Economic and greenhouse gas assessments for two hot water industrial systems: Solar *vs.* natural gas

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ABSTRACT

Recognizing the energy-intensive character of the industrial sector, especially for process heat, this study designs two hot water systems for a textile industry located in Northeast Brazil. Then both systems are compared from financial and environmental viewpoints. The economic analysis uses the Payback period, Internal Rate of Return, and Net Present Value. The environmental analysis uses the Life Cycle Assessment methodology to quantify the greenhouse gas emissions associated with building and operating both systems. The economic analysis confirms that the solar water heating system is viable, with a profitability rate of 29.46, which makes it an attractive investment. The accountancy of greenhouse gases confirmed the potential of the solar system to mitigate climate change, with overall annual emissions 50 times lower than the natural gas system. The results obtained are highly related to sustainable development and cleaner production, and can be employed by decision makers aiming to change consumption and production patterns towards a more sustainable future.

1. Introduction

Worldwide the industrial sector has an essential share of final energy consumed. In Brazil, the industrial sector is the country's second-largest energy consumer (the first being transportation) and is responsible for approximately one-third of all national energy demand, only below the transport sector (Brazil, 2021a). Most of this energy is directed to industrial processes, mainly as electricity and thermal energy (process heat) (Sharma et al., 2017a). Regarding the latter, most industrial processes require temperatures between 60 and 250 °C (Kurup and Turchi, 2015).

The share of solar energy in the Brazilian energy matrix grew 92.2% between 2019 and 2020 (Brazil, 2021a). This percentage encompasses photovoltaic solar energy and solar thermal energy, which the residential and commercial sectors have procured due to significant energy and financial savings.

Solar heating in industrial processes is already considered a consolidated, clean alternative in many countries (Sharma et al., 2017b) as it is possible to reach required temperature levels (and meet industrial energy demands) using well-established technologies such as solar collectors and concentrators. Some industries that have been already benefitting from integrating solar energy include food and beverage (e. g., beer, preserved food, dairy), textile, automotive, paper and pulp, and tannery.

Solar thermal energy reached 396 TWh of installed capacity at the end of 2018, corresponding to savings of 42.6 Mt oil and 137.5 Mt CO_2 (Kannan et al., 2021). This information highlights the potential of solar thermal energy within worldwide efforts to reduce the emissions of greenhouse gases (GHG) (Kurup and Turchi, 2015).

Given the importance of environmental impact analysis in the decision-making process and considering the high thermal energy demand of the industrial sector, it is necessary to develop comparative studies between water heating systems for industrial operations. The Life Cycle Assessment (LCA) is a methodology for quantifying potential environmental impacts, which can reveal critical spots and provide the basis for optimizing a product, service or process (Guinée, 2001). LCA has been applied throughout the years to different solar energy schemes: photovoltaic panels (Carvalho et al., 2016), building-integrated photovoltaic/thermal (Lamnatou et al., 2019), dish-Stirling technology (Bravo et al., 2012), parabolic trough concentrating solar power plants

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(Guillén-Lambea and Carvalho, 2021), and linear Fresnel collectors (Mihoub, 2020).

Focusing on industrial applications, Diniz et al. (2020) evaluated the GHG emissions associated with energy transition in a brewery and confirmed the environmental benefits associated with solar thermal and photovoltaic energy: solar PV electricity resulted in 66% fewer emissions per kWh_e consumed, and solar collectors yielded 95% fewer emissions per kWh_{th}. The economic and environmental benefits of using textile waste to produce thermal energy were reported by Nunes et al. (2018), confirming that cotton waste is a viable alternative from economic and environmental viewpoints. Zhang et al. (2018) applied LCA to an existing polyester-cotton production system to reduce the environmental impacts of the production process and verified that the printing and dyeing stages were the most damaging to the environment. Kılıç et al. (2018) make a point for using LCA by companies to compete in international green markets. The authors analyzed the corporate carbon footprint of a representative Turkish tanning company, where significant environmental impacts were detected during the landfilling of solid wastes and the production of the electricity and fuel required in the tannery. The tannery inventory data presented can be helpful for company managers, for benchmarking purposes, to calculate sustainability key indicators. Mihoub (2020) presented the design, economic, and environmental assessments of linear Fresnel solar power plants, where it was verified that for Algerian climates, a molten salt linear Fresnel solar plant with 25% fossil fuel backup system and 6 h of storage is the best solution.

