Revista Brasileira de Ciências Ambientais
Brazilian Journal of Environmental Sciences

Analysis of the water–energy–greenhouse gas nexus in a water supply system in the Northeast of Brazil

Análise do nexo água-energia-gases de efeito estufa em um sistema de abastecimento de água no Nordeste do Brasil

Isaura Macêdo Alves[1], *Saulo de Tarso Marques Bezerra*[1], *Gilson Lima da Silva*[1], *Armando Dias Duarte*[1], *Henrique Leonardo Maranduba*[2]

ABSTRACT

In recent years, water utilities have been under pressure to increase the efficiency of their processes, mainly due to the decrease in water availability and the need to increase environmental sustainability in their processes. Leak reduction is clearly an important part of sustainable management in the water industry, and its impacts should be assessed with a broader environmental protection objective. This study aimed to present an environmental and energy assessment of the water supply system (WSS) in Caruaru City, northeast of Brazil, for different levels of water loss. This research is one of the first to assess the environmental impacts of a WSS in Latin America. Primary data adopted for preparing the inventory were provided by the water utility, and modeling and analysis were performed with the SimaPro 8.0® program. Cumulative energy demand (CED) was used to track the energy consumption of the system's life cycle. Greenhouse gas (GHG) emissions were calculated through the IPCC GWP 100a method with emissions expressed as CO_2-Eq. The data sets from life-cycle inventories were used from the Ecoinvent 3.1 database. Four scenarios with different levels of water loss were analyzed. Scenario S0 was represented with the real conditions of the system, whereas the others considered hypothetical indices. The percentages proposed for Scenarios S1, S2, and S3 were based on indices that indicate good loss rate in the distribution network for the Brazilian reality (25%), reduction by half of loss rates, and excellent loss rates for the water pipeline system (5%) and distribution network (10%). The analysis of the processes' contributions showed that the electricity consumption

RESUMO

Nos últimos anos, as concessionárias de água têm sofrido pressão para melhorar a eficiência de seus processos, principalmente por causa da diminuição da disponibilidade hídrica e da necessidade de se aumentar a sustentabilidade ambiental de seus processos. A redução de vazamentos é claramente uma parte importante do manejo sustentável no setor de água, e seus impactos devem ser enfrentados com uma visão mais ampla de proteção ambiental. Este estudo tem como objetivo apresentar uma avaliação ambiental e energética do sistema de abastecimento de água da cidade de Caruaru, Nordeste do Brasil, para diferentes níveis de perda de água. Esta pesquisa é uma das primeiras a avaliar os impactos ambientais de um sistema de abastecimento de água na América Latina. Os dados primários adotados para a preparação do inventário foram fornecidos pela concessionária de água, e a modelagem e análise foram realizadas com o programa SimaPro 8.0®. A demanda acumulada de energia (CED) foi usada para rastrear o consumo de energia do ciclo de vida do sistema. As emissões de gases de efeito estufa foram calculadas pelo método IPCC GWP 100ª, com emissões expressas como CO_2–Eq. Os conjuntos de dados dos inventários de ciclo de vida foram usados do banco de dados Ecoinvent 3.1. Analisaram-se quatro cenários com diferentes níveis de perda de água. O cenário S0 representou as condições reais do sistema e os demais consideraram índices hipotéticos. Os percentuais propostos para os cenários S1, S2 e S3 foram baseados em indicadores que apontam: bom índice de perdas na rede de distribuição para a realidade brasileira (25%), redução pela metade dos índices de perdas e excelentes índices de perdas no sistema hidráulico (5%) e rede de distribuição (10%). O consumo de energia

---

[1] Universidade Federal de Pernambuco – Recife (PE), Brazil.

[2] Flextronics Instituto de Tecnologia – Sorocaba (SP), Brazil.

Correspondence address: Saulo de Tarso Marques Bezerra – *Campus* do Agreste – Avenida Marielle Franco, s/n., km 59 – Nova Caruaru – CEP: 55014-900 – Caruaru (PE), Brazil. E-mail: saulo.tarso@ufpe.br

Conflicts of interest: the authors declared that there is no conflict of interest.

Funding: Brazilian National Council for Scientific and Technological Development (Conselho Nacional de Desenvolvimento Científico e Tecnológico—CNPq) (Brazil) and Coordination for the Improvement of Higher Education Personnel (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—CAPES) (Brazil) (financial code 001).

Received on: 01/21/2021. Accepted on: 10/27/2021.

https://doi.org/10.5327/Z217694781036

of the pumping systems of water mains represented the greatest environmental impact in all scenarios. The most efficient scenario would result in a 52% reduction in the emission of GHGs, demonstrating that the increase in the hydraulic efficiency of the distribution networks represents a significant opportunity to reduce the environmental impacts of the processes.

Keywords: water supply system; environmental impact; water loss; hydraulic efficiency; greenhouse gas emissions.

elétrica dos sistemas de bombeamento das adutoras apresentou o maior impacto ambiental em todos os cenários estudados. O cenário mais eficiente resultaria em redução de 52% na emissão de gases de efeito estufa, demonstrando que o aumento da eficiência hidráulica das redes de distribuição representa uma oportunidade significativa para reduzir os impactos ambientais dos processos.

Palavras-chave: sistema de abastecimento de água; impacto ambiental; perda de água; eficiência hidráulica; emissões de gases de efeito estufa.

Introduction

Water, energy, and greenhouse gas (GHG) emissions are interconnected and have complex interactions (Nair et al., 2014; Thiede et al., 2016; Chhipi-Shrestha et al., 2017). The integration of water and energy interdependence processes in water systems improves the understanding of the trade-offs between these resources in management and politics (Escriva-Bou et al., 2018). Current water and energy resource crises are expected to increase progressively because of population growth and future climate change. Energy efficiency interventions can contribute considerably to reducing water use, reducing GHG emissions, and meeting climate-related mitigation goals. Understanding and modeling the complex nature of the interconnections between water and energy is essential for the efficient use of these resources (Basheer and Elagib, 2018). The energy use and GHG emissions associated with water management are poorly understood and have only partially been considered in water management and planning (Rothausen and Conway, 2011).

The global community is looking for new approaches and solutions for adapting to climate change and the challenges of increased water and energy consumption brought about by development. The nexus between energy and water is dynamic. Actions in one area generally have impacts on both, with profound economic, environmental, and social implications (Rasul and Sharma, 2016). The importance of the interdependence between water and energy is widely recognized. The world's energy security depends on the availability of water, as almost all energy production technologies (e.g., nuclear, thermoelectric, and hydroelectric) require large amounts of water (Nair et al., 2014), whereas water systems need energy for their processes.

