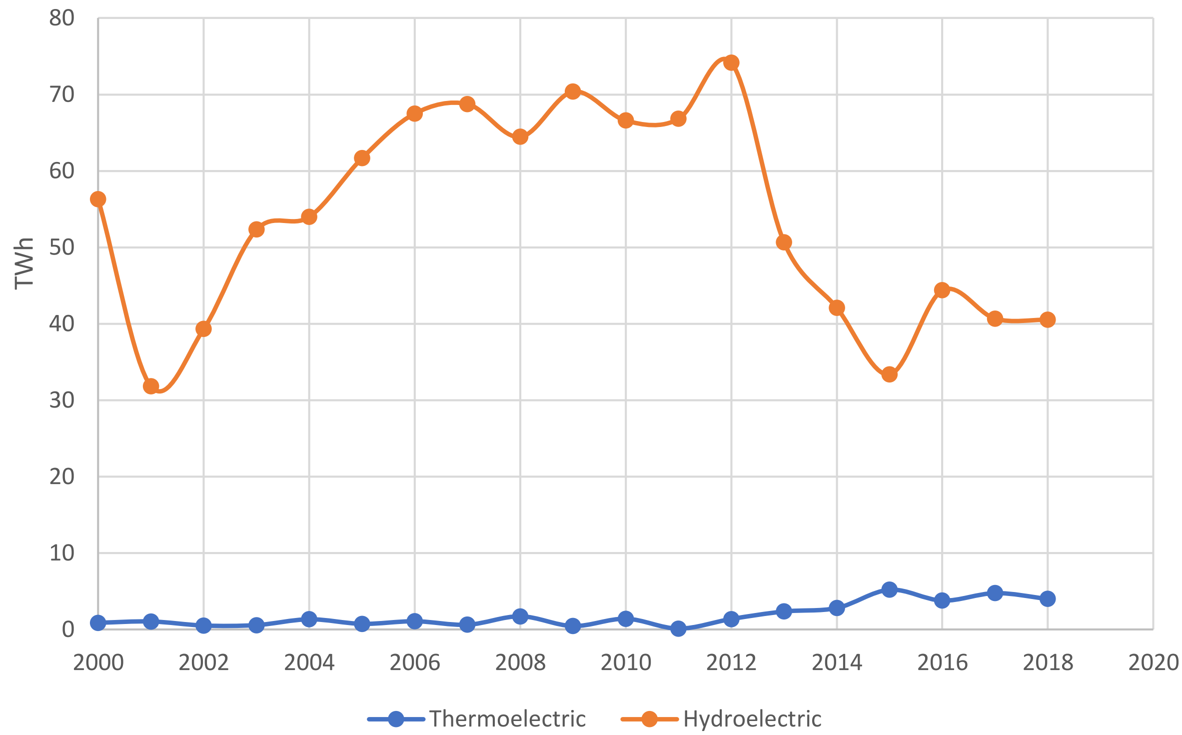


Figure 1: Power generation: Hydroelectricity and thermoelectricity in Minas Gerais. Adapted from [7].