LCA can and should be applied within cleaner production schemes to help achieve the Sustainable Development Goal (SDG) 12 of the UN 2030 Agenda for Sustainable Development (sustainable consumption and production), helping to mitigate the adverse effects of global warming and climate change by identifying low carbon solutions. One of the challenges identified by Li (2021) is the consideration of component-related emissions (embodied emissions) and operational emissions (emissions during the use phase) – although some reports only focus on operational emissions, the importance of considering embodied energy is rising. Muneron et al. (2021) argue that LCAs support decision making and promote energy efficiency from an environmental point of view, increasing sustainability and motivating life-cycle thinking. Research on sustainable, green, or low-carbon energy systems is still in early stages, and requires further investigation and development.

Existing studies must go beyond technical feasibility by including economic and environmental aspects, so it is possible to verify the effects of the implementation of alternative and renewable sources. The purpose of this study is to apply the LCA methodology to a solar thermal energy system designed to meet the energy demands of a textile industry (Barbosa and Carvalho, 2019), quantifying the GHG emissions associated with its construction and operation. An economic analysis is also carried out to determine its economic viability, employing the Payback period, Internal Rate of Return, and Net Present Value. A conventional system based on a gas boiler was used for comparative purposes to verify the economic and environmental advantages associated with solar energy use.

2. Material and methods

By focusing on the industrial sector and identifying the potential of solar thermal energy in the textile industry, this study analyzed the hot water demand in a small processing textile industry located at the industrial district of João Pessoa, Northeast Brazil (Latitude 7.06° South; longitude 34.5° West; Altitude 7.43 m). The textile industry was modeled by Barbosa and Carvalho (2019), considering that 82 L of hot water are required for processing 1 kg of cotton fabric. Under these conditions, the textile industry needs hot water at 50-60 °C, at approximately 0.12 kg/s (432 kg/h). The solar water heating system (SWHS) was designed, and its technical feasibility according to energy demands and local climate conditions was demonstrated by Barbosa and Carvalho

(2019). Fig. 1 shows a scheme of the proposed SWHS.

The technical features of the system are 16 m^3 of storage (8 units of 2000 L tanks), storage temperature of 70 °C, daily demand for useful energy: 401.24 kWh/day, and approximately 95 m^2 of collecting area (55 flat solar collectors) (Barbosa and Carvalho, 2019).

Even with the update of the Brazilian standard NBR 15669 (2020) (which considers that systems without shading on the collectors are acceptable if the solar fraction is at least 70%), the proposed SWHS is viable from technical and operational points of view.

Typical heat production based on fossil fuel (a natural gas boiler) was considered as the conventional system. The Uni Codens 8000F gas boiler (Bosch, 2020) has a nominal power of 377 kW and meets the instant need for the highest daily energy demand required by the industrial process.

2.1. Life Cycle Assessment

LCA is widely applied for the quantification of potential environmental impacts. It is standardized by ISO 14040 (2006) and ISO 14044 (2006) and can encompass all phases of the life cycle of a product or process, or just focus on one step. The first phase of LCA is to define the objective and scope of the study (functional unit to which all inputs and outputs relate). In the second phase, the inventory is built with inputs and outputs (material and energy flows) associated with the functional unit. The third phase applies an environmental impact assessment method to translate the environmental impacts into the desired indicator. The last phase is the interpretation of results and conclusions.

The LCA was developed with SimaPro v.9.1.0.8 software (Simapro, 2020) and the Ecoinvent 3.6 (2019) database. The method adopted was the IPCC Intergovernmental Panel on Climate Change, 2013 GWP 100y (IPCC Intergovernmental Panel on Climate Change, 2013), which expresses the environmental impact in terms of CO_2-eq over a 100-year time horizon.

The LCA includes the extraction of raw material, manufacture of components, transportation, installation and operation, and final disposal. Some elements are common to both systems (conventional and SWHS), such as the amount of hot water, pumps, piping, and control systems. Because the objective of the study is to compare both systems, components that are common to both systems are not included in the analyses. The final disposal of both systems was landfill. Activities related to maintenance were not considered.

The functional unit refers to the satisfaction of the textile industry's annual hot water demands, considering 20 years as the lifetime for both systems.

2.1.1. Conventional system

Fig. 2 shows a scheme of the conventional system.

