Revista Brasileira de Ciências Ambientais
Brazilian Journal of Environmental Sciences

Life cycle assessment of a vapor absorption refrigeration system applied to a university building in Northeast Brazil

Avaliação do ciclo de vida de um sistema de refrigeração por absorção de vapor aplicado em um edifício universitário no Nordeste do Brasil

João Luiz de Medeiros Neto[1], Carlos Antonio Cabral dos Santos[1]

ABSTRACT

Due to the increase in global warming and the growing demand for thermal comfort in tropical climate regions, refrigeration systems have become essential to ensure adequate conditions in residential, commercial, and institutional environments. At the same time, efforts are being made to reduce the environmental impacts associated with their use. In this context, the present study conducts a life cycle assessment (LCA) of a double-effect vapor absorption refrigeration system (SFAVDE) with a cooling capacity of 352 kW, using direct natural gas combustion as an energy source. The main objectives of this work are: i. to provide a life cycle assessment for SFAVDE technologies used to meet the cooling demand of a specific university building in Northeastern Brazil and ii. to perform a dominance analysis to identify the main contributors to environmental impacts in the SFAVDE. The LCA study was conducted using the ReCiPe endpoint method (humanitarian, average weighting – H/A). Simulations were performed using the open-source software openLCA version 1.10.3, utilizing the Ecoinvent 3.7.1 life cycle inventory database. The simulation results showed that, in the ecosystem, human health, and natural resources categories, the greatest environmental impacts were caused by climate change and ecosystems (17.19%), climate change and human health (27.18%), and fossil depletion and natural resources (43.70%). Regarding the dominance study, the results indicated that, for the transport and operation stages, the main impacts were air transport (91.00%) and natural gas usage (97.00%), respectively. In the disposal stage of the SFAVDE, copper recycling resulted in a 34.61% reduction in environmental impact compared to landfill disposal. Therefore, to mitigate the environmental impacts of the SFAVDE, it is recommended to assess transportation alternatives, utilize renewable fuels during the operation phase, and prioritize the reuse of copper during the manufacturing and disposal stages.

Keywords: life cycle management; dominance analysis; ReCiPe; openLCA; absorption refrigeration; environmental impact assessment.

RESUMO

Em consequência do aumento do aquecimento global e da crescente demanda por conforto térmico em regiões de clima tropical, os sistemas de refrigeração têm se tornado essenciais para assegurar condições adequadas em ambientes residenciais, comerciais e institucionais. Paralelamente, busca-se reduzir os impactos ambientais associados ao seu uso. Neste contexto, o presente estudo realiza uma avaliação do ciclo de vida (ACV) de um sistema de refrigeração por absorção de vapor de duplo efeito (SFAVDE) com capacidade de resfriamento de 352 kW, utilizando como fonte energética a queima direta de gás natural. Os principais objetivos deste trabalho são: i. fornecer uma avaliação do ciclo de vida para tecnologias SFAVDE utilizadas para suprir a demanda de resfriamento de um edifício universitário específico no Nordeste do Brasil e ii. realizar uma análise de dominância para identificar os principais responsáveis pelos impactos ambientais no SFAVDE. O estudo de ACV foi realizado utilizando o método ReCiPe endpoint (humanitário, ponderação média – H/A). As simulações foram realizadas por meio do software de código aberto openLCA versão 1.10.3, utilizando o banco de dados de inventário do ciclo de vida Ecoinvent 3.7.1. Os resultados das simulações mostraram que, nas classes ecossistema, saúde humana e recursos naturais, os maiores impactos ambientais foram causados por mudanças climáticas e ecossistemas (17,19%), mudanças climáticas e saúde humana (27,18%) e esgotamento fóssil e recursos naturais (43,70%). Em relação ao estudo de dominância, os resultados indicaram que, para as etapas de transporte e operação, os principais impactos foram, respectivamente, o transporte aéreo (91.00%) e o uso de gás natural (97.00%). Na etapa de descarte do SFAVDE, o reaproveitamento do cobre resultou em uma redução de 34,61% no impacto ambiental em comparação com a destinação em aterro sanitário. Portanto, para mitigar os impactos ambientais do SFAVDE, recomenda-se avaliar alternativas de transporte, utilizar combustíveis renováveis na etapa de operação e priorizar o reúso do cobre durante as fases de fabricação e descarte.

Palavras-chave: gestão do ciclo de vida; análise de dominância; ReCiPe; openLCA; refrigeração por absorção; avaliação de impactos ambientais.

[1]Federal University of Paraíba – João Pessoa (PB), Brazil.

Corresponding author: João Luiz de Medeiros Neto – Federal University of Paraíba – University Campus, s/n – CEP: 58051-900 – João Pessoa (PB), Brazil. E-mail: eng.joaomedeiros@gmail.com

Conflicts of interest: the authors declare no conflicts of interest.

Funding: Research Support Foundation of the State of Paraíba (FAPESQ) for the financial support (through the doctoral scholarship) for the development of this work (Process 88887.616915/2021-00).

Received on: 09/09/2024. Accepted on: 02/22/2025.

https://doi.org/10.5327/Z2176-94782277

This is an open access article distributed under the terms of the Creative Commons license.

Introduction

The growth in the demand for cooling systems has increased global warming due to greenhouse gas emissions and the destruction of the ozone layer (Castaño-Rosa et al., 2021). The growing concern about climate change has spurred research aimed at developing more efficient and sustainable refrigeration systems, particularly in tropical regions such as Northeast Brazil.

The vapor absorption chiller (VAC) is widely employed as one of the most common cooling systems to meet the refrigeration demands in medium- and large-scale applications (Hara Chakravarty et al., 2022). VACs represent a promising technology because they utilize fluids that do not harm the ozone layer and operate using thermal energy as their power source. According to Marques (2018), during the operation of a VAC, only a small amount of work (in the form of electrical energy) is required to drive the solution pump.

However, for the implementation of VACs to become competitive and present itself as a viable alternative compared to traditional systems, it is essential to find ways to improve the efficiency of the equipment. This requires optimizing the design and selecting appropriate technologies (Arshad et al., 2019), as well as defining the best operating conditions (Leite et al., 2021; Panahizadeh et al., 2021). In a study conducted by Panahizadeh et al. (2022), a VAC installation was investigated to determine the optimal operating conditions for a chiller network, considering both energy and financial aspects. The results showed that operating under the optimal conditions defined by the authors reduced the total levelized costs of the installation by 8.5% compared to the initial project conditions. Other researchers have explored different strategies to improve equipment efficiency by investigating the impact of variables such as external temperatures (Yu et al., 2022), component efficiency (Bellos et al., 2021), and the concentration of working fluid pairs (Xu et al., 2022) used on the performance of these systems. However, none of the cited authors conducted an environmental impact study as part of their VAC analyses.