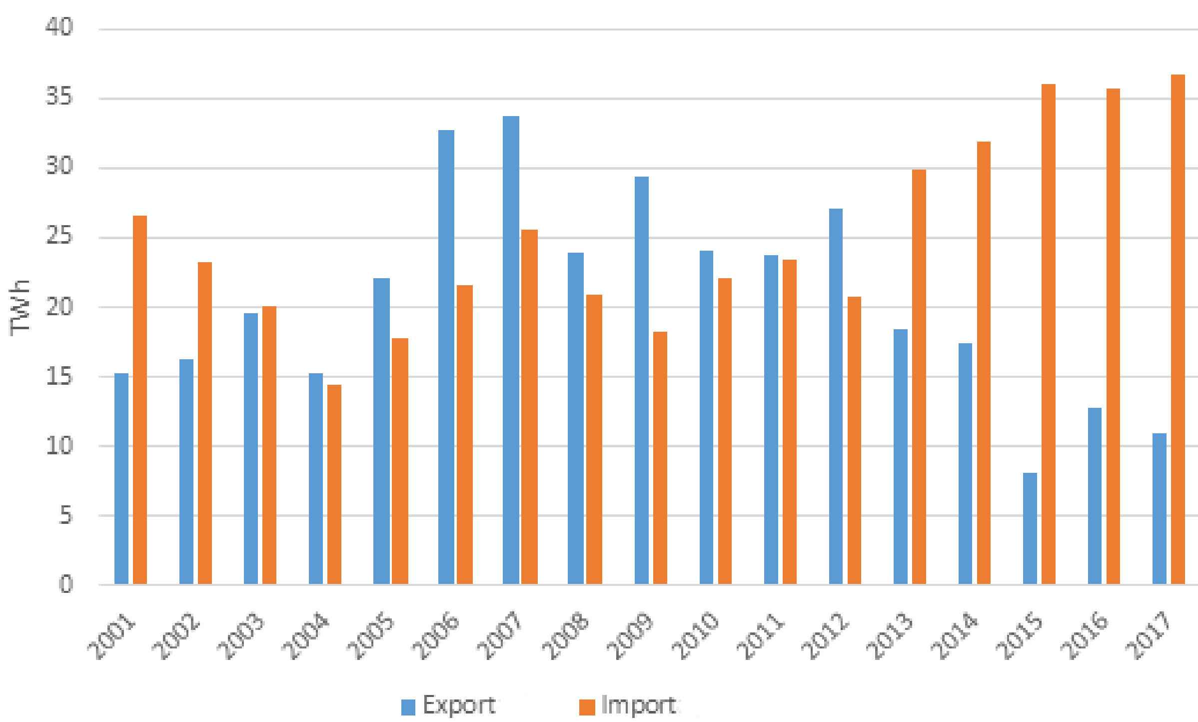


Figure 2: Data of energy imports and exports from Minas Gerais State. Adapted from [8].

water-energy nexus and its consequences, in the context of economic development and climate change. This type of study has not yet been carried out for Minas Gerais.

To this end, the Water Evaluation and Planning System - WEAP [9] and the Low Emissions Analysis Platform - LEAP [10] models were used. Both models were developed by the Stockholm Environment Institute - SEI for integrated planning and analysis of water resources policies and analysis of energy policies, and assessment of climate change mitigation, respectively.

1.1. The Resource Nexus

The meaning of the resource nexus, the categorization of energy systems and the modelling tools that can support decisions to design policies have been explored in the study of Smertzidis, 2015 [11]. The author has provided an overview of various tools used to address the resource nexus. The starting point was the worldwide increase in resource consumption as billions of people are moving towards a better lifestyle while one billion people will remain in poverty. These are complex topics to be assessed and quantified; the LEAP model is mentioned as a tool which performs an analysis of energy systems of a city, a state, a country, between countries and globally.

In another work, the authors presented models dealing with the water-energy-food nexus to better understand what is already known, looking for what may be missing and identifying opportunities and challenges for modelling this nexus [12]. They have identified the following challenges and considerations: the complex interactions and dynamics of the systems constitute the biggest challenges in modelling the nexus; the complexity in collecting detailed input data for a spatial-temporal model; incorporating spatial distribution into the planning approach is an important consideration for nexus modelling; incorporating temporal variation in weather patterns is another important assumption.

According to [13] there are three motivators for the emergence of the resource nexus concept: the interdependence of resources, stimulated by their growing scarcity; increased frequency of resource supply crises; and failures of sector-driven management strategies. An important contribution of this study was the synthesis of the importance of the nexus concept, by clarifying that this concept represents the most recent change in scientific and political thinking towards integrative thinking to face global changes and challenges. Almulla et al., (2018) have considered the role of energy-water nexus on the impacts that would occur for the countries in the Drina River Basin with improvement of cooperation and energy efficiency. They used the Open Source energy Modeling System-OSeMOSYS to develop a multi-country model with a simplified hydrological system to represent the cascade of HPPs in the considered basin [14].

Moreover, the impact that climate change could have on hydropower generation and the consequences for the expansion of the electricity system in the Zambezi basin region, Africa, have been investigated by [15]. The authors also considered the pressure exerted on the demand for resources, resulting from the population increase in the South African region, from 260 million people in 2012 to approximately 500 million in 2042. Hydropower generation, which accounts for 40% of total capacity in southern Africa, is critical to ensuring the region's energy security and stability. When interferences related to the climate change affect hydropower production, several countries in the region may experience difficulties in power generation. The methodology used by the authors involved the use of integrated models (water and energy), tested in future development scenarios, using the LEAP and WEAP models, considering the supply and demand of energy and water.

The "nexus concept" and the LEAP and WEAP tools were also addressed by other researchers whose studies considered the water-energy relationship in the Chinese port city of Xiamen [16]. The challenge pointed out by the authors lies in the enormous pressure on the environment and on resources, including water and energy, due to population growth, especially in urban areas. They considered that the analysis of the water-energy nexus, using computational tools, was little explored from the perspective of demand and even less on a municipal scale. Thus, the authors presented a dynamic, quantitative and synergistic framework for modelling the water-energy nexus at the urban scale based on LEAP and WEAP models. The scenario analysis was applied to examine the cross-sectoral impacts of different future policy choices, including changes in industry structure, conservation and water and energy supply alternatives, both considering the supply and the demand aspects.

1.2. Challenges and Limitations

This work consists of modelling the supply and demand of electric energy using constructive data from the largest hydroelectric power plants located in the State of Minas Gerais, as well as the average flow data in these power plants. The scenarios of changes in the water regime through hypotheses of water scarcity and economic growth allow for verifying the probable consequences in the hydroelectric generation in the horizon of study, estimating the impacts of the GHG emission and identifying externalities.

The main limitations of the research developed are related to the use of WEAP and LEAP. All models are data-limited and have difficulties in dealing with multiple scales of interaction and even an inability to capture complex ecological and social implications.

The choice of these models was supported by the following reasons:

- Reliability, technical and scientific breadth based on published works;
- Availability of enough data for the models to work properly;
- Models known in the academic environment;
- Availability of instructional material, including international discussion forums to clarify doubts and exchange experiences on the website of each program.