Table 1 shows the material composition of the conventional system, along with transportation and energy requirements. This consumption follows annual energy requirements for water heating in the industrial system (Nitkiewicz and Sekret, 2014). The boiler is manufactured in Berlin, Germany, and must be delivered in João Pessoa, so transportation included maritime and road displacements. It was considered that the industry already counts with connection to the natural gas grid. Environmental charges related to maintenance were not included.

2.1.2. Solar water heating system

Tables 2 and 3 detail the material compositions of the collectors and boilers used in the system. The equipment is manufactured in João Pessoa, and a route of approximately 9 km is necessary for its installation.

2.2. Economic analysis

The Net Present Value (NPV) is a widely used method in all economic sectors and is commonly used to assess the long-term profitability of
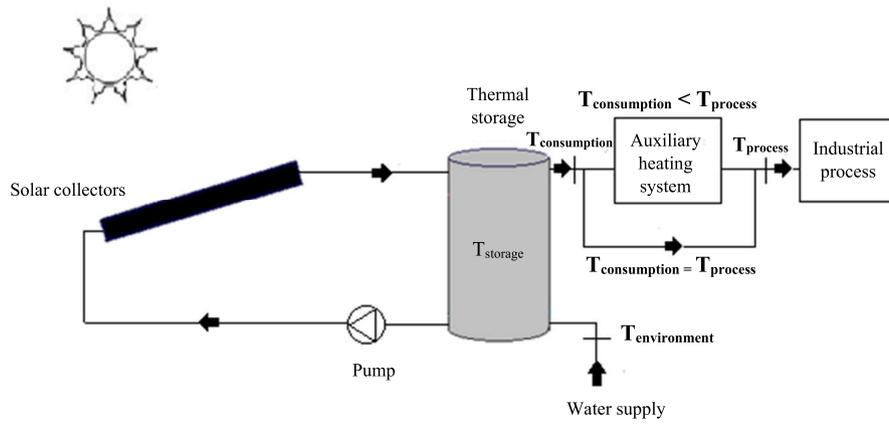
Fig. 1. Schematic representation of the solar water heating system (Barbosa and Carvalho, 2019).
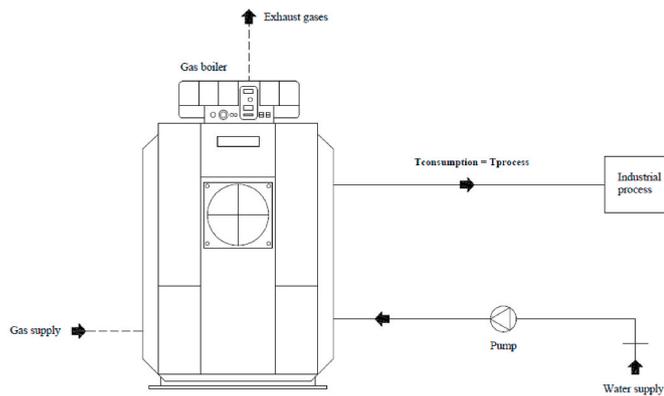

Fig. 2. Schematic representation of the conventional hot water system.

Table 1
Inventory of the conventional system.

Material/Energy input	Amount
Steel	1200 kg
Stainless steel	25 kg
Electricity	0.02 GWh$_{eletricity}$/GWh$_{heat*}$
Gas	1.04 GWh$_{gas}$/GWh$_{heat*}$
Sea transport	8200 km
Road transport	410 km
Annual gas consumption	13,457 m^3

Table 2
Material composition of one flat plate collector.

Component	Material	Amount
Glazing	Glass	0.00516 m^3
Absorber plate	Aluminum + absorber paint	3.85 kg
Enclosure	Extruded aluminum	3.60 kg
Flow tubes	Pure copper	2.18 kg
Seal	Silicone	0.10 kg
Weld	Foscoper	0.02 kg
Thermal insulation	Mineral wool	1.10 kg

Source: manufacturer data (Solartech, 2019).

Table 3
Material composition of the boiler.

Component	Material	Amount
Sacrificial anodes	Magnesium	0.62 kg
Thermal insulation	Expanded Polystyrene	4.56 kg
Outer coating	Aluminum plate	25.20 kg
Inner coating	Stainless steel 304	74.65 kg
Connectors	Stainless steel 304	0.32 kg

Source: manufacturer data (Solartech, 2019).

$$NPV = \sum_{n=1}^{i}\left[\frac{L_n}{(1+r)^n}\right] - C \tag{1}$$

C represents the initial investment, i represents the considered period for the investment feasibility analysis, L_n is the net cash flow obtained after n-period, and r represents the discount rate, also called the Minimum Attractive Rate of Return (MARR) or opportunity cost of the capital to be invested.

