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Life Cycle Assessment of Sustainable Low-Cost Thermal Energy Storage Materials for Solar Water Heating.

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Abstract— **North Africa has a high potential for solar energy. But for the implementation of these systems, considerations of cost and material availability are very important. On that account, this work attempts to contribute reduce barriers for the integration of renewable energies under economic and environmental constraints in developing countries. This paper illustrates some point of view of the use of cheap and locally available materials as a potential candidate for the thermal energy storage in a solar water heater. Furthermore, this research emphasizes the energetic and environmental impact of these materials (Concrete, Clay, Sand and Phase change material (PCM) based on Paraffin) by means of Life Cycle Assessment method (LCA) and compares them with the conventional system that use the water as storage material. These materials were the subject of previous experimental work by building prototypes tested in Gabès, Tunisia Climate. The results show that these materials have a promising environmental and energy performance. Thus, clay, concrete and sand have a competitive result compared to the classical system. The phase change material (PCM) system has a similar energy performance, but a poorer environmental performance. Hence, this inquiry indicates that the solar water heater with integrated thermal energy storage built by one of the thermal storage materials tested during this work presents a promising alternative to the conventional system. Notice that they offer the simplicity of manufacture and no corrosion problems.**

Keywords: Solar water heater, thermal energy storage, sustainable materials, low-cost materials, Life Cycle Assessment.

Nomenclature:

CSWH	Compact Solar Water Heater
DSWH	Domestic Solar Water Heater
DHW	Domestic hot water
LCA	Life Cycle Assessment
LCI	Life-Cycle Inventory
PCM	Phase-Change Material
Qbackup	Backup Energy (Electricity) consumed by the SWH during its lifespan (kWh)
Quseful	Useful Energy (Solar Energy) consumed by the SWH during its lifespan (kWh)
SWH	Solar Water Heater
Tamb	Ambient Temperature (°C)
TClay	Outlet Temperature of Clay Solar Water Heater (°C)
TConcrete	Outlet Temperature of Concrete Solar Water Heater (°C)
TES	Thermal Energy Storage
TPCM	Outlet Temperature of PCM Solar Water Heater (°C)
TSand	Outlet Temperature of Sand Solar Water Heater (°C)

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TWater	Outlet Temperature of Water Solar Water Heater (°C)

I. INTRODUCTION

Fossil fuels are expected to become increasingly scarce and consciousness regarding their environmental impact has evolved. This makes global policy more demanding towards pollutants and harmful emissions to the planet. Regarded this reason, the energy transition towards other sources of cleaner energy systems becomes a necessity, especially since the benefits of the use of renewable energy technologies affect various aspects: energy saving, reduction of pollutant discharges to the environment as well as local jobs [1]. In this context, Tunisia aims in its solar plan to raise the percentage of renewable energy in electricity production from 3% in 2014 to 30% in 2030. The major part of primary energy consumed in Tunisia is devoted to the building sector, with percentage of 30% [2]. One widely used solar energy application is solar domestic water heating. A solar water heater contains essentially two elements: the absorber and the thermal storage. The thermal storage allows storing the excess of thermal energy and releasing it at night or during the non-sunny period of the day. Many authors have carried out studies on solar water heaters and on the improvement of the collector performance [3-9]. The development of a solar thermal collector by substituting traditional metallic materials for the absorber by innovative materials to be more efficient and cheaper than what actual commercial collectors have been studied by Fernández *et al*. [10].