Predominantly, water–energy–GHG emissions nexus has been studied regarding political and regulatory challenges and their interaction with food supply, climate change, growth, and the right to water. From a modeling perspective, this nexus has been studied using various technical and economic approaches, mainly considering co-production facilities as the coupling components between water and energy networks (e.g., Chhipi-Shrestha et al., 2017; Escriva-Bou et al., 2018; Oikonomou and Parvania, 2018; Zahraee et al., 2020).

Nair et al. (2014) highlighted the importance of modern thinking in relation to the increase in water supply, emphasizing that the search for water sources must consider measures that contribute to the mitigation of global warming, reducing energy consumption and GHG emissions. The climate system is largely regulated by the global balance of water and energy and its spatial and temporal variations, which involve the flow of energy and water within this system, besides exchanges with outer space and surface (Zhou et al., 2015). These flows are intrinsically interconnected, largely due to the characteristics and properties of water and energy. Water is essential for most energy-generation processes, while energy is indispensable in the distribution of water for different uses. On average, approximately 80% of the energy consumed by water supply systems (WSS) is spent to transport water from springs to consumers (Jeong et al., 2018; Oikonomou and Parvania, 2018). In Brazil, the sanitation sector uses roughly 2% of the country's total electricity consumption, equivalent to more than 11 billion kWh/year.

Over the last decades, due to the decrease in water availability, the need for environmental sustainability, and the increase in energy costs, Brazilian water utilities are being subjected to pressure to increase the efficiency of their processes. In contrast, most WSS have high levels of water loss. In developing countries, utilities are used to operating with high volumes of losses. The aging of systems, combined with failures in loss management in utilities, results in loss rates well above acceptable. To minimize the problem, the management of supply systems must involve multiple actions that include the control of real and apparent losses, including active leakage control, pressure management, elimination of illegal use of water services, educational campaigns, implementation or replacement of water meters, and rehabilitation of distribution networks.

Although water losses are inherent in all WSS, the high rates of infrastructure deterioration and operational deficiency considerably aggravate the problem. The aging of systems, combined with failures in loss management in utilities, results in loss rates well above acceptable. Lost water includes not only the value of water as a limited resource but also the added value of the treatments to make water potable (e.g., expenses with chemicals for treatment), the cost of operating distribution services (e.g., cost of energy), and the social impact of leaks that may prevent the provision of sufficient supply services to customers (D'ercole et al., 2016). The high rates of loss result in greater water extraction and increase the consumption of electricity for the collection, transportation, treatment, and disposal of water to consumers. Each cubic meter lost directly results in wasted energy, which in turn increases GHG emissions.

Activities that aim to reduce the volume of water abstraction can effectively generate their own environmental impacts, namely, the result of the works, equipment, and infrastructure used (Pillot et al., 2016). Leak reduction is clearly an important part of sustainable management in the water industry, and its impacts should be assessed with a broader environmental protection objective. In this regard, the life-cycle assessment (LCA) can provide more comprehensive analyses of the environmental issues associated with loss from WSS. Recently, this type of assessment is taking on a more prominent role in the formulation of environmental and sustainable development policies. Renowned institutions, such as the World Resource Institute, adopt the concept of life cycle in the evaluation of processes, and there is an increasing number of actors defending the reduction of the environmental impact associated with global consumption.

LCA methodology is a well-established and standardized analytical method to quantify environmental impacts, which has been applied to products or services (Jacquemin et al., 2012; Kjaer et al., 2018; Peña et al., 2021). The ISO 14040-14044 (ISO, 2006a, 2006b) standards demonstrate the methodological procedures for implementing the tool and analysis. This approach allows a comparison of different management systems in the sector and, through the identification of the most impactful phases, provides suggestions for improving environmental performance of goods and services (Bartolozzi et al., 2018). LCA is a versatile environmental tool that can be adapted for different uses in the water industry.

LCA can include the different phases of the urban water cycle, including the abstraction, treatment, transmission, distribution, consumption, and, in some cases, the collection, treatment, and disposal of wastewater (Meron et al., 2016). It has been used to analyze several urban water systems, including water treatment and distribution systems, and wastewater processing. Studies have focused on distribution, proposing predictive maintenance strategies or analyzing the selection of materials. The state of the art concentrates numerous works based on LCA for the analysis of WSS, with an emphasis on the comparison of the impacts caused by different sources or types of systems (Garfí et al., 2016; Li et al., 2016; Ghimire et al., 2017; Jeong et al., 2018; Hsien et al., 2019).

LCA studies on Brazilian WSS are still incipient, and the databases available for assessing environmental impacts are rare. Carrying out local work with a regionalized approach due to the peculiar characteristics of the different regions of the country, such as climatic conditions, production factors, productive systems, management systems, and waste recycling, is important. Therefore, given the fact that the application of LCA in the country is relatively a new field, a significant scarcity of studies available in the literature is noticeable.

In urban water management, LCA is considered the most dominant and appropriate method for assessing environmental impacts. In this context, the objective of this study was to evaluate the environmental and energy impacts of the life cycle of WSS in Caruaru City, Pernambuco State, for different levels of water loss, using system-specific data. Energy intensity and GHG emissions were selected as the major measurements for the water–energy–GHG emissions nexus.

Materials and Methods

Characterization of the study area

Caruaru City (Figure 1) is in the northeast of Brazil, about 130 km from Recife, capital of Pernambuco State (PE), Brazil. The region is

