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Life Cycle Evaluation of Sustainable Practices in a Sauna Bath

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Abstract: To battle climate change, the search for sustainable solutions and the reduction of environmental impacts are activities that must be pursued in all areas of human life. This study aimed to conduct a Life Cycle Evaluation of the environmental aspects and potential benefits associated with two different innovative adaptations to a sauna bath. The first adaptation is related to the selection of wooden materials for the bath's interior construction; the second is related to the source of thermal energy. For the selection of wooden materials, experiments were performed to evaluate a graphene coating and its capacity to increase the durability of wooden materials. For the thermal energy source, a solar air heater was experimentally assessed to confirm its capacity to supply the thermal energy required to operate the sauna bath. Finally, the material selection and the heating operation were integrated in a Life Cycle Impact Assessment, contrasting two scenarios: "business as usual sauna bath" and "sustainable sauna bath." The findings showed a significant reduction of around 61% of total emissions from the application of a solar air heater and wooden materials treated with a graphene coating. At the end of this study, "human well-being," "ecosystems," and "resources" were expressed in monetary values to assess the impact of the above practices in a sauna bath.

Keywords: sauna bath; eco-design; sustainable development; sustainable materials; solar energy; climate change; Life Cycle Impact Assessment

1. Introduction

The concept of sauna bathing arose in various cultures to solve hygienic, therapeutic, and physiological needs [1]. With industrialization, sauna bathing became more popular around the world, so much so that it is now necessary to explore sustainable practices to make sauna baths more efficient; these practices include the use of renewable resources in the construction and operation of saunas, the latter of which entails the generation of heat to produce steam [2]. From a sustainability perspective, the use of wooden materials and solar air heaters for the operation of the sauna bath are two of the most critical factors for increasing its sustainability. Therefore, this study aimed to conduct a Life Cycle Evaluation of the environmental aspects and potential benefits associated with two different innovative adaptations to a sauna bath. The first adaptation is related to the selection of wooden materials for the bath's interior construction; the second is related to the source of thermal energy.

It is noteworthy that the application of sustainable principles in the construction of saunas reinforces efforts made by the United Nations (UN) to reach sustainable development goals. In specific, this study impacts the goals number 7, number 11, and number 12 from the Sustainable Development Agenda 2030 of the UN, which are related to responsible energy consumption, sustainable infrastructure, and the responsible consumption of materials, respectively [3].

1.1. Sustainable Practices in a Sauna Bath

One way to improve the sustainable performance of any human-made construction is by the correct selection of construction materials [4]. Notably, the primary traditional material used in sauna rooms is wood, which plays an important role in its whole operation [5]. Wood is recognized as a sustainable material, and it represents one of the main components used in the manufacture of a sauna bath [6]. This material is an excellent option due to its environmental benefits, specifically for its properties as a renewable and reusable material [7]. Wood has additional positive attributes, such as lightness, mechanical resistance, thermal efficiency, noise regulation, versatility, low environmental impact, and 20% less energy consumption than conventional concrete systems [8]. However, wood may also present certain disadvantages, such as structural limitations in construction, low durability, high maintenance costs, and the requirement for protective treatments [9]. Also, materials integrated by wood compounds are highly influenced by humidity and temperature, which may impact its degradation process, quality, and durability over time [10].

A sustainable practice to potentiate the durability of wooden materials and reduce the overexploitation of this natural resource is the application of additives, coupling agents, protective treatments, drying processes, selected installation and anchoring mechanisms, and proper maintenance and conservation treatments during its lifetime [11]. In particular, the treatment of wood is performed through a physical process that consists of heating and drying in order to dehumidify the pieces to a certain percentage of water content [12].

Protective products represent a good alternative for the optimal maintenance of wood; however, the substitution of treatments formulated from synthetic products with natural components or water-based solvents has been endorsed to reduce the number of emissions of volatile organic compounds, such as formaldehyde, toluene, ethyl acetate, hexane, xylene, trichloro ethyl, and benzene [13]. These chemicals may cause toxicity, irritation, and odors [14], and for this reason some studies have focused on the development of natural components to replace existing synthetic products, distinguishing the use of the following: starch, albumin, resin [15], gluten protein [16], mixtures of boric salt [17], and nanomaterials [18], among others. Nanomaterials have the potential to formulate alloys that may improve the properties of certain components [19]. Notably, one of these components is graphene, which has important application as a protective coating for materials. These properties are achieved mainly because of graphene's chemical inertness, which is due to its two-dimensional configuration, one that does not cause modifications to the electrical, physical, chemical, or thermal attributes of the materials it protects [20]. Also, prior applications of graphene to wooden materials have demonstrated its antibacterial properties courtesy of its oxidative power [21] and adequate level of resistance, adhesion, and durability [22].