Hadjiat *et al* have attempted in their paper to present a new design of low cost solar water heater to improve its performance. They have carried out a theoretical study of the optical and thermal performances of the designed ICS system [11]. Other researchers are carried out on thermal storage and innovation of other ways of storing heat [12-14]. Several research works resort to use phase change materials (PCM) for thermal storage [15, 16]. Canbazoglu *et al* have presented a thermal performance comparison between a solar water-heating system combined with a phase change material (PCM) and a conventional system including no PCM [17]. The results have shown that the thermal storage tank combined with the PCM is more efficient [17]. Bouhal *et al* have studied a solar thermal energy storage system filled with encapsulated PCM connected with solar collectors for solar hot water production in Marrakech, Morocco [18]. Thus, it has shown that the heat losses to surrounding in dynamic mode are proportional to the PCM amount while the melting velocity is inversely proportional to it. Other authors have investigated new materials for sensitive thermal storage [19]. Taheri *et al* have investigated a new design of a compact solar water heater (CSWH) system with using the black colored sands immersed into the water storage tank to build the main portion of the collector absorber section [20]. An averaging daily efficiency higher than 70% has been achieved by the alternative system [20]. Related to this view, this work aims to evaluate four thermal storage materials (concrete, clay, sand and PCM) for a solar water heater and to compare them to the classic system which is composed by a metallic absorber surface and a water thermal storage tank. These materials have been chosen because of their low cost, ease of handling, high specific heat and mechanical properties. More than their energy performance, it is important to analyze their environmental profiles over all their life cycles. Therefore, to evaluate the environmental aspect of these materials and to quantify their emissions, the Life Cycle Assessment method (LCA) from cradle to grave and Simapro software has been used [21]. LCA is a method of life cycle analysis of products, process, or an activity and of quantification of their environmental loads and impacts considering all stages of their life cycle process. The solar water heaters that are the subject of this study have the same compounds (type of materials and dimension) but differ by the materials of thermal storage; a detailed description of the system is made elsewhere (section 2). Many LCA have already been achieved for the assessment of the environmental impacts of solar water heaters compared to other types of conventional energy heating by electricity or gas [22]; some others have evaluated the economic benefits of their facilities [23-26]. Crawford and Treloar have carried out a life cycle energy analysis of five hot water systems (electric-boosted solar, gas-boosted solar, electric storage, gas storage and a gas instantaneous hot water system) in Melbourne, Australia [27].

Battisti *et al* have performed in their article a life cycle assessment of a solar thermal collector with integrated water storage for their entire life cycle using simaPro 5.0 software [28]. The findings of this study have shown a reduction in overall impacts up to 40% and that the most critical phase from an environmental outlook is the production stage of the collector [29]. However, the works that specifically focuses on studying the environmental impact of the thermal storage materials are relatively restricted. Oró *et al* have carried out a comparative LCA of thermal energy storage systems focused only on the DHW storage systems (molten salt and solid medium) [30]. Oró *et al* have studied two forms of thermal storage: sensible thermal storage and latent thermal storage, and they have shown that the solid medium has the lower environmental impact than the PCM system. Then, they have proved that the storage material impact of each system is greater than 94% and that the human health and resources damages impacts are similar and higher than the ecosystem impact [30]. The paper of Miró *et al* has evaluated the

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environmental impact of three thermal energy storage systems 'TES' (concrete, molten salts system for sensible and latent storing heat) used in high temperature application for CSP plants. They have noticed that concrete used as sensible heat storage material has the lower environmental impact than the molten salts and PCM systems [31]. López-Sabirón *et al* have focused on the opportunities to recover the waste thermal energy released in industrial processes through introducing a TES system using different PCMs [32]. They have analyzed the environmental impacts of 20 case studies composed by 4 TES systems varying the added PCM and five application options based on the fossil fuel under the same conditions to make them comparable. The results obtained have shown that the potential energy storage capacity of the TES has been linear with the PCM heat latent content. However, in all cases; except two cases; the environmental benefits got by the energy recovery are not enough to compensate the TES system use [32].
The novelty of this work is to conduct a LCA dedicated to examining the environmental aspects and energy performance of four thermal storage materials (Clay, Concrete, Sand and Paraffin) for the solar water heater and to compare them to those of the conventional solar water heater. Most of these materials offer a low cost and environmental impact as well as their local availability.

II. Description of the methods

Within this paper, five different prototypes of a solar water heater (SWH) with electricity as auxiliary energy for domestic use in the city of Gabes, Tunisia are analyzed; including four SWH with innovative storage materials (Concrete, Clay, Sand, and PCM) and a conventional SWH with water as a thermal storage material. Each system to be analyzed is a typical flat-plate collector. The back and sides cover of the collector comprises a wood and at its front, a double polycarbonate is used for glazing (Figure1).

Fig 1: A photograph of one of the solar water heaters.

A layer of polystyrene with 50mm thickness is used on the sides of the collector and at the back insulation. The collector area, playing the dual role of an absorber and thermal storage, differs from one system to another. It is made from the materials to be analyzed by this LCA and a serpentine-shaped copper tubes emerging into them. The systems have the same technical characteristics (Table 1) and are used to cover the hot water needs of a five-person family.