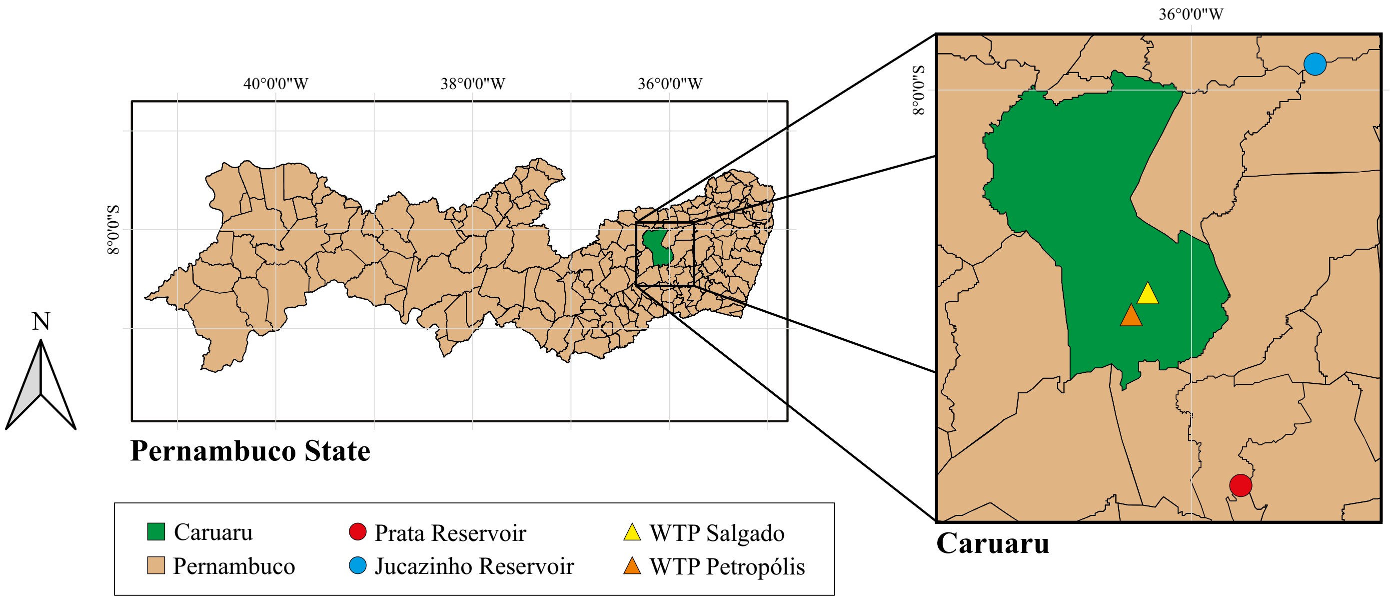

Figure 1 – Study area.

characterized as having a semi-arid climate, with hot, dry summers and mild winters. Its municipal headquarters has an average annual temperature of 22.7°C. The city's population surpasses 350,000 inhabitants, spread over a territorial area of 921 km².

Water supply in Caruaru City is provided by Companhia Pernambucana de Saneamento (Compesa), which is a Brazilian company that holds the concession of basic sanitation services in Pernambuco State. At present, the municipality can be supplied by the Jucazinho and Prata reservoirs, which are located on the Capibaribe and Una rivers, respectively, both in Pernambuco State. In 2016, Caruaru was supplied only by Prata's water system, because the reservoir of Jucazinho, which has a capacity of 202 million m³ and was the city's main source of water, collapsed in November 2016 (Santana et al., 2019).

The Prata reservoir was built in 1998, has a cumulative capacity of 42.1 million m³, and is in Bonito City (PE). It is inserted in the hydrographic basin of the Una river, whose drainage area is 151 km². The Prata pipeline system has three raw water pumping stations (*Estações Elevatórias de Água Bruta* — EEAB) and is responsible for supplying Petrópolis and Salgado Water Treatment Plants (WTPs). Table 1 shows the characteristics of the pumping stations of the water pipeline system, whereas Table 2 shows the electrical energy consumed by them. The average flow of the system is about 700 L/s.

According to information from the local service provider, the pumping stations that supply Caruaru City are among the 10 largest consumers of electric energy in Pernambuco State, demonstrating the importance of conducting energy efficiency studies in these units. Petrópolis and Salgado WTPs adopt the conventional treatment system composed of the following steps: clarification (fast mixing/coagulation, slow mixing/flocculation, decantation and filtration), disinfection, pH correction, and storage. In 2016, WTPs treated a total volume of 19.4 million m³; chlorine and aluminum sulfate are the chemicals used (Table 3).

Table 1 – Characteristics of the EEAB of the Prata pipeline system (base year 2016).

Discrimination	EEAB-01	EEAB-02	EEAB-03
Water origin	Prata reservoir	EEAB-01	EEAB-02
Water destination	EEAB-02	EEAB-03	WTP Petrópolis
Number of pumping systems	3 + 1 (reserve)	3 + 1 (reserve)	3 + 1 (reserve)
Rated motor power (cv)	750	750	750
Flow rate (L/s)	325	450	357
Pumping head (m)	98	96	130

The methodological structure of the LCA included the definition of objectives and scope, inventory analysis, impact analysis, and interpretation. The process cycle, on the other hand, includes the subsystems: water abstraction, transmission, treatment, and distribution. Four scenarios were proposed for WSS of Caruaru with different water loss rates to assess the energy intensity and, consequently, the system's GHG emissions. Scenario S0 was represented with the real conditions of the system, whereas the others considered hypothetical indices. The percentages proposed for Scenarios S1, S2, and S3 were based on indices that indicate good loss rate in the distribution network for the Brazilian reality (25%), reduction by half of loss rates, and excellent loss rates for the water pipeline system (5%) and distribution network (10%). The evaluated scenarios were as follows:

- Scenario S0: corresponds to the real scenario; that is, this scenario adopts the current operating conditions of the pipeline system (loss rate of 12.19%) and the water distribution network (loss rate of 54.09%) in 2016;
- Scenario S1: corresponds to the situation in which the loss rate of the producing system remains unchanged and admits a reduction of water loss in the water distribution network to the value of 25%;
- Scenario S2: admits a 50% reduction in the water loss index of the producing system and the water distribution network;
- Scenario S3: establishes a reduction in the loss rate to 5% in the water pipeline system and admits a loss rate in the water distribution network of 10%.

Life-cycle assessment

LCA was based on the International Organization for Standardization (ISO) 14040 series, which included definition of objectives and scope, inventory analysis, impact analysis, and interpretation.

Table 2 – Energy consumption of the EEAB of the Prata pipeline system (base year 2016).

EEAB ID	EEAB I	EEAB II	EEAB III
Annual consumption (kWh)	11,075,296	11,755,225	14,525,677
Specific energy consumption (kWh/m³)	0.50	0.53	0.66
Cost (BRL)	3,442,404.52	3,618,753.72	4,451,792.25

Table 3 – Annual consumption of chemical products used in Salgado and Petrópolis WTPs.

WTP	Chlorine (kg/year)	Aluminum sulfate (kg/year)
WTP Salgado	59,400	333,150
WTP Petrópolis	144,000	879,140
Total	203,400	1,212,290

GHG emissions were calculated as per the IPCC GWP 100a method (IPCC, 2013), with emissions expressed as CO2-Eq. per cubic meter of water distributed. The life-cycle inventory (LCI) was compiled with the Ecoinvent 3.1 database, available in the SimaPro® 8.0 software. This database is commonly adopted in the literature (e.g., Jeong et al., 2015; Pillot et al., 2016; Buyle et al., 2019; Esnouf et al., 2019; Duarte and Silva, 2020; Valencia-Barba et al., 2020). Cumulative energy demand (CED) (also called "primary energy consumption") was used to track the electricity consumption of the system's life cycle. The Brazilian electrical matrix was adopted in this study.