The life cycle assessment (LCA) is widely recognized as an effective framework for analyzing impacts on the environment, human health, and natural resources in processes, products, and systems. It provides evidence-based data that enable policymakers to make strategic long-term decisions and promote environmental sustainability (Osman et al., 2021).

The literature presents several contributions regarding life cycle studies in energy conversion systems. The study by Kanchiralla et al. (2023) analyzed the technical feasibility, environmental impacts, and economic viability of different energy carriers—such as electric batteries and electrofuels (hydrogen, methanol, and ammonia)—for three types of vessels: RoPax ferry, oil tanker, and service ship.

Studies by Dastjerdi et al. (2021) and Rajput et al. (2020) applied LCA to analyze environmental impacts in different contexts. Dastjerdi et al. (2021) investigated municipal solid waste (MSW) management scenarios in New South Wales, Australia, while Rajput et al. (2020) assessed three photovoltaic (PV) technologies in semi-arid climates. Both studies emphasized the importance of adapting specific technologies to local conditions to maximize efficiency and reduce environmental impacts.

The researchers Guillén-Lambea et al. (2021), Abreu et al. (2022), and Zhou et al. (2023) analyzed the environmental and economic impacts of different energy systems, contributing to the optimization of more sustainable processes. Zhou et al. (2023) investigated the global warming potential of energy production from biomass. Abreu et al. (2022) applied thermoeconomic approaches and LCA to a chilled water system in a shopping mall, highlighting the efficiency of heat exchangers in both monetary and environmental terms. Meanwhile, Guillén-Lambea et al. (2021) compared the environmental efficiency of district heating and cooling systems.

The researchers César et al. (2021) conducted a study on a single-effect vapor absorption refrigeration system using solar energy as the thermal power source. They aimed to develop a computational tool for performing and exergy and life cycle analysis of the system under evaluation. However, the study did not provide a detailed analysis of the environmental impact categories and the life cycle stages of the VAC. Lin et al. (2021) conducted a life cycle and dominance analysis of two heating systems: one consisting of a condensing gas boiler and the other a hybrid heat pump system. Their study provided detailed insights into the most significant environmental impacts at each life cycle stage, as well as the primary impact contributors in each phase through the dominance analysis. Natural gas and electricity were identified as the major impact sources during the operational phase of the systems. The LCA method used in the study was ReCiPe; however, the raw material and transportation stages of the system were not detailed.

The present study aimed to apply LCA to a double-effect vapor absorption refrigeration system (SFAVDE), powered by direct natural gas combustion, previously studied and used to meet the cooling demand of a specific university building in Northeast Brazil.

The main contributions of this study are: i. to comprehensively and integratively assess the environmental impacts of the SFAVDE throughout its life cycle, considering various impact categories such as climate change, resource depletion, pollution, and effects on human health and ecosystems; and ii. to identify the key contributors to environmental impacts at each stage of the SFAVDE life cycle, aiming at providing information to support decision-making to mitigate these environmental impacts.

Methodology

System description

The absorption refrigeration system utilizes low-grade heat sources, such as industrial waste heat and renewable thermal energy (solar, geothermal, and biomass), and is characterized by low energy consumption, few moving parts, and stable operation. It is an efficient technology for low- or zero-carbon energy utilization, applicable both to heat recovery in large industries and to distributed refrigeration on a smaller scale (Zhu et al., 2022; Li et al., 2023).

To better understand the system's operation, it is essential to define the scope of this study. The SFAVDE, designed to meet the cooling demand of a university building, has a capacity of 352 kW and consists of the following components: a first-stage generator, a second-stage generator, two heat exchangers, an absorber, an evaporator, a condenser, an expansion valve, and a solution pump. Figure 1 illustrates the described system.

At point 1 (Figure 1), a lithium bromide-water solution with a high water concentration exits the absorber. After passing through a pump (point 2), the solution's pressure is increased, and it enters the low-temperature heat exchanger, where it is preheated. Upon leaving the low-temperature heat exchanger (point 3), the solution flows through the high-temperature heat exchanger (points 3 and 4) before entering the first-stage generator. In this generator, the solution receives thermal energy from the direct combustion of a fuel (point 20), partially separating the water/lithium bromide solution. The first-stage generator produces high-temperature water vapor (point 7) and a concentrated lithium bromide-water solution (point 5).

The concentrated solution passes through the high-temperature heat exchanger and flows into the second-stage generator (point 6), where it receives high-temperature water vapor and the concentrated lithium bromide-water solution. In the second-stage generator, the water vapor is directed to the condenser (point 8), while the solution with a high lithium bromide concentration is sent to the low-temperature heat exchanger (point 13). As it passes through the heat exchanger, the solution reaches the pressure and temperature required to return to the absorber (point 12).

The low-temperature water vapor enters the condenser (point 8), where it exchanges heat with the cooling water and condenses. At the condenser outlet (point 9), liquid water is observed, which then passes through an expansion valve (point 10), where both the pressure and temperature decrease, allowing it to enter the evaporator. In the evaporator, the refrigerant fluid exchanges heat with the ambient temperature water, cooling the external fluid to an average of 5°C. Upon leaving the evaporator (point 11), the refrigerant fluid returns to the absorber, restarting the cycle.

System utilization

The building selected for the SFAVDE application is part of the Sustainable Energy Institute (IES) facilities, located at the Federal University of Paraíba (UFPB) in João Pessoa, Northeast Brazil. The IES facilities consist of three blocks: IES-1, IES-2, and IES-3 (Figure 2). It is considered that the SFAVDE system has the capacity to meet the entire cooling demand of the conditioned area of the blocks, including the administrative office, the coordination office, the auditorium, three study rooms on the first floor of IES-1, and three laboratories (IES-2 and IES-3). The scope of this work does not include the analysis of the electrical energy consumption of the aforementioned blocks.