Table 1 Technical characteristics of Solar Water Heater.

Collector Type	Flat Plate
Glazing Type	Double Polycarbonate
Selective Paint	Black Solar Powder
Collector inclination	45°
Collector Area	$4m^2$
Hot water demand/person /Day	50L
Maximum temperature of hot water	60°C

The purpose of this study is to evaluate the energetic and environmental impacts of innovative thermal storage materials (Clay, Concrete, Sand, PCM) for the solar water heaters and to compare them with those of the conventional system which uses water as thermal storage material throughout their lifespan, from cradle to grave. The results allow the comparison between five prototypes of solar integrated water heater on material level. Experimental work has already been done on these prototypes of the solar water heaters. Several experimental parameters have been studied based on two configurations: 'Integrated Storage Solar Water Heater' and 'Thermo-siphon Solar Water Heater' [33]. The experimental study was been performed under real operating conditions for two days in continuous measurement for carrying out the performance test. The sensors were oriented to the south-east and thermocouples were positioned at the appropriate places for monitoring the system temperatures. The temperature measurements were taken every hour by type K thermocouples with ± 0.5 ° C uncertainty. To avoid the mask effect, the series of experiments were taken in an open site away from obstacles. These materials have proven their performance experimentally in previous work and in this paper; the Simapro 8 Software is used for conducting LCA based on RECIPE impact assessment method [34, 35] to quantify the environmental performance of these materials (Figure 2). This method follows the ISO 14040 [34,35]. Data are extracted from the database EcoInvent (v.3.5) [36]. The environmental impacts are divided into three different damage categories: human health, ecosystem quality, and resources.

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The main function of a solar water heater is to produce hot water for domestic use and to store heat for the not sunny period. A typical family consisting of five persons requires 250l of hot water at 60°C daily [37]. The life span for all water heating systems is estimated 20 years. The storage materials present different capacities of storing energy; therefore, their evaluation will be done per kWh stored to ensure consistency among each other. The functional unit is thus: 1kWh of thermal energy used for production of hot water within the lifetime of the solar water heater and includes losses throughout loading, storing, and unloading of thermal energy. During use phase, solar water heating produces no emissions; the main impacts of the process are during the manufacture and installations of components and systems. Electricity is taken into account as auxiliary heating for the use phase. In addition, the transportation of the materials/components from the production site to the installation site, then from the installation site to the disposal site is included (50km transportation by lorry). Landfill is assumed for the disposal phase of components of all collectors during the lifespan of the system, including the recycling of certain materials / components.

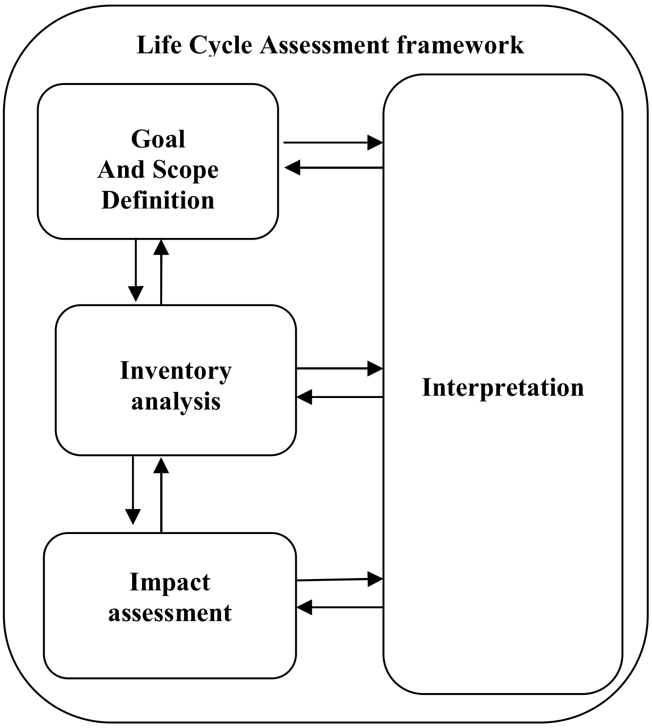

Fig 2: Phases of an LCA ISO 14040 [34].