In addition, the elaboration of a computer modelling work requires the availability of a large number of data and definitions, to portray the existing physical reality as faithfully as possible. At this point lies a known difficulty, the lack of updated data for what it proposes to do. This problem was partially overcome through the search for related scientific and academic works, as well as the adoption of premises for the construction of scenarios. The technical and restricted data of the hydroelectric power plants were also made available by the energy concessionaire of the State of Minas Gerais - CEMIG (Minas Gerais Energy Company).

Because it is a prospective research and it analyses the variations of certain characteristics, or parameters, for a long period, it is difficult to project such parameters in the future. Therefore, the hypothesis and assumptions already represent a limitation of the study.

Another limitation comes from the lack of data related to the effective influences of climate change on short-term precipitation regimes – short when compared to IPCC study periods (50, 70, 100 or more years) –, which makes it difficult to correlate between hot and dry years and the reduction of flows in the reservoirs of the hydropower plants. Therefore, the *ceteris paribus* condition was used to verify the changes caused by different stimuli in the system's inflows and also to quantify the hydroelectric generation.

2. Methodology

In previous work, the authors drew attention to the fact that the reduction in rainfall levels may increase in the coming years and result in a probable change in the energy matrix configuration of the Brazilian State of Minas Gerais [17]. To deepen the studies, this work use WEAP and LEAP models to assess water scarcity scenarios. The results of hydropower generation, with the creation of assumptions and scenarios, are obtained in the WEAP model. The results of the changes in the production of energy from hydroelectric sources in these scenarios are sent directly to the LEAP model, where the representation of supply and demand of the current electricity matrix of the State of Minas Gerais is modelled and where the future evolution of the installed capacity will be projected.

2.1. WEAP Model

For modelling in WEAP, the following input data are required, depending on the applications desired by the user. The data required can be seen in Table 1:

The data used in this work are in the reference [18] including the data about the plants located in Minas Gerais, provided by the CEMIG, and the average data of the flows obtained from the ONS. The calculation method that the WEAP algorithm uses to obtain power production can be checked in the WEAP User's Guide [19]. The WEAP model was used to simulate the electricity generation in the horizon from 2019 to 2049 of the 22 largest Hydroelectric Power Plants (HPP) located in the State of Minas Gerais, in a deterministic approach. These 22 most representative HPP in terms of granted capacity are identified in Table 2.

2.2. LEAP Model

The LEAP modelling operates on two basic conceptual levels. At one level, built-in calculations of the LEAP handle energy, emissions, and cost-benefit accounting operations. At the second level, the users enter

Table 1: Input data required by WEAP

Input	Data
Reservoirs	Total storage capacity; Initial reservoir volume (amount of water stored); Volume/elevation curve (relationship between the volume and the elevation of the reservoir); Evaporation (monthly net evaporation rate: evaporation minus precipitation on the reservoir surface); Groundwater "losses" (reservoir infiltration into groundwater).
Operation	Maximum volume of water in the reservoir; Maximum security level (below this level, water releases will be restricted); Maximum level of inactivity (reservoir volume not available for allocation).
Hydroelectricity	Maximum turbine flow (in m³/s); Water elevation (maximum water level over the turbine); Plant availability factor (percentage of time per month of the hydroelectric plant's operation); Generation efficiency (ratio between the electrical energy generated and the hydraulic energy that enters the system).
Water courses	Historical series of flow at the points of the hydroelectric plants.
Climate	Precipitation (historical series, monthly average); Temperature (historical series, monthly average).

Table 2. Hydroelectric Power Plants (HPP) in Minas Gerais [20].

HPP **(names in Portuguese)**	**Start of Operation** **(day/month/year)**	**Power** **(MW)**
Itumbiara	24/04/1980	2082.0
Marimbondo	25/10/1975	1440.0
Água Vermelha (old *José Ermírio de Moraes*)	22/08/1978	1396.2
Furnas	04/09/1963	1216.0
Emborcação	02/08/1982	1192.0
Nova Ponte	01/01/1994	510.0
Marechal Mascarenhas de Moraes (old *Peixoto*)	01/04/1957	492.1
Miranda	30/05/1998	408.0
Irapé	20/07/2006	399.0
Três Marias	01/01/1962	396.0
Simplício	05/06/2013	333.7
Aimorés	30/07/2005	330.0
Porto Colômbia	29/06/1973	320.0
Amador Aguiar I (old *Capim Branco I*)	21/02/2006	243.7
Amador Aguiar II (old *Capim Branco II*)	09/03/2007	210.0
Funil	30/12/2002	180.0
Baguari	09/09/2009	140.5
Guilman Amorim	02/11/1997	140.0
Risoleta Neves (old *Candonga*)	07/09/2004	140.0
Porto Estrela	04/09/2001	112.0
Queimado	16/06/2004	105.5
Salto Grande	01/01/1956	102.0
	Total:	11888.7

expressions which can be used to specify time-varying data or to create a wide variety of sophisticated multivariate models, allowing econometric approaches and simulation to be incorporated into the overall LEAP accounting framework. LEAP is designed around the concept of scenario analysis. The scenarios consider distinct assumptions of how an energy system might evolve over time. Using LEAP, it is possible to create and evaluate alternative scenarios, comparing their energy requirements, their social costs and benefits, and their environmental impacts.