Another critical practice for a sustainable sauna is an efficient heating system for its operation. More traditional (and more common) saunas burn wood to generate heat, while more modern saunas incorporate electric heaters. This widely used type of heating system involves considerable electrical consumption, which, according to the UN, represents the most significant contributor to climate change, accounting for about 60% of total global greenhouse gas emissions [3]. One valuable clean energy alternative is solar energy, which has the greatest potential to transfer dependence on fossil fuels to renewable sources [23]. Solar energy is becoming increasingly attractive because the cost of producing energy from solar radiation has reached a competitive level compared to the generation of energy by traditional gas turbines [24].

Two different technologies exist in solar energy generation; they differ according to the way in which they gather solar radiation. The first technology are solar collectors without concentration, which gather energy without any optical manipulation; the second technology concentrates solar power, collecting and redirecting solar radiation into a smaller area using optical instruments [25]. Concentration technologies are used in engineering applications and large-scale energy-producing facilities [26], while flatbed collectors are used in low-temperature applications. The latter equipment type is the most straightforward for solar energy use, since such collectors do not involve moving parts and are easy to install. As such, flatbed collectors can be regarded as simple appliances with low installation and maintenance costs [27].

One of the most promising technologies for solar heat generation without concentration are evacuated tubes, which are contraptions that consist of a glass heat pipe contained inside a vacuum-sealed concentric glass tube. The heat pipe is covered with a selective coating that prevents heat from escaping in the form of radiation, while the vacuum surrounding the heat pipe is intended to reduce heat losses to the environment [28]. The use of these two technologies results in equipment capable of working at temperatures above 80 °C. The most significant advantage of evacuated tubes is that they result in only slight heat losses to the environment [29]. These systems are currently used for water heating and space conditioning in the residential sector [30], but they can also be used in the heating of air.

1.2. Life Cycle Impact Assessment with a Monetization Approach

One of the most well-known ways to analyze and make improvements to the environmental performance of a system is through the use of a Life Cycle Impact Assessment (LCIA). This tool helps in the comparison of impacts from different scenarios. The LCIA method, "IMPACT 2002+," represents a feasible approach that combines midpoint and endpoint categories and involves the implementation of all types of Cycle Inventory results and elementary flows. IMPACT 2002+ confers all the information results in 14 midpoint categories expressed in reference units (characterization factors) of the substances involved in the investigated product system [31]. Also, these midpoint categories are grouped into four larger damage classes (human health, ecosystem quality, climate change, and resources), which are indicated, respectively, in the following units: DALY (Disability Adjusted Life Year), PDF*m^2*yr. (Potentially Disappeared Fraction of species over a certain area over a certain time), kg CO_2 eq (Carbon Dioxide Equivalent), and MJ Primary (Primary Energy Use) [32].

The LCIA helps to identify the potential environmental impacts of the four evaluated damage categories to determine the real benefits involved in the applied sustainable practices [31]. The impact categories can be redefined in monetary values using the data gathered from the LCIA and referencing these data in terms of Biodiversity Adjusted Hectare Years (BAHY) and Quality Adjusted Life Years (QALY). This procedure is based on a study that determined that QALY represents 74,000 EUR and defined it as "the maximum that an average person can pay for an additional life year [33]. On the other hand, the same investigation stated that QALY expresses the value of an ecosystem in monetary terms as the "share of our well-being that we are willing to sacrifice to protect the ecosystems," which was reported with a value of 1,400 EUR per BAHY [33]. The comparison of different LCIA methods based on midpoint results and monetary units from an endpoint panorama helps to assess all category impacts (human, ecosystem, and resources) with the same reference and scale [32].

As mentioned before, the goal of this study was to conduct an LCIA to assess the environmental aspects and potential benefits associated with two different innovative adaptations to a sauna bath. Before achieving this goal, it first had to be considered that conducting an LCIA of sauna bathing is complicated for several reasons. First, the use of natural resources is often poorly covered in LCIA studies [34]. Second, previous studies reporting emissions from sauna stoves are scarce; that said, it is known that they are a significant source of pollutants not only for the environment but also for human health [35]. One study estimated the production of organic gaseous carbon in sauna stoves to be higher than in other appliances [36]. Third, there is a lack of specific LCA databases for sectors like tourism, where saunas can be found [37]. Finally, in other studies, sauna stoves were excluded from calculation because they are not predominant in buildings [38].

2. Materials and Methods

This study was conducted in Hermosillo, the capital city of Sonora State in Mexico. Due to their latitude, 29°06′9.36″N, and longitude, −110° 58′38.35″W, this city and state are located within the global Sun Belt, i.e., a region marked by considerable sunshine throughout the year. Accordingly, in this region, investment in sustainable initiates to foster the use of solar energy, and thereby the conservation of natural resources, is justified.