III. Results and Discussion

To study the environmental benefits of using the new thermal storage materials (Concrete, Clay, Sand, PCM) instead of the water used in conventional solar water heaters, we have estimated and compared their different emissions resulting from the different life cycle stages.

A. *Life cycle inventory*

The inventory of the life-cycle of the different prototypes is detailed in Table 2. In this table, we have just presented the materials constituting the prototypes, but there are several other factors involved in the inventory of the life cycle (disposal stage, transport ...), which have the same impact point for all systems. Table 2 shows that some components are common for different prototypes (in terms of material type and quantity). This is obvious since this study is devoted just to the comparison of thermal storage materials.
It is remarkable in table.2 and also supported by Oró *et al* [30], that thermal storage materials have the highest percentage of the total impact of 99.6%, 47%, 23%, 94%, 87% and 99% respectively for PCM, Water, Sand, Clay and Concrete and that the impact of all other components is low this may be due to the remarkable difference in high amount of thermal storage materials.

Table 2 Life Cycle Inventory and impact in different prototypes.

Materials	Quantity	Unit	Impact points (RECIPE)	Impact/amount material used
Polystyrene Insulator	208	kg	80,8	0,388
Double Polycarbonate Glazing	12	kg	7,98	0,665
Copper tube	2,67	kg	17,8	6,667
Wood Frame	0,0992	m^3	18,5	18,649
Sand	330	kg	1,13E7	3,424E5
PCM	156	kg	8,1 E8	5,192E6
Water	200	kg	8,36E4	4,18E2
Concrete	460	kg	1,18E8	2,565E5
Clay	340	kg	4,71E6	1,385E4

Clay	340	kg

The total impact differs from one system to another in relation to the characteristics of each system such as the thermal capacity of the material, the demand for extra energy...

B. *Energy analysis*

The time-wise variations of the solar radiations as well as the outlet water and ambient temperature variations for three successive days from 06-06 to 08-06 are shown in Figure 3. The radiation sensors were oriented to the south and tilted 45 ° and the thermocouples were positioned at the appropriate places for monitoring the energetic performance of the prototypes. Figure 3 shows the evolution of the solar flux density as a function of local time. In fact, the solar flux curve followed the same shape during the 3 days of measurement. It increases in the morning and becomes significant between 9 a.m. and 3 p.m. reaching a maximum value of around 1000 W / m2 at noon, then it decreases towards the end of the day. The shape of the temperature curve is similar for the different storage materials and it is in agreement with that of the solar radiation with a slight shift of the hour of obtaining maximum. The difference between the outlet water temperature for the various systems and the ambient temperature is around 25 ° C, which is very significant with the simplicity of the system. Related to Figure 3, the outlet temperature for the thermal storage materials tested during this work, increases by reaching its maximum between 1 p.m. and 3 p.m. depending on the materials, and then it decreases towards the sunset. It increases by a few degrees for the 2nd and 3rd day compared to the 1st day.

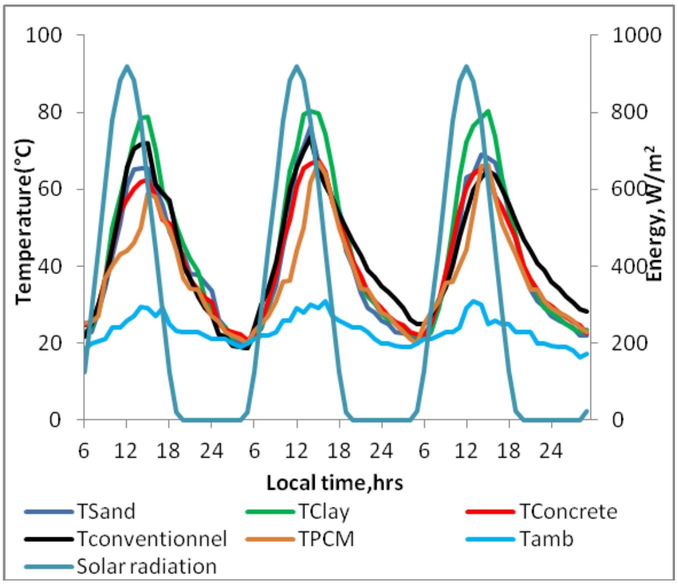

Fig3: Variation of the incident solar flux, the ambient temperature and the water outlet temperature according to the local time during two successive days (06-08/06).