The SimaPro® software, faculty version, which has a large database and impact assessment methods, was used to build the LCI. This software has been widely applied by several researchers (e.g., Uche et al., 2015; Garfí et al., 2016; Rodriguez et al., 2016; Pokhrel et al., 2020; Rasul and Arutla, 2020; Trinh et al., 2020), as it allows creating a model of the studied system, inserting the inventory (manually or using databases), and calculating impacts using different life-cycle impact assessment methods.

The LCA aims to understand the process-based life-cycle model based on actual data from a WSS, so that utility managers can make targeted decisions; the importance of analyzing the environmental impacts associated with the cradle-to-gate life cycle of a system with different rates of water loss; and the environmental and energy impacts of WSS. Figure 2 shows the system limit of the LCA model. The processes begin with water collection in the Prata reservoir and end with distribution to consumers, excluding all subsequent phases (e.g., water use; and sewage collection, treatment, and discharge). The study considers the electricity consumption of the subsystems and the use of chemicals from the treatment plant, which included the processes of flocculation, sedimentation, filtration, adsorption, treatment, and primary disinfection.

The functional unit was defined as a 1 m^3 of drinking water distributed. In the literature, this functional unit is widely adopted for LCA in WSS (Jeong et al., 2015; Uche et al., 2015; Garfí et al., 2016; Rodriguez et al., 2016; Hsien et al., 2019; Meron et al., 2020). Primary inventory data were provided by Compesa. In parallel, technical visits to the site and periodic discussions were carried out with the company's technicians, in order to ensure the correct use of data. Electricity consumption and chemical products were inventoried, according to the system boundary. For chemical processes, data were taken from the Ecoinvent 3.1 database. The infrastructure was excluded from the LCI, as it is not directly impacted by the reduction of water loss (i.e., the existing pipes will not be replaced by smaller pipes due to the reduction of water loss). For applying the LCI, the collected data were processed to quantify GHG emissions and the CED for all evaluated processes.

The consumption of electricity from the pumping stations, the Sector Units of Petrópolis and Salgado WTPs, and the distribution of water to Caruaru City (Pernambuco State) were inventoried. Table 4 shows the data on the electricity consumption of the evaluated subsystems. The characterization factors allow to quantitatively compare the contribution of each elementary flow to the impact category indicator. The Impact Category for electric energy was Global Warming Potential (GWP), the class that represents the relevant environmental issues to which the results of the life-cycle impact assessment can be associated, that is, the IPCC method, 100-year horizon, was chosen for the study, considering the IPCC GWP 100 category. Cumulative Energy Demand V1.09 was used for energy charges.

The chemicals used in water treatment mainly consist of products for disinfection, coagulation, and flocculation. The manufacture of chemical products requires energy and, therefore, produces GHG emissions. The use of these products was determined using the raw data provided by Compesa. The energy required to manufacture the chemicals was determined using values published in the literature and was combined with chemical usage data to establish the energy intensity incorporated in the values for each chemical. With the type and quantity of chemical products used in kg/m^3 of treated water, the amount of carbon dioxide equivalent (CO2-Eq.) was obtained from the system, directly from the Ecoinvent 3.1 database. This international database

Table 4 – Electricity consumption of WSS in 2016.

Subsystem	Electricity consumption (kWh/year)
Abstraction and transmission	37,356
Treatment	3,828.
Distribution	14
Total	41,199

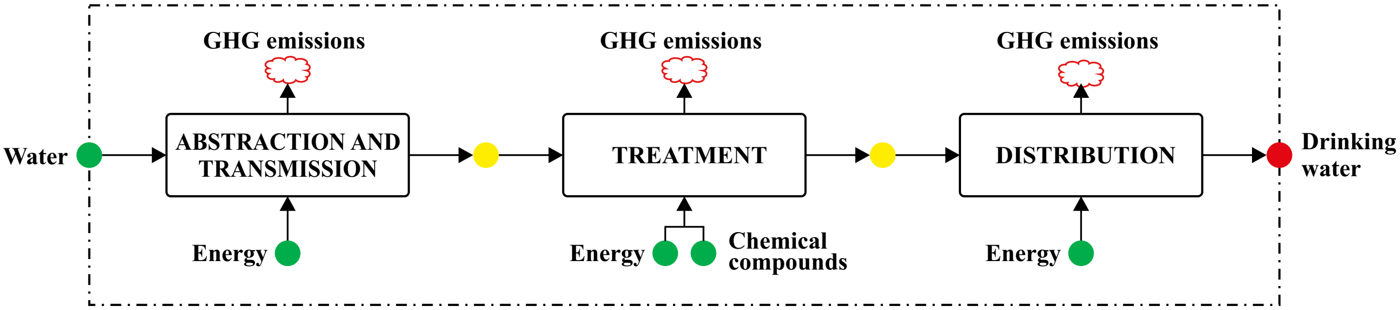

Figure 2 – Flowchart of the border of the evaluated system.

gathers elementary components, such as existing material, energy, processes, transports, and equipment. Input of resources and materials came from internal data of the water utility and was processed with the databases category IPCC GWP 100-year method.

The requirements considered in the life-cycle impact assessment were as follows:

- Temporal coverage: The collected data correspond to 2016; the spreadsheet contains monthly data of this year;
- Geographic coverage: The Prata reservoir is located in Bonito City, whereas the WTPs and the water distribution network are in Caruaru City;
- Technological coverage: This included raw water pumping stations, Petrópolis and Salgado WTPs, and water distribution network;
- Representativeness: The data for the study were acquired and collected at the operating site of the units under study, from internal company reports, satisfactorily reflecting the studied system.

Results and Discussions

Impacts of water loss on the WSS in Caruaru City (Pernambuco State), considering the water–energy–carbon nexus, were evaluated for each proposed scenario. Table 5 shows the water volume in each phase of the system. The great expansion of the city's water demand in recent years combined with the region's water scarcity has spurred the search for distant sources of supply, which makes the supply extremely energy intensive.