Once calculated, the rule for decision-making regarding the NPV of independent projects is: NPV >0, then the project is viable, but if NPV <0, the project is not economically feasible.

MARR represents the minimum profit of an investment or the maximum amount intended to pay for this investment. MARR consists of three components: the opportunity cost, the business risk, and the business liquidity. The opportunity cost was adopted as the current *Selic* rate in Brazil (*Sistema Especial de Liquidação e de Custódia* - Special Settlement and Custody System), set as 2.00% on August 5, 2020 (Central Bank of Brazil, 2020). The business risk and the investment's liquidity were considered 5% per year, which results in a discount rate (r) of 12% per year.

The Internal Rate of Return (IRR) corresponds to the discount rate that zeroes the NPV of an investment. The IRR represents profitability, as it is the rate that cancels the value of the capital initially invested in the project. The IRR can be compared with the desired MARR, or be attributed as a rate of return. When the estimated value of the IRR is higher than MARR, the investment is economically viable - in addition to recovering the capital initially invested and paying the costs of this investment, it will possibly bring profits (Brigham and Ehrhardt, 2013).

Mathematically, the IRR is calculated by obtaining the r value from Equation (1) and equaling the NPV to zero, as shown in Equation (2):

$$C = \sum_{n=1}^{i}\left[\frac{L_n}{(1+r)^n}\right] \tag{2}$$

Payback is the required time for the entire initial investment to be recovered. The shorter this period, the faster the initial investment will be recovered (Wang et al., 2009). In other words, the payback time

energy projects (Wang et al., 2009). It is the sum of the present values of cash flows that occur over the period determined for the analysis. In other words, it is the difference between the present value of revenues less the present value of costs, as shown in Equation (1):

indicates the period required for NPV to be zero and the investment to begin to be profitable.

Payback is used to analyze investments with specific technologies that promote the reduction of GHG emissions. It enables the comparison of the operational costs of low investment technologies with the operating costs of high investment technologies, capable of promoting considerable reductions in emissions during a specific time. The comparison is possible even without considering the environmental and social perspectives in the economic analysis (Zis et al., 2016). Tables 4 and 5 show costs associated with installing the proposed SWHS and conventional system, respectively.

The cost of SWHS pipes, connections, and accessories refers to the connections between the panels and between the panels and thermal reservoirs (boilers). The pipes and connections for water distribution at the industry are common to both systems and were not part of the investment analysis.

Regarding operation and maintenance (O&M) costs, the SWHS does not entail operational costs and has very low maintenance costs over its lifetime (Solartech, 2019). Maintenance and safety inspections follow the Brazilian standards for pressure vessels NR-13 (2019). The maintenance of SWHS consists mainly of replacing damaged components (wear), which is basic corrective maintenance. These damages are more likely to occur in regions with significant thermal amplitudes or when the water has a high content of salts, which is not the case for João Pessoa. No annual O&M was considered for the SWHS. The economic and environmental assessments considered 20 years as the lifetime of both systems.

Considering the consumption of natural gas, the tariff is BRL 2.41/m^3 (PBGÁS, 2020) which yields BRL 13,639.14/week. For the traditional system, fire tube boilers must undergo inspections every 12 months, and preventive maintenance must be performed according to the reports obtained after each inspection. For the conventional system, the O&M costs are BRL 24,000 + BRL 654,678, totaling BRL 678,678.

In the investment analysis, only the investments that can be planned and controlled were considered. Corrective maintenance costs were not accounted for.

3. Results and discussions

The analyses considered an annual hot water demand of 136,836 kWh, totaling 2,736,729 kWh over 20 years. The following sections present and discuss the results of the GHG accountancy and economic analysis.

3.1. Environmental analysis

For both systems, the emissions associated with construction are related to the equipment and materials necessary to assemble the system (extraction of raw material, manufacture of components, transport, installation and operation of the product, and disposal in landfill). For operational emissions, these were only considered for the conventional system and are related to natural gas consumption, totaling 22,136 m^3/month (241,722 kWh/month).

Table 6 shows the GHG emissions associated with each system. The total emissions related to the construction of the systems were divided

Table 4
Capital costs of the solar water heating system.