The analysis of this figure shows that it possible to reach temperatures sufficient for the use of hot water applying one of the innovative thermal storage materials since the early hours of the day. The highest temperature value obtained is 80.3 ° C for clay. The thermal storage materials tested during this work don't have the same thermo-physical characteristics; clay and concrete having a higher diffusivity and thermal conductivity than those of water, sand and PCM have an acceptable heat capacity. This gives them a strong ability to absorb and store thermal heat. Indeed, the experimental results are in agreement with the nature and the thermal properties of the materials used. This is the effect of the thermal inertia of these materials. Comparing the materials results, some of these materials heat up quickly and they store heat for a long time (Clay, water) by having a temperature value around 50°C since the first hours of the day until the end of the day, others heat up quickly with a value temperature more than 40°C since 10am and cool down quickly (PCM, Sand) with a great temperature gradient after mid-day, while there are others that heat up and cool down slowly (Concrete). The water outlet temperature decreases during the day; hence there is a need for additional heating. Figure 4 shows the amount of useful solar energy and the auxiliary energy that is the electricity in this study consumed for the entire life cycle of our prototypes.

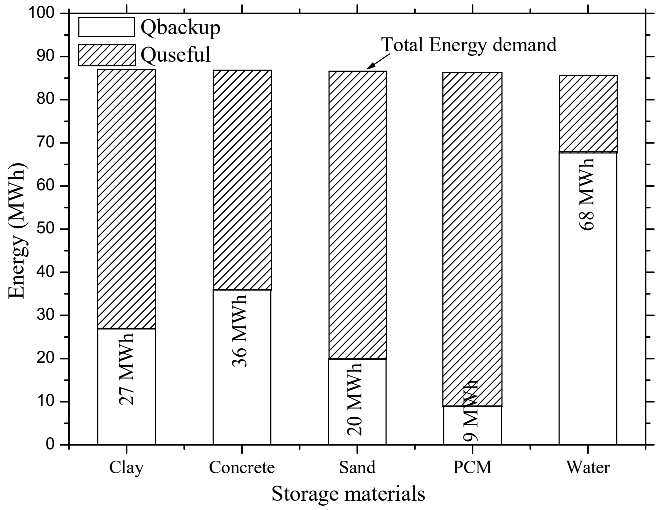

Fig 4: Comparative study for thermal storage materials energetic performance during their lifespan (20 years).

As is clear in this Figure, the SWH with PCM requires the least additional energy against the conventional SWH with water thermal storage material, which is the most demanding backup energy compared to other prototypes. All prototypes of solar water heaters with the proposed thermal storage materials provide about 3/4 of energy demand for the production of hot water by solar way.

C. *. Environmental impact assessment*

Waste streams and emissions to the environment of each prototype during its lifespan are calculated using the Life Cycle Inventory LCI. Thus Table 3 summarizes the emissions responsible for the most important environmental problems

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and they are expressed in physical units of these substances. Emissions are analyzed in three categories (Ecosystems, Human Health and Resources) and their overall impact throughout the prototypes' life cycle divided by stored energy is listed in Table 4. Emission flows are standardized and evaluated using weighting factors.

Table 3 Environmental impact of the solar water heater with different storage materials.

Emissions	Unis	Clay	Concrete	PCM	Sand	Water
Carbon dioxide CO_2	kt	0,37	26,86	107,82	1,32	0,52
Carbon monoxide CO	t	0,018	0,295	11,046	0,068	0,003
Nitrogen oxides NO_x	kg	0,435	5,08	11,65	0,68	0,044
Methane CH_4	kg	0,016	1,14	12,60	0,19	0,008
Hydrocarbons	kg	0,088	1,37	1,78	0,308	0,0037
Sulfur dioxide SO_2	kt	0,083	3,28	15,55	0,31	0,082
Carbon disulfide CS_2	g	3,77	36,30	52,94	8,5	0,68
Hydrogen Fluoride HF	t	0,249	6,02	27,33	0,957	0,346
Nicosulfuron	g	0,026	0,49	9,82	0,08	0,028
Hydrocarbons chlorinated	kg	1,63	54,64	673,98	12,005	1,21

It is noted according to the Figure 5 and Table 4 that the overall impact of human health is the highest of the order of 45% for most prototypes and that the impact of the ecosystem is the weaker except that with PCM, the impact of the resources is the highest followed by the impact of human health then the impact of the ecosystem [30].