The energy consumption of Caruaru's WSS varied from 1.98 to 2.13 kWh/m^3, being higher than the specific energy consumption of Pernambuco's (0.29 kWh/m^3), the Northeast's (0.33 kWh/m^3), and Brazil's WSS (0.42 kWh/m^3) (SNIS, 2018). The process contribution analysis indicates that the electricity used for water supply was the main contributor to the categories of environmental impact. This study found that the system has a higher energy consumption than other systems in the United States. Arpke and Hutzler (2006) focused on the GWP energy consumption of water systems in the United States and reported that direct electrical consumption ranges from 0.32 to 1.43 kWh/m^3; whereas studies conducted in Cincinnati (Xue et al., 2019) and Atlanta (Jeong et al., 2018) resulted in 1.25 and 0.62 kWh/m^3, respectively. Given these results, the importance of adopting water demand management actions as an alternative to reduce the system's energy consumption is highlighted.

Table 5 – Water volume at each stage of WSS.

Scenario	Volume (m^3)		
	Abstraction and transmission	Treatment	Distribution
S0	22,075,200	19,383,485	19,383,485
S1	13,512,912	11,865,688	11,865,688
S2	12,990,038	12,198,295	12,198,295
S3	10,408,498	9,888,073	9,888,073

WTPs had an energy demand of 0.223 KWh/m^3, which is less than the values presented by Arpke and Hutzler (2006), 0.11–0.66 kWh/m^3, and Xue et al. (2019), 0.38 kWh/m^3. WTPs had the lowest GHG emissions (0.124 kg of CO2-Eq./m^3) because energy consumption is small and the content of chemical agents' requirements for water potability had a low impact. The chemical element with the greatest impact was aluminum sulfate, which represented 37.1% of emissions. This fact was also presented in the study by Mohamed-Zine et al. (2013), who estimated that the greatest environmental burden results from the preparation of coagulants (> 30% for all impacts). In this study, data related to the chemicals were analyzed using the Ecoinvent 3.1 database. Information may not accurately represent the Brazilian reality. Preparing an inventory with Brazilian data is thus highlighted.

The assessment and interpretation of impacts represents the fourth phase of the LCA. According to the proposed methodology, the energy consumption of the life cycle was tracked with the CED method, with the quantification of impacts of WTPs' chemical products quantified based on the data from Ecoinvent 3.1. The energy intensity of subsystems in water abstraction and transmission, treatment, and distribution resulted in 1.750, 0.223, and 0.0007 kWh/m^3, respectively. In all the analyzed stages of WSS, the greatest impacts are related to electricity consumption. The results are similar to those found in studies by Lemos et al. (2013), Mohamed-Zine et al. (2013), Igos et al. (2014), Rodriguez et al. (2016), and Xue et al. (2019), who assessed the environmental profile of the water sector based on the LCA in different regions and stated that the greatest impacts of these systems are attributable to energy consumption.

It is noteworthy that energy consumption and GHG emissions are strongly influenced by intrinsic characteristics of the systems (e.g., distance from water sources to consumers, topography of the region) and by the management models adopted by water utilities (e.g., efficiency in loss management). In addition, utilities located in more developed countries have more financial resources to improve the infrastructure of their systems, which generally allows for better conditions to increase energy efficiency.

Figures 3 and 4 show the estimate of environmental and energy impacts of the system for each scenario, respectively. Water loss was found to have significantly influenced the results. Scenario S0 represents the real operating conditions of Caruaru's WSS for 2016. In 2016, the system was estimated to have emitted more than 11.5 million kg of CO2-Eq. The high values are corroborated with the study by Pillot et al. (2016), whose results indicated that the main source of impact of WSS is the energy consumed in water abstraction and transmission (pumping). Therefore, local geography and distance from water source to WTPs are important aspects and must be considered when designing

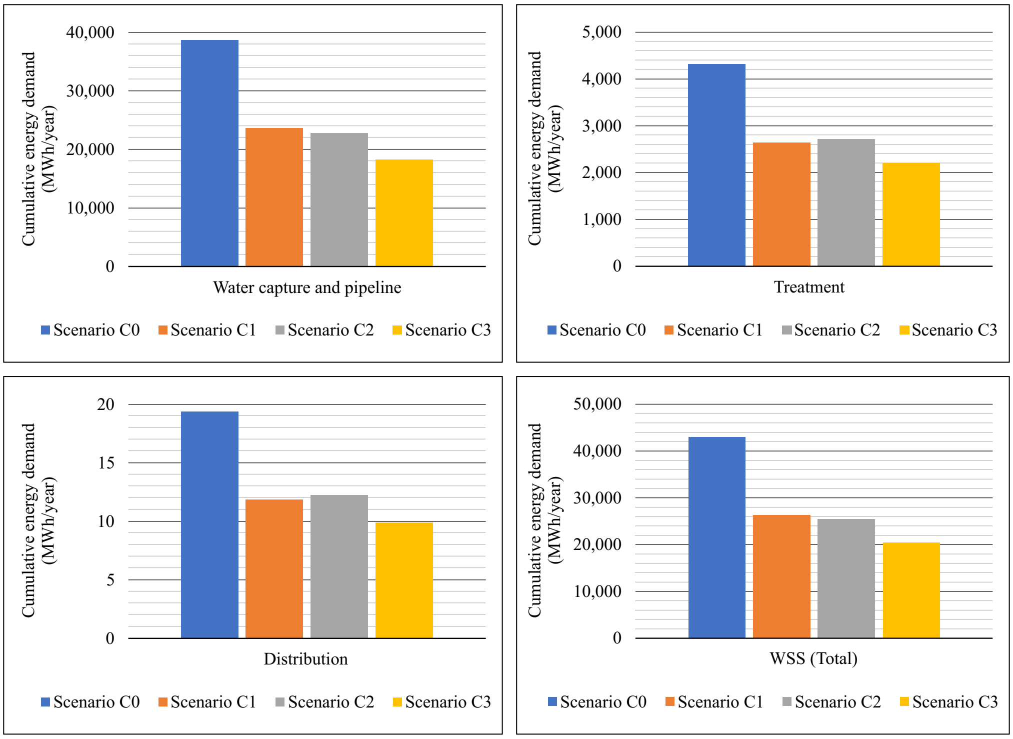

Figure 3 – Cumulative energy demand for the evaluated scenarios.

the urban water cycle. The water distribution network had an insignificant contribution to the impacts, as pipeline interventions were not considered, and the local topology allows for distribution by gravity (practically all the supply of treated water is carried out by gravity).