In order to model in LEAP, the following data are required, depending on the application desired by the user:

- Demographic data;
- Economic data;
- General energy data (data contained in the energy balance such as production and consumption, by sector, national energy policies and plans, annual statistical reports for each energy source, emissions, and others);
- Demand data;
- Transformation sector data;
- Environmental data;
- Fuels data.

The data required for the LEAP model were obtained from several references, such as data about the State energy matrix [8], population data [21], energy supply technologies [22] and restricted data about the HPPs in the State of Minas Gerais [23].

In this work, characteristic parameters of generation technologies were used, obtained from the [24], as shown in Table 3. There is no forecast for the entry of new hydroelectric plants in the study horizon. For the other sources, growth rates obtained from the granted capacities were adopted, according to ANEEL data [25].

2.3. LEAP-WEAP Connection

The WEAP and LEAP programs are very similar tools in design and operation. Both were developed at SEI - Stockholm Environment Institute, with mutual collaboration between the development teams of each program, so they share some technical characteristics. After selecting the scenarios that will be developed in each model, the configuration data that describe the WEAP model are read by the LEAP, based on the choices of elements that will be mapped between them. An error check button makes it possible to verify any connection problems.

It is necessary to observe four restrictions that apply to the connection between models:

1. Both models must have the same base year and study horizon;
2. In LEAP, there must be only one year specified for data entry in *Current Accounts* mode;
3. The LEAP model must have only a single region;
4. LEAP and WEAP must have exact correspondence in terms of time slices, usually monthly.

Table 3. Characteristic parameters of generation technologies [24].

Technology	Investment cost US$/kW	Fixed cost US$/kW	Variable cost US$/GJ	Capacity Factor %	Efficiency %	Lifetime Years
Biogas	2449	50	1.8	85	40	25
Biomass Incineration	1905	13	0.5	66	35	25
Photovoltaics	1944	40	0	25	25	25
Photovoltaics Distributed	3000	40	0	32	25	25
Fuel Oil	1400	25	1.7	85	15	20
Hydro Large	2939	45	1	na	100	60
Hydro Small	3499	35	1	na	100	60
Hydro Strategic Large	2351	26	0	na	100	60
Natural Gas Combined Cycle	1260	20	2.5	85	57	30
Natural Gas Open Cycle	583	10	2.5	85	38	40
Nuclear (PLWR and PHWR)	7200	115	3.1	85	35	40
Wind on-shore	1620	36	0	31	100	30

na = not available

2.4. Scenarios

The modelling aims to investigate and quantify the behaviour of hydropower generation in plants located in the State of Minas Gerais, according to the definition of the assumptions, as well as pointing out the needs for expanding the generation capacity of the electricity supply system. To this end, five scenarios were established; they are presented and classified in Table 4.

The HGW is the reference scenario. In this scenario, the current data of the variables are based on the year 2019; there is no forecast of changing parameters influenced by policies or regulations. The monthly averages of the last 20 years for the flow recorded by ONS, data from the plants and the considerations for the energy demand are the necessary information to start the study of this scenario. The energy intensity increases 1.0% per annum based on the previous year.

The lack of data related to the effective influences of climate change on short-term precipitation regimes – short when compared to Intergovernmental Panel on Climate Change (IPCC) study periods (50, 70, 100 or more years) – makes it difficult to correlate hot and dry years and the reduction of flows in the plants' reservoirs. Thus, the *ceteris paribus* condition was used to verify the changes caused by different *stimuli* in the system's inflows and also to quantify the hydropower generation, as it was explained earlier in the Section 1.2. Thus, in the first scenario of water restriction, HGD, an average reduction of 0.5% p.a. was defined in the inflow of hydroelectric plants. For a sequence of very dry years, the HGVD scenario was designed, with the adoption of the index of 1.0% p.a. of water restriction. For both scenarios of water restriction, the increase of energy intensity is the same as for the reference scenario, HGW.

Such reductions for river inflows, 0.5% and 1%, could even be considered as optimistic reductions. However, they serve the purpose of shedding light on how the substitution of the hydropower source would have an additional environmental burden. More pessimistic forecasts indicate that between 2007 and 2040 these reductions in the river inflows located in basins in the Southeast region may reach 59% and 63% [26, 27]. This equates to an average reduction in flow rate of 1.4% to 1.5% per year.

The energy scenarios defined in LEAP were designed to observe responses to demand growth under different assumptions and assume economic growth reflected in energy intensity – EI (kWh/inhabitant). The D1 scenario imposes a growth of 1.5% p.a. for this parameter and, in the D2 scenario, the growth rate is 2.0% p.a. These indexes follow the initial assumption for this parameter, adopted in the HGW scenario, plus 0.5% and 1%, respectively, for scenarios D1 and D2, in order to quantify the interference in the values of electricity for demand and supply.