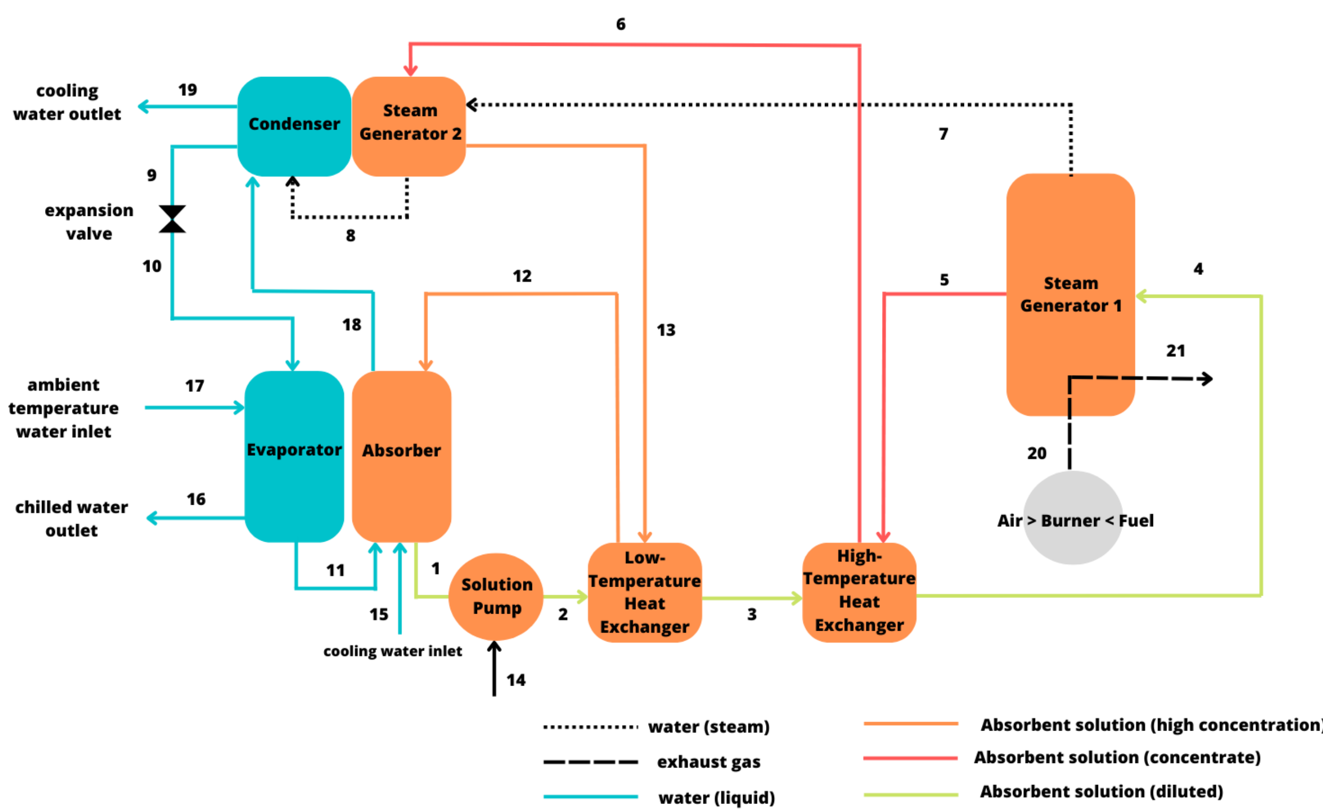

Figure 1 – Double-effect vapor absorption refrigeration system with a capacity of 352 kW.

Figure 2 – Complete structure of the Federal University of Paraíba - Campus I (on the left) and the Sustainable Energy Institute facilities (on the right).
Source: Souza et al. (2020).

Life cycle assessment

The LCA is an analytical technique, regulated by the International Organization for Standardization (ISO) 14040/14044 standards (ABNT, 2006a; 2006b), that quantifies the environmental aspects of energy conversion systems throughout their life cycle, considering the consumption of material/energy resources and the emissions of pollutants resulting from them (Ayer and Dias, 2018; Nwodo and Anumba, 2019). In other words, LCA is an analytical tool that enables the assessment of potential environmental impacts at each stage of a product or service's life cycle, from raw material extraction to final disposal (Marques et al., 2021).

LCA is a structured method that encompasses four main stages: goal and scope definition; life cycle inventory; life cycle impact assessment; and interpretation of results.

Scope definition

The goal and scope definition phase must be conducted clearly, outlining the expected outcomes of the study (Marques, 2018). This stage justifies the conduction of the LCA, with the definition of the object of study (product, system, or activity) and its life cycle, as well as a description of the system boundaries (which may include raw material extraction, material processing, manufacturing, transportation, distribution, use, repair, maintenance, and disposal) (Cavalcanti et al., 2019).

The present study covered the manufacturing, transportation, operation, and disposal stages of the SFAVDE system. In the manufacturing phase, the materials and energy used in the production of all system components were analyzed. Then, the impacts associated with the transportation of the chiller were assessed. In the operation phase, environmental impacts related to the use of electricity to power the pump, the consumption of thermal energy from natural gas, the use of the lithium bromide-water solution, and the water used as the cooling fluid for the system were considered.

In the final phase of the scope, the chiller was disposed of in a sanitary landfill. Figure 3 illustrates the overall scope of the study. A system lifespan of 20 years was adopted (Zhang et al., 2022).

Inventory description

In the life cycle inventory, all inputs and outputs associated with the object of study were recorded. The manufacturing phase evaluated the consumption of raw materials and energy based on the mass of the components while the operation phase analyzes the thermal energy (from natural gas), the lithium bromide-water solution, the cooling water, and the electricity required. Transportation from the manufacturer to the operational site and the disposal of the chiller were also considered, with more details provided in Table 1.

According to LG (2020), the absorption chiller has a total mass of 4,200 kg, distributed as follows: the first steam generator weighs 900 kg, the upper section (comprising the second steam generator and the condenser) weighs 600 kg, and the lower section (including the evaporator, absorber, solution pump, and heat exchangers) amounts to 2,700 kg. The mass of accessories, such as piping and sensors, was not included; therefore, for the analysis, a total mass of 3,600 kg was considered.

The manufacturing of the chiller took place in Gyeonggi-do Province, South Korea, and the study did not account for the transportation of raw materials to the factory. The chiller was transported by truck from the factory to Incheon International Airport, covering a distance of 69 km. From there, it was shipped by cargo aircraft to Guarulhos International Airport in Brazil, traveling 18,315 km. Finally, the transportation from Guarulhos Airport to the IES facilities in João Pessoa was carried out by truck, covering approximately 2,732 km. Figure 4 illustrates the route.