GHG emissions, considering the impact category chosen in the IPCC 100-year method, were 0.54 kg of CO2-Eq. for each cubic meter of water distributed in Scenario S0. The results were compatible with those by Meron et al. (2016), who stated that the GWP varies between 0.16 and 3.4 kg of CO2-Eq./m^3 of water supplied. Water abstraction and transmission stage was responsible for the GHG emissions of 0.42 kg of CO2-Eq./m^3, the treatment of 0.12 kg of CO2-Eq./m^3, and the distribution of 0.0002 kg of CO2-Eq./m^3. The low emission in distribution can be justified due to the low use of energy for pumping compared to the water pipeline system, which requires a high energy due to the topographic conditions of the water pipeline system of the Prata river. This is also justified by Rodriguez et al. (2016), who demonstrated that the topographic conditions of WTP location significantly influenced results. In that study, WTP presented a less favorable topology, emitting 0.38 kg of CO2-Eq./m^3, of which 86% corresponded to the prolonged consumption of energy during the pumping process.

In Scenario S1, the current operating conditions of the water pipeline system (loss rate equal to 12.19%) remain unchanged, whereas there is a reduction in the loss rate in the water distribution network to 25%. Results for this scenario estimated total emissions of 7.10 million kg of CO2-Eq. per year, a 38.8% reduction when compared to S0. According to D'ercole et al. (2016), even a small increase in operational efficiency can result in significant savings for water utilities.

In Scenario S2, by reducing the system's water loss index by 50% in relation to the value for 2016, there would be a reduction in the CED and GHG emissions of 40.7 and 40.3%, respectively. Scenario S3 is the one that considers the greatest reduction in water loss and, consequently, the best hydraulic and energy efficiency. It establishes a loss rate of 5% for the water pipeline system and admits a water loss rate in the water distribution network of 10%. The results showed a reduction of more than 50% in demand and emissions in Scenario S3 compared to S0, which corroborates the statement by Basheer and Elagib (2018), who highlighted that efficiency interventions in the sanitation sector can contribute considerably to reduce water use, decrease emissions, and meet climate-related mitigation goals.

To develop more environmentally responsible and sustainable WSS, the environmental implications of water loss must be incorporated into planning decisions. Pillot et al. (2016) demonstrated that the reduction of real water loss is clearly beneficial for ecosystems, human health, and the preservation of resources.

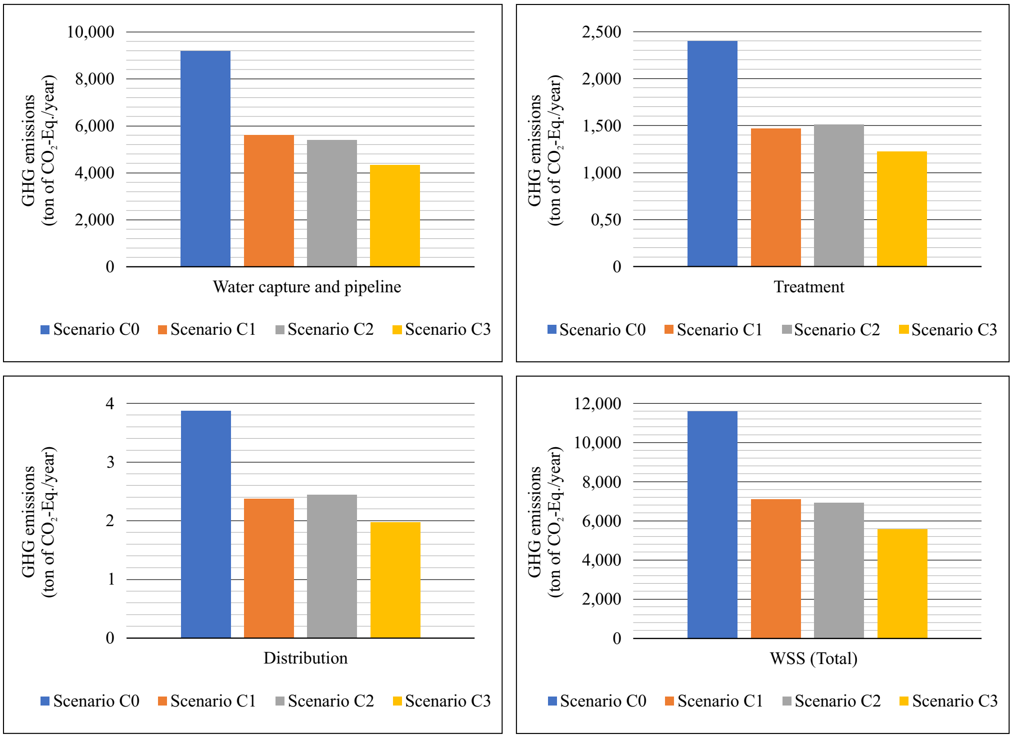

Figure 4 – GHG emissions (kg of CO2-Eq.) of the evaluated scenarios.

Conclusions

In a context of increasing water scarcity worldwide, the reduction of water loss is a key object to guarantee sustainable water management. In view of the hydrological conditions in which the northeast of Brazil is inserted, this region needs an even more effective position to combat the reduction of loss in WSS. The water–energy–carbon nexus arises from a perspective of water and energy security and environmental sustainability.

LCA was used to estimate the environmental and energy impacts of a WSS in the northeast of Brazil for different levels of losses, presenting utility managers with a tool that can include eco-efficiency values from project design, through implementation and finally to operation. This work is another study that highlights the importance of incorporating effective measures to control water losses in the management of systems, since these actions are expressively positive for water utilities and for the environment. The most efficient scenario evaluated showed a reduction in the CED and in the GHG emission higher than 50% in relation to the 2016 operating conditions.

Water pipeline is responsible for most of the GHG emissions and electricity demand, as it has the largest pumping stations in the system. In the water treatment phase, the chemical element with the greatest impact was aluminum sulfate, which accounted for 37% of environmental charges. Data related to the chemicals were analyzed with the Ecoinvent 3.1 database in this present study. Information in this database may not accurately represent the Brazilian reality. Therefore, the importance of collecting specific data for water treatment in Brazil is evident. The water distribution network has a low environmental and energy impact, as the water supply is carried out almost completely by gravity.

This study highlights the importance of incorporating LCA into other impact assessment tools to assist decision-making by managers, since most studies in the sanitation sector involve only wastewater treatment systems. LCA confirms that the environmental benefits of reducing both water and energy loss will increase as the efficiency of the system increases. Results show that improvement actions in the hydraulic efficiency of the distribution network and in the energy efficiency of pumping systems are clearly positive for the environment. Increasing the efficiency of these systems represents a significant opportunity to reduce electricity consumption, increase water availability, and reduce GHG emissions.