The growth assumption for EI is based on the recorded history of the Energy Balance of Minas Gerais (BEEMG), since the beginning of the series in 1978, an average annual growth rate of 2.97% p.a. until 2017 [8]. Thus, for the HGW, HGD and HGVD water scenarios, the value of 1% p.a. was adopted for this parameter, in order to maintain a conservative pattern of growth in relation to that calculated (2.97% p.a.).

3. Results

The EI growth for the HGW reference scenario is shown in Figure 3, being 4100 kWh/inhabitant in 2019

Table 4. Definition of the scenarios

Classification	Scenario	Abbreviation	Premises
Reference	*Hydro Gen From WEAP*	HGW	No policies or regulations (EI: +1.0% p.a.)
Climatic (flow rate)	*Hydro Gen Dry*	HGD	Dry scenario (Flow rate: -0.5% p.a.)
Climatic (flow rate)	*Hydro Gen Very Dry*	HGVD	Very dry scenario (Flow rate: -1.0% p.a.)
Energetic (EI)	*Demand 1*	D1	Economic growth (EI: +1.5% p.a.)
Energetic (EI)	*Demand 2*	D2	Strong economic growth (EI: +2.0% p.a.)

EI = Energy Intensity (kWh/inhabitant)

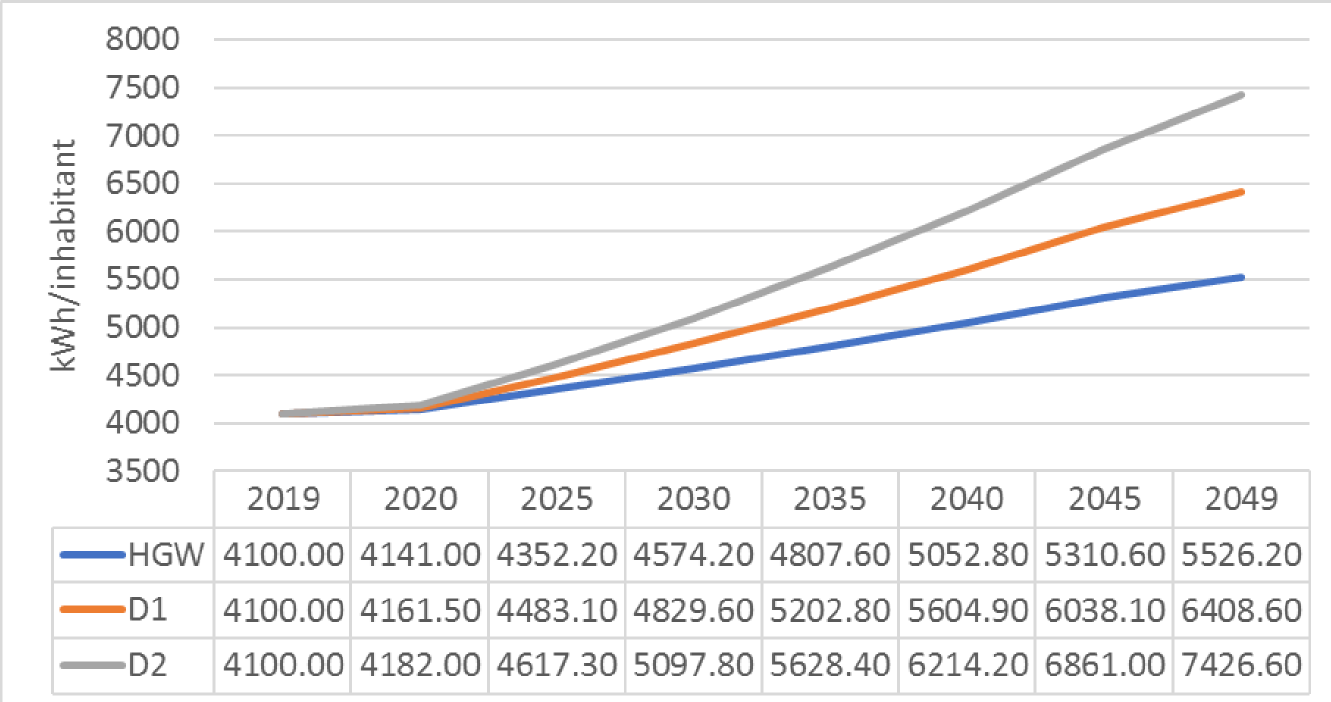


Figure 3: Energy Intensity in energy scenarios in kWh/inhabitant.

Table 5. Energy generation from HPPs in water scenarios, in TWh

Scenario	2019	2020	2025	2030	2035	2040	2045	2049
HGW	43.5	43.5	43.5	43.5	43.5	43.5	43.5	43.5
HGD	43.5	43.4	42.9	42.4	41.8	41.2	40.6	40.1
HGVD	43.5	43.3	42.3	41.1	39.9	38.6	37.3	36.2

Table 6. Electricity generation in energy scenarios, in TWh.