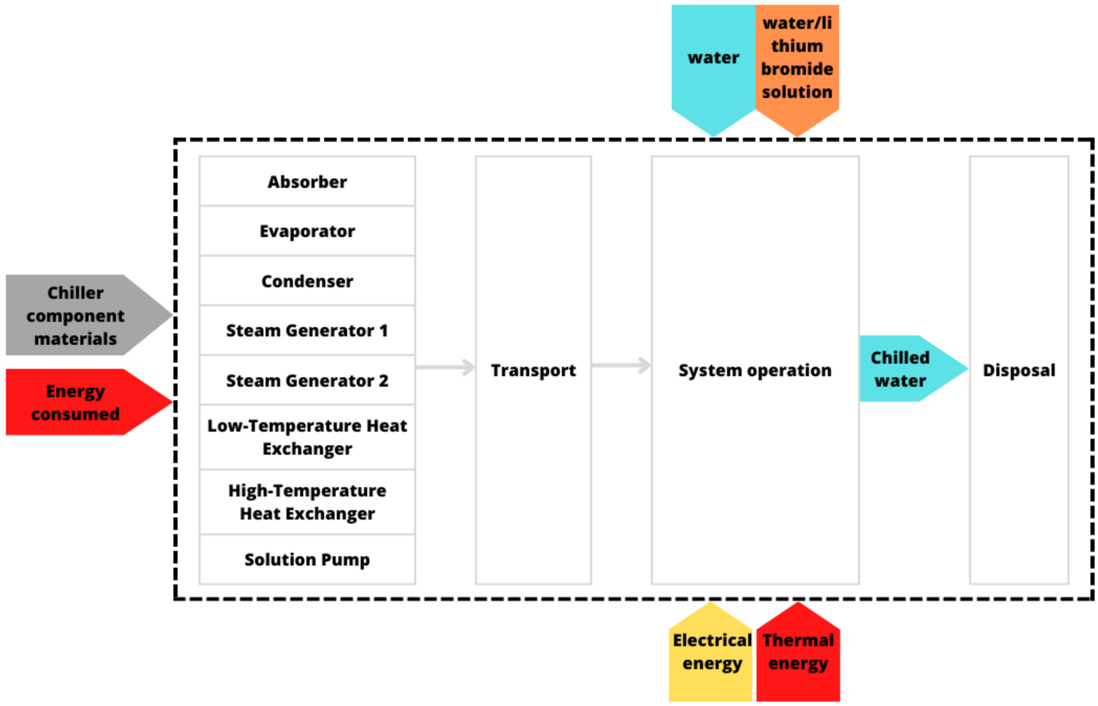

Figure 3 – Scope of the study.

Table 1 – Input data for life cycle assessment of the double-effect vapor absorption refrigeration system.

Component	Mass (kg)	Raw material (%)	Transportation	Distance (km)	Disposal
Absorber	700	80% Copper / 20% Rolled Steel	Gyeonggi Province, South Korea / João Pessoa (PB), Brazil	21,116	Municipal landfill with incineration
Evaporator	700	80% Copper / 20% rolled steel	Gyeonggi Province, South Korea / João Pessoa (PB), Brazil	21,116	Municipal landfill with incineration
Condenser	300	80% Copper / 20% rolled steel	Gyeonggi Province, South Korea / João Pessoa (PB), Brazil	21,116	Municipal landfill with incineration
Steam Generator 1	900	80% Stainless Steel / 20% rolled steel	Gyeonggi Province, South Korea / João Pessoa (PB), Brazil	21,116	Municipal landfill with incineration
Steam Generator 2	300	80% Copper / 20% rolled steel	Gyeonggi Province, South Korea / João Pessoa (PB), Brazil	21,116	Municipal landfill with incineration
Low-Temperature Heat Exchanger	300	80% Copper / 20% rolled steel	Gyeonggi Province, South Korea / João Pessoa (PB), Brazil	21,116	Municipal landfill with incineration
High-Temperature Heat Exchanger	300	80% Copper / 20% rolled steel	Gyeonggi Province, South Korea / João Pessoa (PB), Brazil	21,116	Municipal landfill with incineration
Solution Pump	100	Carbon steel 50% / PVC 40% / Copper 5% / Aluminum 3% / Rubber 2%	Gyeonggi Province, South Korea / João Pessoa (PB), Brazil	21,116	Municipal landfill with incineration

PVC: polyvinyl chloride.

System operation

The system operation stage included cooling water, the electrical energy required to drive the pump, water-lithium bromide solution, which serves as the working fluid, and thermal energy required to activate the first steam generator.

According to LG (2020), the volumes of cooling water and chilled water are 0.028 m^3 and 0.0168 m^3, respectively. Therefore, the total volume is 0.0448 m^3, noting that water losses were not considered, as the cycle is closed and any potential losses over the chiller's service life are negligible. The solution volume in the absorber is 0.019 m^3, consisting of 55% lithium bromide (absorbing fluid) and 45% water (refrigerant fluid).

The chiller has a cooling capacity of 352 kW and a coefficient of performance (COP) of 1.51 (LG, 2020). Therefore, the thermal energy required to operate the chiller is calculated using Equation 1.

$$\dot{Q}_{input} = \frac{\dot{Q}_{cooling}}{COP} \quad (1)$$

Within the scope of the study, it was considered that the system included a solution pump (the only equipment that consumes electrical energy) with a power of 1.5 kW, operating 24 hours per day. Therefore, Equation 2 provides the calculation for electrical energy (EE) consumption. Table 2 describes the utilities required for the operation of the chiller.

$$EE_{input} = Power\ (kW) x\ Time\ (h) \quad (2)$$

Disposal

According to the Brazilian Association of Technical Standards (ABNT, 2004) ABNT NBR 10004, the double-effect vapor absorption chiller is classified as a hazardous waste of class 1 due to the presence of lithium bromide as one of its working fluids.

The hazardous solid waste classified as class 1 was sent to the sanitary landfill in the metropolitan region of João Pessoa, managed by a private company for proper disposal, considering the risks to human health and soil contamination. For the purpose of environmental impact analysis, it was assumed that the chiller would be incinerated at the landfill.

Life cycle impact assessment

After defining the inventory stage, the life cycle impact assessment (LCIA) phase linked this information to potential environmental impacts and human health. For this stage, the openLCA software version 1.10.3 was used, with the Ecoinvent 3.7.1 database. The study followed the ISO 14040 (ABNT, 2006a) and ISO 14044 (ABNT, 2006b) standards, and the simulation was performed based on the ReCiPe Endpoint method (humanitarian, average weighting – H, A). The functional unit considered was 1 kWh of cooling capacity provided by a 352 kW vapor absorption chiller over 20 years.

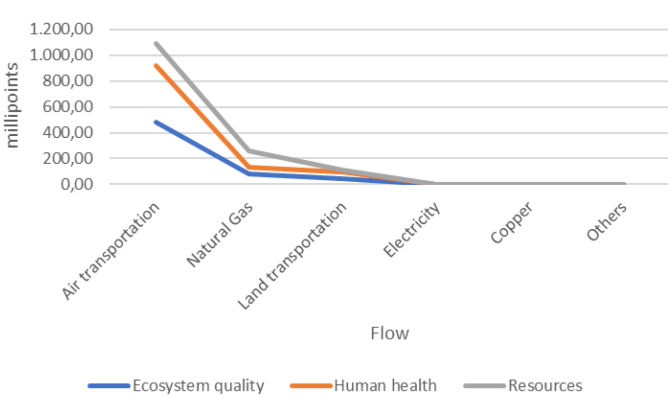

Figure 4 – Schematic diagram of transportation routes.
Source: adapted from Google (2024).