Component	Unit value	Total
Solar collector	BRL 1256	BRL 69,080
Boiler 2000 L	BRL 8990	BRL 71,920
Pipes, connections and accessories	–	BRL 8630
Installation and direct costs	–	BRL 22,445
Initial investment		**BRL 172,075**

Source: Solartech (2019).

Table 5
Capital cost of the conventional system.

Component	Unit value
Natural gas boiler	BRL 136,184
Installation and direct costs	BRL 34,046
Initial investment	**BRL 170,230**

Source: Bosch (2020).

Table 6
Emissions associated with conventional and solar systems.

	Conventional	SWHS
Construction ((kg CO_2-eq/y)	189.17	642.87
Operation (kg CO_2-eq/y)	32,909.45	–
Total	**33,098.62**	**642.87**

by 20 (years), which resulted in kg CO_2-eq/y. Operational emissions were recorded annually, and also expressed in kg CO_2-eq/y.

The conventional system is characterized by lower emissions during the construction phase (189.17 kg CO_2-eq/y), while the operation phase contributes to the most significant portion of emissions (32,909.45 kg CO_2-eq/y). For the SHWS, only the construction phase contributes (642.87 kg CO_2-eq/y) to the overall emissions.

The effect of adopting different operational lifetimes (5, 10, and 20 years specifically) was investigated for both systems, as shown in Fig. 3.

Fig. 3 shows that the conventional system is characterized by much higher emissions during the operation phase due to natural gas consumption. The value for a 5-year lifetime is slightly higher because the emissions related to installation are relatively low compared to operation. However, the trend is towards stabilizing operation emissions over the years, with an emission rate of 0.24 kg CO_2-eq kWh^{-1} for a 20-year lifetime.

The GHG emissions for the SWHS only refer to equipment (Table 2). The longer the system's lifetime, the higher the amount of energy produced – lowering the emission rate of kg CO_2-eq kWh^{-1}. As illustrated in Fig. 3, when the lifetime is five years, this rate is 0.019 kg CO_2-eq kWh^{-1}, further reducing to 0.05 kg CO_2-eq kWh^{-1} for a 20-year lifetime.

Fig. 4 shows the contributions of the materials involved in the components for both analyzed systems and the emissions related to transportation and landfilling.

Disaggregating the material emissions in Fig. 4 shows that steel had the highest contribution, with 66.6% of the emissions, in the conventional system. For SHWS, aluminum presented the highest contribution (47.8%), followed by stainless steel (22.3%), copper (7.9%), and glass (6%). Regarding the final impact of the SWHS, 224.77 kg CO_2-eq/y is due to the boilers, and 418.10 kg CO_2-eq/y to the collectors.

The information displayed in Fig. 4 can be used to explore new material options for the systems. It also shows essential points about equipment purchasing, such as the distance between the manufacturing
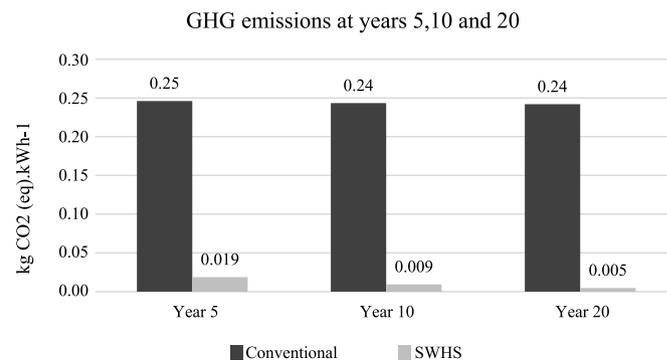
Fig. 3. Emissions, in CO_2-eq. kWh^{-1}, for different lifetimes of the systems.
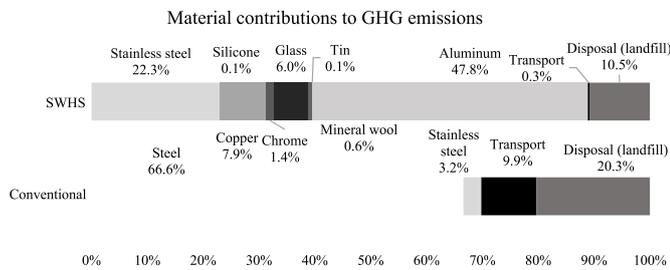
Fig. 4. Disaggregation of material emissions for the conventional and SWHS.

and the installation sites. The SWHS is manufactured in João Pessoa, while the conventional system is manufactured in Berlin, Germany (and requires sea and road transportation, responsible for 9.9% of GHG emissions along its 20-year operation).