Scenario	2019	2020	2025	2030	2035	2040	2045	2049
HGW	86.8	103.7	111.8	119.6	126.9	133.6	139.6	144.0
D1	86.8	104.2	115.1	126.3	137.3	148.2	158.8	167.0
D2	86.8	104.7	118.6	133.3	148.5	164.3	180.4	193.5

until the end of the period, when it will reach 5526 kWh/in habitant in 2049 considering that this index is the total consumption of electricity of the State of Minas Gerais per inhabitant and encompass all economic sectors. The EI growth is the same observed in the HGW scenario for the HGD and HGVD water restriction scenarios. In Fig. 3, the HGW reference scenario is compared to scenarios D1 and D2, when applying the EI growth indices to the energy scenarios. At the end of the study period in 2049, the EI growth in scenarios D1 and D2 will be higher than in the HGW reference scenario, demonstrating the growth in electricity demand per inhabitant, of 1.5% p.a. in D1 and 2.0% p.a. on D2.

Energy generation, exclusively from the HPP in the HGD and HGVD water scenarios, is presented in Table 5 related to the water restriction in the inflows of the HPP. These are results from the WEAP and which are later used by LEAP for the composition with the other energy sources to meet the final energy demand.

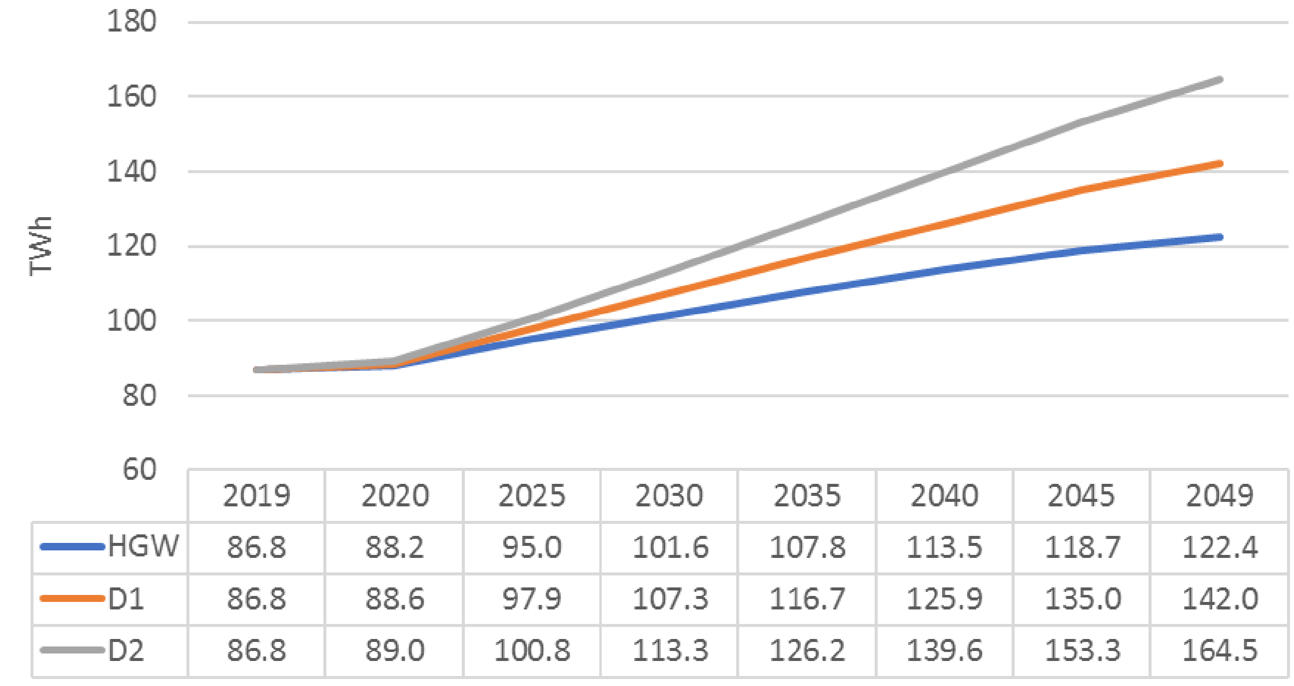


Figure 4: Final electricity demand in energy scenarios, in TWh.

Table 7. Electricity generation - HGD scenario, in TWh.

Source	2019	2020	2025	2030	2035	2040	2045	2049
PVP	1.2	1.8	2.4	3.0	3.4	3.8	2.8	4.1
THP biomass	3.2	6.5	8.6	10.6	12.2	13.5	9.8	14.6
THP fossil	1.8	8.8	11.5	14.1	16.3	18.1	25.4	20.7
Electricity Import	32.4	35.4	38.1	41.1	44.2	47.6	51.3	54.5
SHP	4.0	6.4	6.7	7.1	7.4	7.8	8.2	8.5
HGP	0.8	1.4	1.4	1.4	1.4	1.5	1.5	1.5
HPP	43.5	43.4	42.9	42.4	41.8	41.2	40.6	40.1
Total (TWh):	86.9	103.7	111.8	119.6	126.9	133.6	139.6	144.0

In the LEAP energy scenarios, the results of power generation are presented in Table 6, in TWh.