Table 4 Impact results during lifespan for different systems.

	Clay DSWH	Concrete DSWH	PCM DSWH	Sand DSWH	Water DSWH
Human health [Impact /kWh]	3,3E-05	9,85E-04	0,001556	6,3E-05	3,9E-05
Ecosystem quality [Impact/kWh]	1,4E-05	4 ,96E-04	0,000682	3,3E-05	1,7E-05
Resources [Impact /kWh]	2,7E-05	4,42E-04	0,006355	5,2E-05	2,5E-05
Total	7,4E-05	18,96E-04	0,008593	14,8 E-05	8,1E-05

Based on the overall impact assessment, it is remarkable that despite the energetic benefits reached by the solar water heater with PCM; this system is the more impacting on all environmental categories than other prototypes with sensible storage [32]. The Clay Water Heater is the best prototype in terms of overall environmental impacts per stored kWh (Tab.4) with lower overall impact than the conventional water heater. In comparison, the other materials (Concrete, sand) have more elevated impacts.

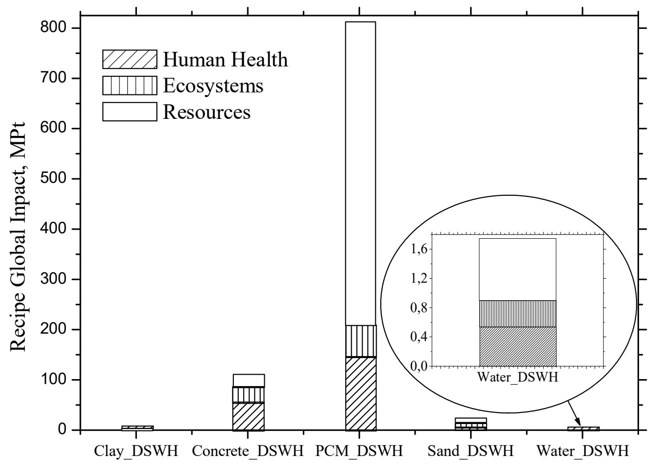

Fig 4. Global impact of each storage materials for solar water heater

Therefore, the present work results are in accordance with those of several studies that compare the environmental impacts of sensible thermal storage systems and latent thermal storage systems using PCMs [30, 31] and concluded that sensible systems are the lower environmental impacted.

II. Conclusion

Any energy system, especially renewable energy systems, must consider their environmental impact and their potential to reduce pollutants besides their energetic performance. In that context, this study analyzes four prototypes of solar water heaters built with different low cost and impact thermal storage materials (clay, concrete, sand and phase change material "PCM"). We compare them to the conventional solar water heater regarding to the environmental benefit offered by these systems followed by energy performance using Life Cycle Assessment method "LCA" based on the Simapro program and the Ecoinvent database. ReCiPe has been used as environmental metrics. The systems to be analyzed have the same components (same dimensions and same type of materials), but differ by the thermal storage materials. The life cycle assessment (LCA) results showed that most of the overall impact for all prototypes comes from thermal storage material, over 94% for most systems. The Clay solar water heater has the lowest global impact per kWh stored. Concrete and Sand systems show moderate impacts compared to that of the classical system. The Phase Change Material (PCM) solar water heater has the best energetic performance as it requires the least amount of backup energy compared to other prototypes but it is the one with the highest overall environmental impact including all life cycle stages. All the tested materials are more energy efficient than classic system. Nevertheless water has a lower impact than the Phase Change Material (PCM) and has a global impact almost similar to that of concrete and sand which makes them competitive to it. Clay is more efficient and has a lower impact than water. Hence it can be concluded that the most of the innovative materials are more efficient, more environmentally friendly and cheaper than the actual commercial system, so it should be used instead of the conventional system.

Relevant to the results obtained, this work tries to reduce some barriers for integrating renewable energies under economic and environmental constraints in developing countries.

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