According to Marques et al. (2021), the Eco-Indicator-99 is still considered a traditional LCIA method, but the ReCiPe method has emerged as its successor. This method collects the calculated environmental damages and groups them into three categories: i. human health, that is related to diseases caused by environmental factors, considering both the number of diseases and their duration, as well as the years of life lost due to premature deaths; ii. ecosystem quality, which assesses damage to species diversity, including specific plants and lower organisms; and iii. natural resources, that considers the additional energy required in the future to obtain mineral and fossil resources.

Results and Discussion

Table 3 presents the contribution of the total environmental impacts of the absorption chiller in the categories of human health, ecosystem quality, and natural resources. The results were obtained considering the phases covered by the scope of this study (Figure 3), which included manufacturing, transportation, system operation, and disposal. The values in the table are expressed in millipoints (mPt) and percentages.

Data indicate that the relative contributions are distributed across three main impact categories: ecosystems (604.66 mPt; 18.83%); human health (1,149.88 mPt; 35.80%); and natural resources (1,458.09 mPt; 45.40%).

This information suggests that the greatest impact of the refrigeration system is on natural resources, followed by human health, and finally, ecosystems.

Within the ecosystem impact category, the main subcategories with significant contributions are climate change, ecosystems: 552.00 mPt (17.19%); and natural land transformation: 38.00 mPt (1.18%).

The largest contribution comes from climate change in ecosystems, which represents the majority of the impact in this category. This may be due to greenhouse gas emissions throughout the life cycle of the refrigeration system.

In the human health category, the impacts are more diversified. The most relevant subcategories include climate change, human health: 873.00 mPt (27.18%); and particulate matter formation: 223.40 mPt (6.95%).

Climate change has the greatest impact on human health, suggesting that the indirect effects of climate change, such as extreme weather events, may have significant implications for health.

Table 2 – Description of the utilities required for the operation of the double-effect vapor absorption refrigeration system.

Type	Quantity
Electricity	262.800 kWh (20 years)
Thermal energy	40.840.842 kWh (20 years)
Water (cooling and chilled)	0.0448 m^3
Solution volume	0.00855 m^3

Table 3 – Relative contribution of the impact categories considered in ReCiPe 2016 (H/A).

Impact Category	Ecosystem		Human Health		Resources	
	mPt	%	mPt	%	mPt	%
Agricultural Land Occupation	3.00	0.09				
Climate Change, Ecosystems	552.00	17.19				
Freshwater Ecotoxicity	0.07	0.00				
Freshwater Eutrophication	0.09	0.00				
Marine Ecotoxicity	0.01	0.00				
Natural Land Transformation	38.00	1.18				
Terrestrial Acidification	1.50	0.05				
Terrestrial Ecotoxicity	0.45	0.01				
Urban Land Occupation	9.54	0.30				
Climate Change, Human Health			873.00	27.18		
Human Toxicity			51.76	1.61		
Ionizing Radiation			0.56	0.02		
Ozone Depletion			0.28	0.01		
Particulate Matter Formation			223.40	6.95		
Photochemical Oxidant Formation			0.88	0.03		
Fossil Fuel Depletion					1,403.71	43.70
Metal Depletion					54.38	1.69
Total	**604.66**	**18.83**	**1,149.88**	**35.80**	**1,458.09**	**45.40**

The impacts on natural resources are dominated by two main subcategories: fossil fuel depletion (1,403.71 mPt; 43.70%) and metal depletion (54.38 mPt; 1.69%).

Fossil fuel depletion is the greatest concern in this category, which is expected in a system that relies on the direct combustion of natural gas. This depletion reflects the dependence on fossil fuels and the consequent impact on the future availability of these resources.

Figure 5 shows the main contributors to environmental impacts in the three categories addressed by the ReCiPe method (ecosystem, human health, and resources), concerning the stages of the scope (Figure 3).

The three main contributors to the environmental impacts of the SFAVDE are: air transport, direct combustion of natural gas, and land transport. This is explained by the use of kerosene as fuel in aviation. The combustion of this fuel emits carbon dioxide (CO_2), contributes to global warming, and pollutes the air with nitrogen oxides (NOx) and fine particles. In 2018, CO_2 emissions from the aviation sector amounted to approximately 1.04 gigatons, representing around 2.5% of global anthropogenic emissions. Emissions are expected to double by 2050 due to the growth of the aviation sector, exacerbating its environmental impacts (Micheli et al., 2022).

The difficulty in decarbonizing the aviation sector is exacerbated by the continued dependence on kerosene, especially considering that commercial aircraft have a lifespan of approximately 30 years. Currently, there are no viable electric technologies for long-distance flights. However, various efforts are being made to minimize these impacts, with the development of alternative fuels such as e-kerosene and sustainable aviation fuels, which can reduce CO_2 emissions by up to 88.0%, depending on the source of electricity used in their production (Micheli et al., 2022).

Dominance analysis

The dominance analysis is a method used to identify the largest contributors to the environmental impacts of a product or process in an LCA study. The purpose is to compare the relative importance of each component that is part of a specific object of study (Baumann et al., 2011). The researchers Longo et al. (2020) used dominance analysis to identify the main factors contributing to the environmental impacts associated with the chimney resulting from the combustion of waste-derived fuel. According to the context, this section aims to identify the main sources of environmental impacts in the production, transportation, system operation, and disposal phases described in the scope of the study (Figure 3).

Figure 5 – Main contributors to the environmental impacts of the double-effect vapor absorption refrigeration system.

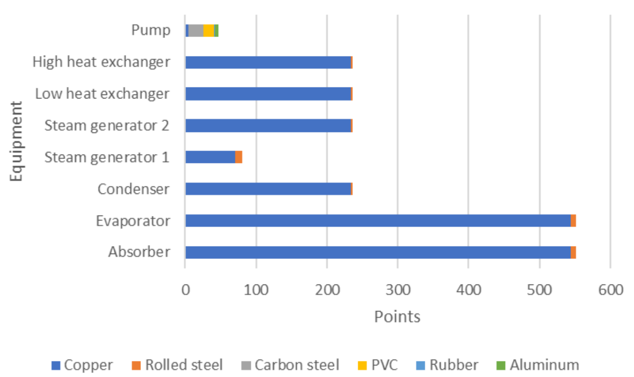

Figure 6 – Dominance study of the manufacturing process of the 352 kW double-effect vapor absorption refrigeration system using the ReCiPe method.