Total electric energy losses in transmission and distribution, including technical losses - those inherent to the distribution processes - and non-technical losses were estimated at 15%, an index close to the average calculated (14%) by utilities [28]. This results in a difference between the results in Table 6 and Figure 4. It can be considered that the value of electricity demand of 86.8 TWh, in the base year 2019, already considers the index of technical and non-technical losses. The year 2020 was the first year of the projection calculated by LEAP and considers the discount of these losses from then on in the study horizon, according to the specific field for inserting this parameter (Losses) in the LEAP software. This explains why the same value appears in Table 6 and Figure 4 for the year 2019.

In the water scenarios, there is a reduction in electricity generation in the study horizon, according to the assumptions. As it is possible to verify in Table 7, in the HGD scenario, the annual generation value of the HPP is decreasing over the study period, while the electricity production by Photovoltaic Plants (PVP) and Thermoelectric Plants (THP) increase.

Table 8 shows a more severe reduction for HPP electricity generation in the HGVD scenario, which implies a greater share of generation and dependence on PVP and THP sources to meet the demand.

As Table 9 shows, in the energy scenarios in which there is greater growth of the EI and with the limitation of the HPP source, the largest growths of the other sources are observed. The total demand in the D1 scenario is almost 16% higher than in the HGW scenario.

In the scenario D2, there is the greatest variation in EI in the study horizon when it reaches 7426.6 kWh/inhabitant in 2049, as it can be seen in the Table 10, according to the initial assumption for this scenario.

The result of this modelling points to a growth of 34% in relation to the HGW scenario; it is a scenario especially more intensive in the use of the fossil source.

The predictions for the GHG emissions considered only the two more significant sources, THP biomass and THP fossil; the results are shown in Figure 5 for all scenarios.

The estimated GHG emission results presented in the Figure 5 have significant growth in all scenarios. The model shows a decrease for two renewable sources, PVP and THP biomass, from 2040 to 2045. This decrease is filled by THP fossil, what increases GHG emissions in 2045. On the other hand, these renewable sources grow again in 2049, regaining their place at the expense of THP fossil. Consequently, a reduction in GHG emissions can be observed. These values indicate the possibility of the growth of externalities associated with emissions. The way to mitigate these externalities may occur through the implementation of policies to encourage the increase of energy efficiency with greater rigor, as well as making solar energy effectively important in the State energy matrix, eventually subsidising the dissemination of this technology. The State of Minas Gerais has excellent conditions for expanding the distributed generation of photovoltaic solar energy, through microgeneration systems (up to 75 kW) and minigeneration (above 75 kW up to 5 MW) implemented in homes, businesses, industries, public buildings and rural properties, although they were not considered in this work.

As it was the first time these scenarios were evaluated, there are no other results to compare. However, considering that the results obtained followed the

Table 8. Electricity generation - HGVD scenario, in TWh.

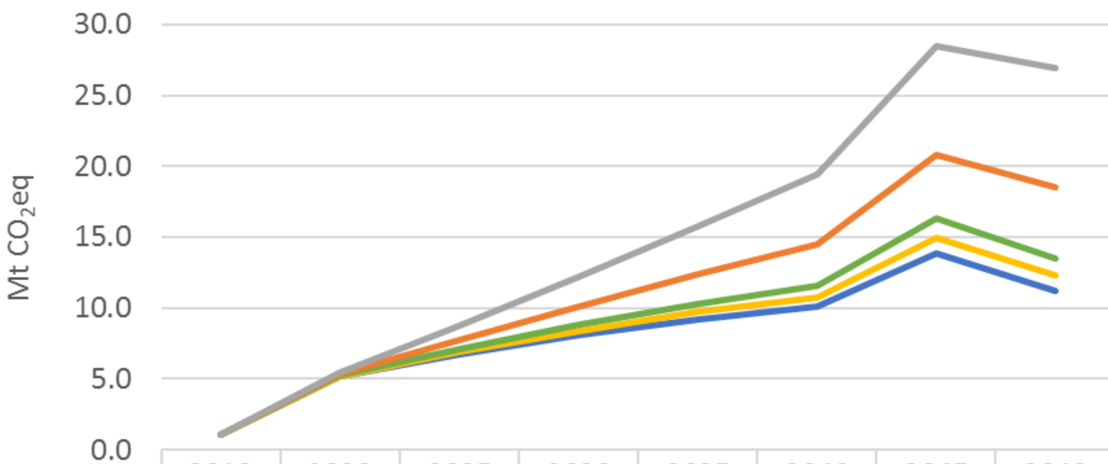
Source	**2019**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2049**
PVP	1.2	1.8	2.5	3.1	3.6	4.1	3.0	4.6
THP biomass	3.2	6.6	8.9	11.0	12.9	14.5	10.7	16.0
THP fossil	1.8	8.8	11.9	14.8	17.3	19.4	27.7	22.7
Electricity Import	32.4	35.4	38.1	41.1	44.2	47.6	51.3	54.5
SHP	4.0	6.4	6.7	7.1	7.4	7.8	8.2	8.5
HGP	0.8	1.4	1.4	1.4	1.4	1.5	1.5	1.5
HPP	43.5	43.3	42.3	41.1	39.9	38.6	37.3	36.2
Total (TWh):	86.9	103.7	111.8	119.6	126.9	133.6	139.6	144.0