Another critical issue for discussion is the final disposal of the system, as both options employed landfilling. This is a realistic scenario for Northeast Brazil. However, considerations on reuse and recycling can provide environmental benefits for both systems. Unger et al. (2017) mentioned an increase in recycling as an essential contribution towards a circular economy. However, adequate accounting for dismantling, shredding, sorting, materials recycling, and disposal of non-recyclable fractions must be accomplished. Effective end-of-life strategies for electrical and electronic equipment are required to balance resource recovery and environmental impacts better.

As verified, the systems analyzed have different characteristics in terms of GHG emissions. Fig. 5 depicts the behavior of both systems regarding the accumulated emissions over 20 years. From installation until just before the end of year 1, the conventional system has lower GHG emissions.

Fig. 5 shows an expected behavior in agreement with scientific literature. In general, solar generation systems present lower CO_2-eq emissions than conventional, fossil-fuel systems. Table 7 compares the environmental results obtained with scientific literature. All systems analyzed presented a reduction in emissions. This reduction is more significant in countries with higher radiation rates, which demonstrated the influence of climatic conditions on the thermal efficiency of solar water heating systems.

The reference indicator was calculated to provide an equivalence parameter between the compared results and assess the compared systems under the same conditions.

The higher the daily hot water volume, the more energy required for heating and higher GHG savings when using solar thermal energy. Larger SWHS provide even higher savings in CO_2/L of heated water as they also save a higher share of energy that could have originated from fossil fuels.

3.2. Economic analysis

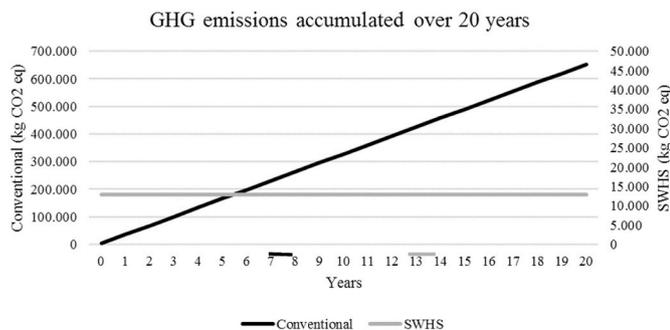Table 8 shows the cash flows discounted at zero time associated with

Fig. 5. GHG emissions accumulated over the years for both systems.

each year. The values referring to the revenue from SWHS represent the amount saved annually with fuel and preventive maintenance, which are characteristic of the conventional natural gas system. Table 8 also shows the NPV for each specific year, adjusted according to Equation (2). Since the first year, the investment in SWHS proves to be economically viable according to the NPV criterion, as it already presents NPV >0.

Fig. 6 shows the increasing behavior of the NPV (positive since the first year) and the behavior of the Internal Rate of Return (IRR), which also classifies the SWHS as economically viable, as it presents a value higher than the rate of discount *r* considered (12%).

The IRR value has a value of 294% already in the first year, which is almost 25 times higher than the adopted discount rate (*r*). IRR stabilizes at 394% from the fourth year onwards.

Regarding the payback times, the SWHS has a payback period of 5 months. It means that after the fifth month of operation, this system will have paid for itself and started to generate profit from the savings caused by the replacement of a conventional natural gas heating system.

All the economic parameters employed in the analysis displayed positive results. The profitability rate was also calculated for the SWHS, representing the sum of all present values divided by the initial investment. The estimated profitability rate is 29.46 – this means that for each BRL 1.00 initially invested, the SHWS returns BRL 29.46 over its lifetime.

Table 9 compares results with existing studies, consistent with the characteristics of the analyzed SWHS.

When comparing the return on investment, it is essential to note that facilities located in lower latitude regions (Brazil and Pakistan) present lower paybacks due to more favorable solarimetric indices and higher average temperatures. All solar heating systems demonstrated economic advantages for residential purposes and at larger scales (student accommodations and industries).

From the results obtained, the importance of considering a higher number of design variables is verified, going beyond technical specifications. The utilization of solar energy to obtain process heat can be extended to several other industry sectors, not limited to the textile industry. Although the research is applied and has a Brazilian focus, in terms of the case study adopted, the work is of global scientific importance. The local dimension, even the specific textile industry focus, is just a way to demonstrate the relevance of the science, which herein was able to mitigate emissions considerably and will serve as a benchmark for the Brazilian textile industry.