The impacts are presented through the results obtained using the ReCiPe method.

Figure 6 presents the main contributors to the environmental impact related to the manufacturing phase of the SFAVDE components. The reference unit is the kilogram (kg), and the results are shown in points (Pt).

The use of copper in the manufacturing of many components generates significant environmental impacts, mainly due to the extraction and production phases, which require high levels of energy consumption. This is especially relevant in producing countries like China, where electricity is often generated from coal (Dong et al., 2020). In 2019, China was responsible for 40% of globally processed copper (IEA, 2021).

The next result of the dominance study (Figure 7) focuses on identifying the main factors causing environmental impacts in the transportation, operation, and disposal phases of the SFAVDE. For the transportation phase, the reference unit used is t.km (ton-kilometer). In the operation phase, the reference units are kWh for electricity and natural gas consumption, kg for lithium bromide, and m^3 for water consumption. For the disposal phase, the reference unit is kg. The results are presented as percentages, based on the environmental impact measured in Pt. The environmental impacts observed in the dominance study related to transportation and operation reveal that air transport generates the highest impact, primarily due to CO_2 emissions and other pollutants associated with the consumption of aviation fuel, exacerbated by the chiller's weight and the long distance between the manufacturing plant and Guarulhos Airport in São Paulo, Brazil. In the operation phase, the most significant environmental impact is caused by the use of natural gas over the chiller's 20-year lifespan, resulting in greenhouse gas emissions, such as CO_2, and contributing to the depletion of fossil resources.

Figure 8 reveals that the greatest impact on the chiller's disposal is related to copper, which accounts for 93% of the total. Copper is a recyclable material and could be selectively collected at the landfill, avoiding its incineration or burial.

For analysis purposes, Figure 9 compares the disposal of copper in two scenarios. In scenario 1, copper is discarded in a municipal landfill, and in scenario 2, the material is reused in a metal recovery facility (recycling). Data is presented in Pt.

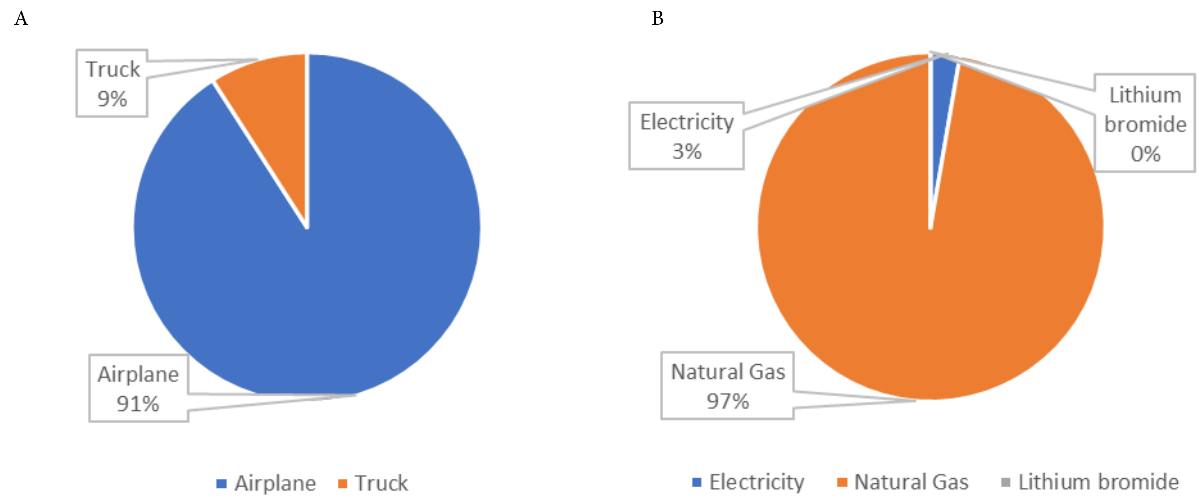

Figure 7 – Results of the dominance study for transportation (A) and operation (B) of the 352 kW double-effect vapor absorption refrigeration system, using the ReCiPe method.

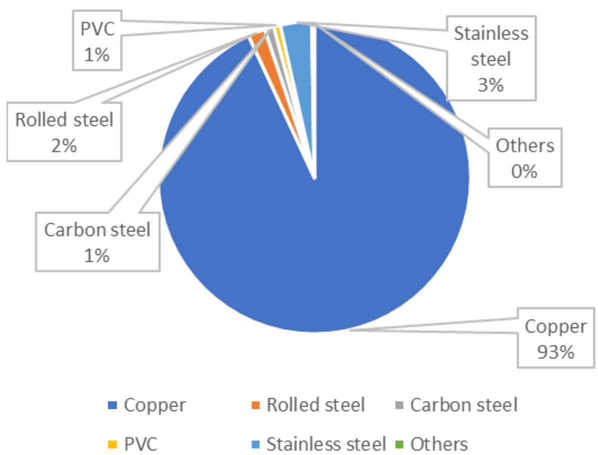

Figure 8 – Result of the dominance study on the disposal of the SFAVED using the ReCiPe method.
PVC: polyvinyl chloride.

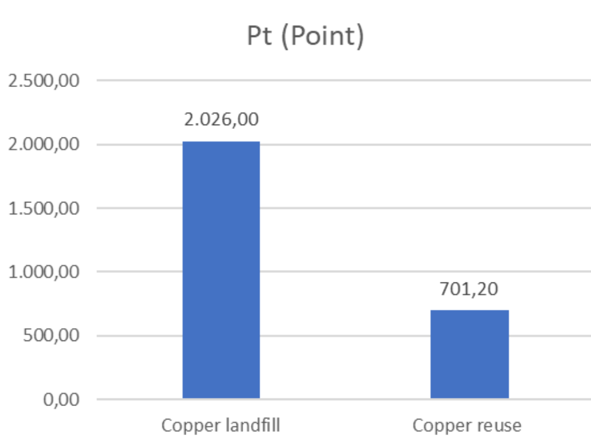

Figure 9 – Comparative study of the environmental impact of copper disposal in two scenarios.

The change from scenario 1 to scenario 2 results in a reduction in the environmental impacts related to copper disposal. This shift led to a 34.61% decrease in impacts, highlighting the significance of the proposal in mitigating environmental effects.

Conclusions

This research enabled the assessment of the environmental impacts of the SFAVDE life cycle, highlighting resource consumption as the primary factor influencing environmental impact. The analysis revealed that the extraction and use of raw materials, as well as the energy consumed throughout all life cycle phases, are key determinants of the observed impacts. This underscores the need to pursue more sustainable alternatives, such as material substitution and the use of renewable energy sources.