Table 9. Electricity generation - Scenario D1, in TWh

Source	**2019**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2049**
PVP	1.2	1.9	2.7	3.6	4.4	5.2	4.2	6.2
THP biomass	3.2	6.7	9.7	12.7	15.5	18.2	14.7	21.7
THP fossil	1.8	9.0	13.0	16.9	20.8	24.4	35.3	31.1
Electricity Import	32.4	35.4	38.1	41.1	44.2	47.6	51.3	54.5
SHP	4.0	6.4	6.7	7.1	7.4	7.8	8.2	8.5
HGP	0.8	1.4	1.4	1.4	1.4	1.5	1.5	1.5
HPP	43.5	43.5	43.5	43.5	43.5	43.5	43.5	43.5
Total (TWh):	86.9	104.2	115.1	126.3	137.3	148.2	158.8	167.0

Table 10. Electricity generation - Scenario D2, in TWh.

Source	**2019**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2049**
PVP	1.2	1.9	3.1	4.3	5.6	6.9	6.1	8.9
THP biomass	3.2	6.9	11.0	15.3	19.8	24.3	21.5	31.3
THP fossil	1.8	9.2	14.7	20.5	26.5	32.6	48.3	45.3
Electricity Import	32.4	35.4	38.1	41.1	44.2	47.6	51.3	54.5
SHP	4.0	6.4	6.7	7.1	7.4	7.8	8.2	8.5
HGP	0.8	1.4	1.4	1.4	1.4	1.5	1.5	1.5
HPP	43.5	43.5	43.5	43.5	43.5	43.5	43.5	43.5
Total (TWh):	86.9	104.7	118.6	133.3	148.5	164.3	180.4	193.5



	2019	2020	2025	2030	2035	2040	2045	2049
HGW	1.1	5.2	6.7	8.1	9.2	10.1	13.8	11.2
HGD	1.1	5.2	6.9	8.4	9.7	10.8	15.0	12.3
HGVD	1.1	5.2	7.1	8.8	10.3	11.6	16.3	13.5
D1	1.1	5.3	7.7	10.1	12.4	14.5	20.8	18.5
D2	1.1	5.5	8.8	12.2	15.8	19.4	28.5	26.9

Figure 5: GHG emissions - results for all scenarios.

expected behaviour, and that the programs used in the simulations are widely used by the academic community to perform these types of predictions, we can say that the model was qualitatively validated. The next step would be to redo the scenarios using other tools to enrich the found results.

4. Conclusions

In this work, an integrated analysis of the water-energy-emissions nexus was presented. Computational models developed on LEAP and WEAP were used to predict scenarios considering cases of decreasing in the rainfall regime in the Brazilian State of Minas Gerais and increasing energy intensity. Final electricity demand, in the reference scenario, increased by 40.8% and, in alternative scenarios, there was an increase between 63.6% and 89.5% when reductions in the rainfall regime were considered.

Hydroelectric power generation reduces by 7.8% if the flow rate reduction is 0.5% per year according to the HGD scenario. On the other hand, a reduction of 16.8%

in hydroelectric power generation occurs when the flow rate reduction is 1.0% per year according to the HGVD scenario. These reductions in HPP were supplied by the expansion of PVP and THP.

The scenarios of increased energy intensity, D1 and D2, showed an increase in demand, in 2049, 16% and 34% higher than in the base scenario, HGW, respectively. Since hydroelectric plants have restrictions on increasing their installed capacity, this increase in demand was almost entirely supplied by THP.

About the estimation of GHG emissions, two energy sources, THP biomass and THP fossil have significant growth in all scenarios, indicating the possibility of the externalities increasing associated with emissions. A possible way to mitigate these externalities is directly connected with policy implementation to encourage the increase of energy efficiency with greater rigour and also with the possible insertion of other energy sources, for example, solar and nuclear energy in the State energy matrix, eventually subsidising the dissemination of these technologies.

The results found are important when discussing the planning of the expansion of the electrical system. The characteristic of reliability is a fundamental condition to guarantee the supply of future energy demand. Therefore, it is necessary to plan the expansion of the energy system, since the environmental restrictions for the construction of new large hydroelectric projects are even more restrictive. Furthermore, it is necessary to discuss the technical availability for the viability of these projects since the complementation of these projected capacities falls on the other energy sources. Therefore, such results are extremely important for decision-making about the future of the energy matrix of the State of Minas Gerais and its influence on the national energy matrix.

Future work could: evaluate the importation of electricity to the State of Minas Gerais, considering the impacts of water restrictions in other regions of the country; study the water balance of hydroelectric plants, carry out projections and evaluate the issue of energy security in the State of Minas Gerais in the long term, considering the age of the plants in operation; consider the assessment of the resource nexus between water and energy, and quantify the flow of hydrographic basins for different uses, under adverse conditions; use other planning programs to verify the results found.

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