Finally, it is recommended for future research works to include actions to control water losses in the LCA of WSS. The reduction of losses generates its own environmental impacts, notably the results of the works to implement the actions, equipment, and infrastructure used for this purpose. This broader assessment can be used to establish at what point loss reduction is no longer effective in mitigating the environmental impacts of the systems.

Contribution of authors:

Alves, I.M.: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing — original draft; Bezerra, S.T.M.: Conceptualization, Methodology, Supervision, Project administration, Writing — revision and editing; Silva, G.L.: Investigation, Methodology, Supervision. Duarte, A.D.: Data curation, Investigation, Methodology; Maranduba, H.L.: Investigation, Methodology.

References

Arpke, A.; Hutzler, N., 2006. Domestic water use in the United States: a life-cycle approach. Journal of Industrial Ecology, v. 10, (1-2), 169-184. https://doi.org/10.1162/108819806775545312.

Bartolozzi, I.; Baldereschi, E.; Daddi, T.; Iraldo, F., 2018. The application of life cycle assessment (LCA) in municipal solid waste management: a comparative study on street sweeping services. Journal of Cleaner Production, v. 182, 455-465. https://doi.org/10.1016/j.jclepro.2018.01.230.

Basheer, M.; Elagib, N.A., 2018. Sensitivity of water–energy nexus to dam operation: a water–energy productivity concept. Science of the Total Environment, v. 616-617, 918-926. https://doi.org/10.1016/j.scitotenv.2017.10.228.

Brazilian National Sanitation Information System – SNIS. 2018. Diagnóstico dos serviços de água e esgotos 2016. Secretaria Nacional de Saneamento Ambiental, Ministério do Desenvolvimento Regional, Brasília.

Buyle, M.; Anthonissen, J.; Van Den Bergh, W.; Braet, J.; Audenaert, A., 2019. Analysis of the Belgian electricity mix used in environmental life cycle assessment studies: How reliable is the Ecoinvent 3.1 mix? Energy Efficiency, v. 12, (5), 1105-1121. https://doi.org/10.1007/s12053-018-9724-7.

Chhipi-Shrestha, G.; Hewage, K.; Sadiq, R., 2017. Water–energy–carbon nexus modeling for urban water systems: System dynamics approach. Journal of Water Resources Planning and Management, v. 143, (6), 04017016. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000765.

D'ercole, M.; Righettia, M.; Ugarellib, R.M.; Berardic, L.; Bertolad, P., 2016. An integrated modeling approach to optimize the management of a water distribution system: Improving the sustainability while dealing with water loss, energy consumption and environmental impacts. Procedia Engineering, v. 162, 433-440. https://doi.org/10.1016/j.proeng.2016.11.085.

Duarte, A.D.; Silva, G.L., 2020. Aplicação da ferramenta de análise de ciclo de vida (ACV) no processo de tratamento de efluentes em uma lavanderia de beneficiamento de jeans. Exacta, v. 18, (2), 355-367. https://doi.org/10.5585/exactaep.v18n2.8370.

Escriva-Bou, A.; Lund, J.R.; Pulido-Velazquez, M.; Hui, R.; Medellín–Azuara, J., 2018. Developing a water–energy–GHG emissions modeling framework: insights from an application to California's water system. Environmental Modelling & Software, v. 109, 54-65. https://doi.org/10.1016/j.envsoft.2018.07.011.

Esnouf, A.; Heijungs, R.; Coste, G.; Latrille, É.; Steyer, J.P.; Hélias, A., 2019. A tool to guide the selection of impact categories for LCA studies by using the representativeness index. Science of the Total Environment, v. 658, 768-776. https://doi.org/10.1016/j.scitotenv.2018.12.194.

Garfí, M.; Cadena, E.; Sanchez-Ramos, D.; Ferrer, I., 2016. Life cycle assessment of drinking water: comparing conventional water treatment, reverse osmosis and mineral water in glass and plastic bottles. Journal of Cleaner Production, v. 137, 997-1003. https://doi.org/10.1016/j.jclepro.2016.07.218.

Ghimire, S.R.; Johnston, J.M.; Ingwersen, W.W.; Sojka, S., 2017. Life cycle assessment of a commercial rainwater harvesting system compared with a municipal water supply system. Journal of Cleaner Production, v. 151, 74-86. https://doi.org/10.1016/j.jclepro.2017.02.025.

Hsien, C.; Low, J.S.C.; Fuchen, S.C.; Han, T.W., 2019. Life cycle assessment of water supply in Singapore – A water–scarce urban city with multiple water sources. Resources, Conservation and Recycling, v. 151, 104476. https://doi.org/10.1016/j.resconrec.2019.104476.

Igos, E.; Dalle, A.; Tiruta-Barna, L.; Benetto, E.; Baudin, I.; Mery, Y., 2014. Life cycle assessment of water treatment: what is the contribution of infrastructure and operation at unit process level? Journal of Cleaner Production, v. 65, 424-431. https://doi.org/10.1016/j.jclepro.2013.07.061.

Intergovernmental Panel on Climate Change (IPCC). 2013. Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York.

International Standard Organization (ISO), 2006a. ISO 14040: Environmental management — life cycle assessment — principles and framework. Geneve.

International Standard Organization (ISO), 2006b. ISO 14044: Environmental management — life cycle assessment — requirements and guidelines. Geneve.

Jacquemin, L.; Pontalier, P.-Y.; Sablayrolles, C., 2012. Life cycle assessment (LCA) applied to the process industry: a review. International Journal of Life Cycle Assessment, v. 17, (8), 1028-1041. https://doi.org/10.1007/s11367-012-0432-9.

Jeong, H.; Broesicke, O.A.; Drew, B.; Crittenden, J., 2018. Life cycle assessment of small scale greywater reclamation systems combined with conventional centralized water systems for the City of Atlanta, Georgia. Journal of Cleaner Production, v. 174, 333-342. https://doi.org/10.1016/j.jclepro.2017.10.193.

Jeong, H.; Minne, E.; Crittenden, J.C., 2015. Life cycle assessment of the city of Atlanta, Georgia's centralized water system. The International Journal of Life Cycle Assessment, v. 20, (6), 880-891. https://doi.org/10.1007/s11367-015-0874-y.

Kjaer, L.L.; Pigosso, D.C.; McAloone, T.C.; Birkved, M., 2018. Guidelines for evaluating the environmental performance of product/service–systems through life cycle assessment. Journal of Cleaner Production, v. 190, 666-678. https://doi.org/10.1016/j.jclepro.2018.04.108.

Lemos, D.; Dias, A.C.; Gabarrell, X.; Arroja, L., 2013. Environmental assessment of an urban water system. Journal of Cleaner Production, v. 54, 157-165. https://doi.org/10.1016/j.jclepro.2013.04.029.