According to the Brazilian Association of Textile and Clothing Industry (2019), Brazil has approximately 25,500 industries of the sector, with an annual revenue of approximately US$ 33.74 billion. The number of industries in Brazil confirm the mitigation potential associated with the application of renewable energy technologies in the sector.

Regarding the reduction in the emission of pollutants, it is evident that the proposal is aligned with the most recent Brazilian emission reduction policy. At the 26th United Nations Climate Change Conference (COP 26), the Brazilian government presented a reduction goal of up to 50% by 2030 (Brazil, 2021b). In this sense, one of the strategies employed to reach this target is to incentivize the use of solar thermal energy in the industry sector, given the increasing behavior associated with the conventional heating system shown in Fig. 5.

Another important ramification of the results is related to the sustainability economic pillar, regarding the textile sector. The investment in solar technology is capable of generating revenue for the sector in less than one year. This factor is very positive, considering the current contribution of the purchase of fuel to the operational costs of industries that only employ fossil fuels. The initiative to begin energy transition can, therefore, be an economic motivator for small and medium industries in a short time interval, with almost the same capital cost.

This energy adjustment (energy transition) is in conformity with the concept of cleaner production. Although there are initial technical barriers, the dramatic reduction of emissions throughout the lifetime of

Table 7
Comparison of environmental results.

	This study	Herrando & Markides (2016)	Yuan et al. (2017)	Kylili et al. (2018)	Greening & Azapagic (2014)
Location	João Pessoa, Brazil	London, UK	Shandon, China	Europe	UK
Goal	Hot water (industrial)	Hot water (residential)	Hot water (Student accommodation)	Hot water (industrial)	Hot water (residential)
Volume	16,000 L	150 L	360,000 L		
Energy	144.45 MWh/y	1.0 MWh/y		9.72–20.83 MWh	
Reduction in emissions	32 t CO_2-eq/y	0.8 t CO_2/y	460 kt CO_2/y	2-5 t CO_2/kW	70% less than conventional systems
Reference indicator	0.002 t CO_2 -eq/y L	0.005 t CO_2/y L	1.27 t CO_2/y L		

Table 8
Cash flows and NPV analysis for SWHS over 20 years.

		Annual cash flow		Present net flow		NPV	
Initial investment	C	-BRL	172,074.96	-BRL	172,074.96	BRL	–
Year 1	L1	BRL	678,678.72	BRL	605,963.14	BRL	433,888.18
Year 2	L2	BRL	678,678.72	BRL	541,038.52	BRL	974,926.70
Year 3	L3	BRL	678,678.72	BRL	483,070.11	BRL	1,457,996.81
Year 4	L4	BRL	678,678.72	BRL	431,312.60	BRL	1,889,309.41
Year 5	L5	BRL	678,678.72	BRL	385,100.53	BRL	2,274,409.94
Year 6	L6	BRL	678,678.72	BRL	343,839.76	BRL	2,618,249.70
Year 7	L7	BRL	678,678.72	BRL	306,999.79	BRL	2,925,249.49
Year 8	L8	BRL	678,678.72	BRL	274,106.95	BRL	3,199,356.44
Year 9	L9	BRL	678,678.72	BRL	244,738.35	BRL	3,444,094.79
Year 10	L10	BRL	678,678.72	BRL	218,516.38	BRL	3,662,611.17
Year 11	L11	BRL	678,678.72	BRL	195,103.91	BRL	3,857,715.09
Year 12	L12	BRL	678,678.72	BRL	174,199.92	BRL	4,031,915.01
Year 13	L13	BRL	678,678.72	BRL	155,535.65	BRL	4,187,450.66
Year 14	L14	BRL	678,678.72	BRL	138,871.11	BRL	4,326,321.77
Year 15	L15	BRL	678,678.72	BRL	123,992.06	BRL	4,450,313.83
Year 16	L16	BRL	678,678.72	BRL	110,707.20	BRL	4,561,021.03
Year 17	L17	BRL	678,678.72	BRL	98,845.71	BRL	4,659,866.75
Year 18	L18	BRL	678,678.72	BRL	88,255.10	BRL	4,748,121.85
Year 19	L19	BRL	678,678.72	BRL	78,799.20	BRL	4,826,921.05
Year 20	L20	BRL	678,678.72	BRL	70,356.43	BRL	4,897,277.48
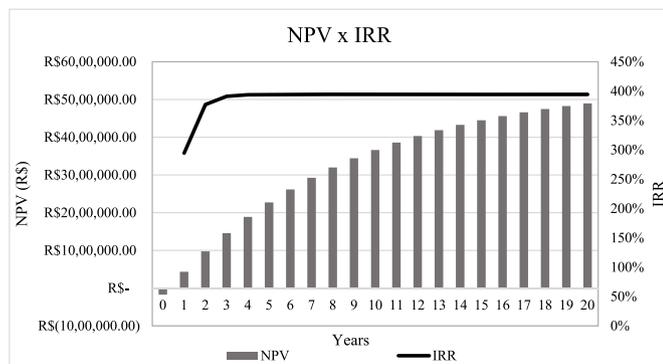
Fig. 6. NPV and IRR for the 20-year lifetime.