Additionally, the impacts on human health demonstrated the significance of atmospheric emissions from fossil fuel combustion. This finding highlights the urgency of adopting cleaner and more efficient technologies that reduce pollutant emissions and minimize risks to public health. Meanwhile, although ecosystem impacts are lower compared to other categories, they indicate the need for strategies that promote environmental regeneration and mitigate adverse effects on biodiversity.

The research also indicated that different phases of the SFAVDE life cycle present mitigation opportunities. Replacing copper with alternative materials or using recycled copper in manufacturing can reduce environmental impacts. In the transportation phase, avoiding air transport can be a viable strategy to minimize the impacts associated with fossil fuel use. During the operation stage, replacing natural gas with more sustainable fuels, such as biomethane, solar thermal energy, and green hydrogen, can contribute to reducing emissions.

Finally, the disposal analysis demonstrated that copper recycling is an environmentally more advantageous alternative compared to sending the system to landfills. This result reinforces the importance of the circular economy in the industrial sector, promoting material reuse and reducing natural resource consumption. Thus, this study provides relevant contributions to the development of sustainable strategies in the manufacturing, transportation, operation, and disposal of vapor absorption refrigeration systems, encouraging the adoption of environmentally responsible practices.

Acknowledgment

The first author acknowledges the Sustainable Energy Institute of the Federal University of Paraíba for the technical support provided in the development of this work and the Research Support Foundation of the State of Paraíba (FAPESQ) for the financial support (through doctoral scholarship) provided for the development of this work (Process number 88887.616915/2021-00).

Authors' contributions

Neto, J. L. M.: conceptualization, data curation, formal analysis, funding, acquisition, investigation, methodology, project administration, resources, software, writing – original draft, writing. **Santos**, C.A.C.: supervision, visualization, writing – review & editing.

References

Associação Brasileira de Normas Técnicas (ABNT), 2006a. ABNT NBR ISO 14040 Second Edition Environmental Management - Life Cycle Assessment - Principles and Framework (Accessed April 11, 2024) at:. https://www.abntcatalogo.com.br/pnm.aspx?Q=dFBqV0RVdHpNVVBGeUdqb1lrUi85Y1d1N-Vl4bFhvUFRocVBDZFBGUjFTWT0=

Associação Brasileira de Normas Técnicas (ABNT), 2006b. ABNT NBR ISO 14044. Environmental Management - Life Cycle Assessment - Requirements and Guidance (Accessed April 29, 2024) at:. https://www.abntcatalogo.com.br/pnm.aspx?Q=QndvbDhMYldGMWdWR1lrY3g4K3ZqKzlHbncySVUr-VGYydDZqTG1wVXh0UT0=

Abreu, R.P.; Correia, V.H.L.; Lourenço, A.B.; Marques, A.S.; Carvalho, M., 2022. Thermoeconomic and thermoenvironmental analysis of the chilled water system in a shopping mall. International Journal of Refrigeration, v. 134, 304-311. https://doi.org/10.1016/j.ijrefrig.2021.11.011.

Arshad, M.U.; Ghani, M.U.; Ullah, A.; Güngör, A.; Zaman, M., 2019. Thermodynamic analysis and optimization of double effect absorption refrigeration system using genetic algorithm. Energy Conversion and Management, v. 192, 292-307. https://doi.org/10.1016/j.enconman.2019.03.083.

Associação Brasileira de Normas Técnicas (ABNT). ABNT NBR 10004: solid waste classification. Rio de Janeiro: ABNT, 2004.

Ayer, N.W.; Dias, G., 2018. Supplying renewable energy for Canadian cement production: Life cycle assessment of bioenergy from forest harvest residues using mobile fast pyrolysis units. Journal of Cleaner Production, v. 175, 237-250. https://doi.org/10.1016/j.jclepro.2017.12.040.

Baumann, H.; Berlin, J.; Brunklaus, B.; Lindkvist, M.; Löfgren, B.; Tillman, A.-M., 2011. The usefulness of an actor's perspective in LCA. In: Finkbeiner, M. (Eds.), Towards Life Cycle Sustainability Managemen. Springer, Dordrecht, pp. 73-83. https://doi.org/10.1007/978-94-007-1899-9_8.

Bellos, E.; Chatzovoulos, I.; Tzivanidis, C., 2021. Yearly investigation of a solar-driven absorption refrigeration system with ammonia-water absorption pair. Thermal Science and Engineering Progress, v. 23, 100885. https://doi.org/10.1016/j.tsep.2021.100885.

Castaño-Rosa, R.; Barrella, R.; Sánchez-Guevara, C.; Barbosa, R.; Kyprianou, I.; Paschalidou, E.; Thomaidis, N.S.; Dokupilova, D.; Gouveia, J.P.; Kádár, J.; Hamed, T.A.; Palma, P., 2021. Cooling degree models and future energy demand in the residential sector. A seven-country case study. Sustainability (Switzerland), v. 13 (5), 2987. https://doi.org/10.3390/su13052987.

Cavalcanti, E.J.C.; Carvalho, M.; Ochoa, A.A.V., 2019. Exergoeconomic and exergoenvironmental comparison of diesel-biodiesel blends in a direct injection engine at variable loads. Energy Conversion and Management, v. 183, 450-461. https://doi.org/10.1016/j.enconman.2018.12.113.

César, J.C.; Ortiz, J.C.; Ochoa, G.V.; Restrepo, R.R.; Nuñez Alvarez, J.R., 2021. A new computational tool for the development of advanced exergy analysis and lca on single effect libr-h2o solar absorption refrigeration system. Lubricants, v. 9 (8), 76. https://doi.org/10.3390/lubricants9080076.

Dastjerdi, B.; Strezov, V.; Kumar, R.; He, J.; Behnia, M., 2021. Comparative life cycle assessment of system solution scenarios for residual municipal solid waste management in NSW, Australia. Science of the Total Environment, v. 767, 144355. https://doi.org/10.1016/j.scitotenv.2020.144355.

Dong, D.; van Oers, L.; Tukker, A.; van der Voet, E., 2020. Assessing the future environmental impacts of copper production in China: Implications of the energy transition. Journal of Cleaner Production, v. 274, 122825. https://doi.org/10.1016/j.jclepro.2020.122825.

Google. Google Maps (Accessed November 28, 2024) at: https://www.google.com/maps.

Guillén-Lambea, S.; Carvalho, M.; Delgado, M.; Lazaro, A., 2021. Sustainable enhancement of district heating and cooling configurations by combining thermal energy storage and life cycle assessment. Clean Technologies and Environmental Policy, v. 23 (3), 857-867. https://doi.org/10.1007/s10098-020-01941-9.