Li, Y.; Xiong, W.; Zhang, W.; Wang, C.; Wang, P., 2016. Life cycle assessment of water supply alternatives in water–receiving areas of the South–to–North Water Diversion Project in China. Water Research, v. 89, 9-19. https://doi.org/10.1016/j.watres.2015.11.030.

Meron, N.; Blass, V.; Garb, Y.; Kahane, Y.; Thoma, G., 2016. Why going beyond standard LCI databases is important: lessons from a meta–analysis of potable water supply system LCAs. International Journal of Life Cycle Assessment, v. 21, (8), 1134-1147. https://doi.org/10.1007/s11367-016-1096-7.

Meron, N.; Blass, V.; Thoma, G., 2020. A national–level LCA of a water supply system in a Mediterranean semi–arid climate – Israel as a case study.

International Journal of Life Cycle Assessment, v. 25, 1133-1144. https://doi.org/10.1007/s11367-020-01753-5.

Mohamed-Zine, M.B.; Hamouche, A.; Krim, L., 2013. The study of potable water treatment process in Algeria (boudouaou station) – by the application of life cycle assessment (LCA). Journal of Environmental Health Science and Engineering, v. 11, 37. https://doi.org/10.1186/2052-336X-11-37.

Nair, S.; George, B.; Malano, H.M.; Arora, M.; Nawarathna, B., 2014. Water-energy-greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods. Resources, Conservation and Recycling, v. 89, 1-10. https://doi.org/10.1016/j.resconrec.2014.05.007.

Oikonomou, K.; Parvania, M., 2018. Optimal coordination of water distribution energy flexibility whit power systems operation. IEEE Transaction on Smart Grid, v. 10, (1), 1101-1110. https://doi.org/10.1109/TSG.2018.2824308.

Peña, C.; Civit, B.; Gallego-Schmid, A.; Druckman, A.; Caldeira-Pires, A.; Weidema, B.; Mieras, E.; Wang, F.; Fava, J.; Milà i Canals, L.; Cordella, M.; Arbuckle, P.; Valdivia, S.; Fallaha, S.; Motta, W., 2021. Using life cycle assessment to achieve a circular economy. International Journal of Life Cycle Assessment, v. 26, (2), 215-220. https://doi.org/10.1007/s11367-020-01856-z.

Pillot, J.; Catel, L.; Renaud, E.; Augeard, B.; Roux, P., 2016. Up to what point is loss reduction environmentally friendly?: The LCA of loss reduction scenarios in drinking water networks. Water Research, v. 104, 231-241. https://doi.org/10.1016/j.watres.2016.07.025.

Pokhrel, P.; Lin, S.L.; Tsai, C.T., 2020. Environmental and economic performance analysis of recycling waste printed circuit boards using life cycle assessment. Journal of Environmental Management, v. 276, 111276. https://doi.org/10.1016/j.jenvman.2020.111276.

Rasul, M.G.; Arutla, L.K.R., 2020. Environmental impact assessment of green roofs using life cycle assessment. Energy Reports, v. 6, (suppl. 1), 503-508. https://doi.org/10.1016/j.egyr.2019.09.015.

Rasul, M.G.; Sharma, B., 2016. The nexus approach to water–energy–food security: an option for adaptation to climate change. Climate Policy, v. 6, (16), 682-702. https://doi.org/10.1080/14693062.2015.1029865.

Rodriguez, O.O.O.; Villamizar-Gallardo, R.A.; García, R.G., 2016. Life cycle assessment of four potable water treatments plants in northeastern Colombia. Ambiente & Água, v. 11, (2), 268-278. http://dx.doi.org/10.4136/ambi-agua.1759.

Rothausen, S.G.; Conway, D., 2011. Greenhouse–gas emissions from energy use in the water sector. Nature Climate Change, v. 1, (4), 210-219. https://doi.org/10.1038/nclimate1147.

Santana, R.A.; Bezerra, S.T.M.; Santos, S.M.; Coutinho, A.P.; Coelho, I.C.L.; Pessoa, R.V.S., 2019. Assessing alternatives for meeting water demand: A case study of water resource management in the Brazilian Semiarid region. Utilities Policy, v. 61, 100974. https://doi.org/10.1016/j.jup.2019.100974.

Thiede, S.; Schönemann, M.; Kurle, D.; Herrmann, C., 2016. Multi-level simulation in manufacturing companies: The water-energy nexus case. Journal of Cleaner Production, v. 139, 1118-1127. https://doi.org/10.1016/j.jclepro.2016.08.144.

Trinh, L.T.K.; Hu, A.H.; Lan, Y.C.; Chen, Z.H., 2020. Comparative life cycle assessment for conventional and organic coffee cultivation in Vietnam. International Journal of Environmental Science and Technology, v. 17, (3), 1307-1324. https://doi.org/10.1007/s13762-019-02539-5.

Uche, J.; Martínez-Gracia, A.; Círez, F.; Carmona, U., 2015. Environmental impact of water supply and water use in a Mediterranean water stressed region. Journal of Cleaner Production, v. 88, 196-204. https://doi.org/10.1016/j.jclepro.2014.04.076.

Valencia-Barba, Y.E.; Gómez-Soberón, J.M.; Gómez-Soberón, M.C.; López-Gayarre, F., 2020. An epitome of building floor systems by means of LCA criteria. Sustainability, v. 12, (13), 5442. https://doi.org/10.3390/su12135442.

Xue, X.; Cashman, S.; Gaglione, A.; Mosley, J.; Weiss, L.; Cissy Ma, X.; Cashdollar, J.; Garland, J., 2019. Holistic analysis of urban water systems in the Greater Cincinnati region: (1) Life cycle assessment and cost implications. Water Research X, v. 2, 100015. https://doi.org/10.1016/j.wroa.2018.100015.

Zahraee, S.M.; Shiwakoti, N.; Stasinopoulos, P., 2020. A review on water-energy-greenhouse gas nexus of the bioenergy supply and production system. Current Sustainable/Renewable Energy Reports, v. 7, (2), 28-39. https://doi.org/10.1007/s40518-020-00147-3.

Zhou, L.; Bao, Q.; Liu, Y.; Wu, G.; Wang, W.; Wang, X.; He, B.; Yu, H.; Li, J., 2015. Global energy and water balance: Characteristics from finite-volume atmospheric model of the IAP/LASG (FAMIL1). Journal of Advances in Modeling Earth Systems, v. 7, (1), 1-20. https://doi.org/10.1002/2014MS000349.