the energy system clearly justifies the substitution of existing conventional, fossil fuel-based, heat generation schemes as well as the implementation of solar technologies for new projects.

One of the main challenges for the installation of solar thermal energy systems in industries is conservatism, as traditionally process heat is associated with gas or oil boilers. Additional barriers include the lack of governmental incentives and subsidies, and scarcity of actions with the purpose of disseminating and promoting the introduction of renewable energy in the industrial sector. This leads to a slower transition, as it depends on the progressive awareness process of isolated companies that are interested in leading the search for a more sustainable economy.

Although sustainable goals have been established for the reduction of emissions in Brazil (Brazil, 2021b), this is still a starting point. A more assertive action plan is still necessary, including studies on the technical, environmental and economic viability of energy systems, pointing to effective solutions for the decrease in emissions, preserving technical quality and economic growth. Companies and organizations must start to adopt and trust sustainable technologies as viable alternatives.

This study is written while the COVID-19 pandemic is still unfolding. Still, some impacts have already been felt beyond the health sector, such as in Carvalho et al. (2021) and Delgado et al. (2021), who verified the impacts on electricity consumption and load patterns. Although the

Table 9
Comparison of economic results with scientific literature.

	This study	Herrando & Markides (2016)	Yuan et al. (2017)	Hussain et al. (2020)	Hang et al. (2012)
Location	João Pessoa, Brazil	London, UK	Shandong, China	Pakistan	USA
Goal	Hot water (industrial)	Hot water (residential)	Hot water (Student accommodation)	Hot water (industrial)	Hot water (residential)
Daily volume	16,000 L	150 L	360,000 L	120,000 L	
Energy	144.45 MWh/y	1.0 MWh/y		640.43 MWh/y	
Payback	5 months	11.2 years	7.6 years	3.5 years	13 years (maximum)
Reference indicator	0.009 day/L	26.88 day/L	0.0076 day/L	0.01 day/L	

energy transition has globally slowed down, some countries are already formulating response packages to address the generalized crisis. In the medium- and long-terms, the resilience and competitiveness of some renewable technologies, such as solar energy, will help support the transition to resilient, cleaner, and low carbon energy systems (Jiang et al., 2021). Adopting renewable energy solutions is an interesting strategy for the post-COVID-19 dilemma, as industries can be revived by ramping up renewable energy technologies and creating new jobs (Hosseini, 2020). The solar energy pathway (which includes photovoltaic and solar thermal) towards a low carbon society in the aftermath of the pandemic requires a combination of efforts from governments, industries, and small players. The pandemic can be seen as an opportunity to build recovery plans that change consumption and production patterns towards a more sustainable future.

Finally, within the context of SDG and more specifically of SDG 12, it is important to employ LCA to identify *hot spots* in energy systems where interventions have the highest potential to improve the overall environmental impact.

4. Conclusions

This study quantified and analyzed the economics and greenhouse gas emissions (GHG) of a solar water heating system (SWHS) and compared it with a natural gas boiler.

The economic assessment of the SWHS presented the best performance. The Net Present Value was positive, and the Internal Rate of Return was 25 times higher than the acceptable minimum since the first year (demonstrating economic viability and attractiveness). The payback time was just five months. And according to the Profitability Rate, for each BRL 1.00 invested in the SHWS, the return is BRL 29.46.

Although the GHG emissions associated with the equipment were higher for the SWHS, its overall annual emissions were 50 times lower than the natural gas system, due to the intense consumption of fossil fuel in the latter. Most equipment-related emissions are associated with aluminum and stainless steel.

Aiming to connect the obtained results with sustainable development and cleaner production, future research solutions include searching for alternative materials that maintain the technical requirements and reduce environmental impacts at this stage.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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