Hara Chakravarty, K.; Sadi, M.; Chakravarty, H.; Sulaiman Alsagri, A.; James Howard, T.; Arabkoohsar, A., 2022. A review on integration of renewable energy processes in vapor absorption chiller for sustainable cooling. Sustainable Energy Technologies and Assessments, v. 50, 101822. https://doi.org/10.1016/j.seta.2021.101822.

International Energy Agency (IEA), 2021. The Role of Critical Minerals in Clean Energy Transitions. Paris: IEA (Accessed March 10, 2022) at:. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

Kanchiralla, F.M.; Brynolf, S.; Olsson, T.; Ellis, J.; Hansson, J.; Grahn, M., 2023. How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels? A life cycle study. Applied Energy, v. 350, 121773. https://doi.org/10.1016/j.apenergy.2023.121773.

Leite, C.A.A.F.; Alcântara, S.C.S.; Ochoa, A.A.V.; dos Santos, C.A.C.; Dutra, J.C.C.; Costa, J.A.P.; Michima, P.S.A.; Silva, H.C.N., 2021. Natural gas based cogeneration system proposal to a textile industry: a financial assessment. Energy Efficiency, v. 14 (2), 20. https://doi.org/10.1007/s12053-021-09927-2.

LG, 2020. Absorption Chiller Catalog (Accesed May 21, 2022) at:. https://www.lg.com/br/business/download/airsolution/202004_Catalogo_ChillerAbsorcao[20210429_024814580].pdf?srsltid=AfmBOoqDUAiAblZRDMTUuN7pqg3hpvi_OnNZkOfG2d7h23ugfTZl5DS6.

Li, Q.; Zhao, S.; Wang, D.; Song, Q.; Zhou, S.; Wang, X.; Li, Y., 202). Simulation Study on Solar Single/Double-Effect Switching LiBr-H2O Absorption Refrigeration System. Energies, v. 16 (7), 3220. https://doi.org/10.3390/en16073220.

Lin, H.; Clavreul, J.; Jeandaux, C.; Crawley, J.; Butnar, I., 2021. Environmental life cycle assessment of heating systems in the UK: Comparative assessment of hybrid heat pumps vs. condensing gas boilers. Energy and Buildings, v. 240, 110865. https://doi.org/10.1016/j.enbuild.2021.110865.

Longo, S.; Cellura, M.; Girardi, P., 2020. Life Cycle Assessment of electricity production from refuse derived fuel: A case study in Italy. Science of the Total Environment, v. 738, 139719. https://doi.org/10.1016/j.scitotenv.2020.139719.

Marques, A.C., 2018. Exergoeconomic and environmental evaluation of a micro-cogeneration unit. Doctoral Thesis, technology center, Universidade Federal da Paraíba, Paraíba. Retrieved 2023-09-05, from https://repositorio.ufpb.br/

Marques, A.S.; Carvalho, M.; Ochoa, A.A.V.; Abrahão, R.; Santos, C.A.C., 2021. Life cycle assessment and comparative exergoenvironmental evaluation of a micro-trigeneration system. Energy, v. 216, 119310. https://doi.org/10.1016/j.energy.2020.119310.

Micheli, M.; Moore, D.; Bach, V.; Finkbeiner, M., 2022. Life-cycle assessment of power-to-liquid kerosene produced from renewable electricity and CO2 from direct air capture in Germany. Sustainability (Switzerland), v. 14 (17), 10658. https://doi.org/10.3390/su141710658.

Nwodo, M.N.; Anumba, C.J., 2019. A review of life cycle assessment of buildings using a systematic approach. Building and Environment, v. 162, 106290. https://doi.org/10.1016/j.buildenv.2019.106290.

Osman, A.I.; Mehta, N.; Elgarahy, A.M.; Al-Hinai, A.; Al-Muhtaseb, A.H.; Rooney, D.W., 2021. Conversion of biomass to biofuels and life cycle assessment: a review. In Environmental Chemistry Letters, v. 19 (6), 4075-4118. https://doi.org/10.1007/s10311-021-01273-0.

Panahizadeh, F.; Hamzehei, M.; Farzaneh-Gord, M.; Villa, A., 2022. Thermo-economic analysis and optimization of the steam absorption chiller network plant. Thermal Science, v. 26 (1 Part A), 95-106. https://doi.org/10.2298/TSCI200619058P.

Panahizadeh, F.; Hamzehei, M.; Farzaneh-Gord, M.; Villa, A.A.O., 2021. Evaluation of machine learning-based applications in forecasting the performance of single effect absorption chiller network. Thermal Science and Engineering Progress, v. 26, 101087. https://doi.org/10.1016/j.tsep.2021.101087.

Rajput, P.; Malvoni, M.; Kumar, N.M.; Sastry, O.S.; Jayakumar, A., 2020. Operational performance and degradation influenced life cycle environmental-economic metrics of mc-si, a-si and hit photovoltaic arrays in hot semi-arid climates. Sustainability (Switzerland), v. 12 (3), 1075. https://doi.org/10.3390/su12031075.

Xu, S.; Wang, J.; Sun, H.; Huang, L.; Xu, N.; Liang, Y., 2022. Life cycle assessment of carbon emission from natural gas pipelines. Chemical Engineering Research and Design, v. 185, 267-280. https://doi.org/10.1016/j.cherd.2022.07.018.

Yu, M.; Liu, X.; Chen, Y.; Zhang, Z.; Wang, Y.; Zhang, J.; Han, Y., 2022. A 4E analysis of a novel coupling process of syngas purification and CO2 capture, transcritical CO2 power and absorption refrigeration. Chemical Engineering Journal, v. 445, 136757. https://doi.org/10.1016/j.cej.2022.136757.

Zhang, F.; Yan, Y.; Liao, G.; E.J., 2022. Energy, exergy, exergoeconomic and exergoenvironmental analysis on a novel parallel double-effect absorption power cycle driven by the geothermal resource. Energy Conversion and Management, v. 258, 115473. https://doi.org/10.1016/j.enconman.2022.115473.

Zhou, Y.; Xu, G.; Li, H.; Chen, Y.; Xu, X.; Li, M., 2023. Effect of greenhouse gas emissions on the life cycle of biomass energy production and conversion under different straw recycling modes. Environmental Research, v. 238 (Part 2), 117184. https://doi.org/10.1016/j.envres.2023.117184.

Zhu, H.; Guo, B.; Geng, W.; Chi, J.; Guo, S., 2022. Simulation of an improved solar absorption refrigeration system with phase change materials. Energy Reports, V. 8, 3671-3679. https://doi.org/10.1016/j.egyr.2022.02.306.