This experimental study tested two options for building a sustainable sauna. The first option tested the effects of a protective graphene coating on the lifetime of wooden materials; the second option assessed the use of solar air heaters to reduce the electricity consumption of electric stoves in a sauna bath and/or the environmental impacts of a wooden stove. The two experimental phases of the study are reported below. The results of these phases comprised part of the LCIA's inventory information used in the final section of this study, which compared two scenarios: a "business as usual sauna" against a "sustainable sauna."

2.1. Wooden Material Evaluation

This part of the evaluation focused on estimating the dimensional deformation caused by thickness swelling of three different conifer wood species: pine, cedar, and teak. These three wooden materials were selected from seven wooden materials after conducting a theoretical LCIA study. Data for this LCA belong to the Consortium for Research on Renewable Industrial Materials (CORRIM) which has a cradle-to-gate mill output scope and it is based to ISO 14040. Since it was added to the transportation phase, the scope of the LCIA can be considered as mill gate to point of use. The pine, cedar, and teak materials were found to be those with less environmental impact. These three wooden materials were then exposed to physical tests to evaluate their thickness swelling after certain experimental conditions. Thickness swelling may arise from the natural anatomy of wood and its behavior after the application of a graphene-based coating. The thickness swelling evaluation was performed according to the methodology: ASTM D1037-99 "Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials" [39]. In preparation for the test, it was necessary to prepare the wooden materials as follows:

- Enabling of wooden blocks with a dimension of 15 x 15 cm with a brushed and polished finish.
- Preparing a mixture of graphene and deionized water for four different concentrations: deionized water and 0% graphene (blank samples); deionized water and 0.01% graphene; deionized water and 0.03% graphene; and deionized water and 0.05% graphene.
- Applying the mixture on the wooden samples by submersion in water for one hour. Subsequently, the wooden samples were autoclaved for three hours at 1 atmosphere and at 140 °C.

Table 1 shows the experimental design for the wooden samples at different graphene concentrations.

Table 1. Experimental design for the study of the different graphene treatments.

Experimental Design		
A) Pine B) Cedar C) Teak	Without Graphene	3 repetitions
	Graphene 1: 0.01% concentration	3 repetitions
	Graphene 2: 0.03% concentration	3 repetitions
	Graphene 3: 0.05% concentration	3 repetitions

Once the samples were prepared, one cycle of the ASTM D1037-99 methodology was performed through the following six steps:

1. Submersion of the test blocks at 49 °C for a duration of 1 h.
2. Application of water vapor at 93 °C for a duration of 3 h.
3. Freezing at –12 °C for a duration of 20 h.
4. Heating with dry air at 99 °C for a duration of 3 h.
5. Application of water vapor at 93 °C for a duration of 3 h.
6. Heating with dry air at 99 °C for a duration of 18 h.

After the cycle had been completed, the samples were allowed to stand for 48 h at a temperature of 27 °C and a relative humidity of 65%. Subsequently, the final measurement of thickness swelling was taken at the center of the four edges of the wooden blocks.

Finally, a statistical analysis was conducted in which an ANOVA model was developed to obtain the final difference of thickness swelling of the 36 analyzed wood samples. Also, a complementary analysis was made based on a Duncan multiple range test. The statistical analysis included the following variables:

- Wood types: pine, cedar, and teak.
- Graphene-based coatings: 0%, 0.01%, 0.03%, and 0.05% graphene in deionized water.

The final data recording weight loss of the 36 test blocks were worked through a statistical design ANOVA of one factor, three levels, and four blocks, with three repetitions using the Minitab software.

2.2. Solar Air Heating

Concerning the solar air heater, an experimental approach was taken to measure the useful heat that it can supply to a test chamber. The purpose of this experiment was to determine the amount of energy that a solar air heater pumps into the system. Through this, an estimation of the expected reduction in electricity consumption from a "business as usual" sauna stove was calculated. To be able to assess the heat, a test chamber was built and equipped with temperature sensors to measure the temperature of the internal air. By measuring the temperature of the air, it was possible to calculate the useful heat transferred into the air by the solar collector. The test methodology used was a modification of the Mexican norm that outlines the procedure used to test solar water-heating appliances: "NMX-ES-001-NORMEX-2005 ENERGÍA SOLAR" [40]. Although this norm applies to water heaters, it was applied in this case to an air heater because the equations for the calculation of useful heat can also be applied to solar heating systems.

The experimental set consisted of four main component parts: first, a sauna test chamber; second, an evacuated tube solar collector; third, a temperature monitoring system; and finally, a ducting system to transport the air. The test chamber was constructed from a plywood board, 15 mm in thickness, with a 2 × 2 square bar and a 2-inch-thick insulating material. The solar collector used evacuated tube technology to gather heat, and a manifold was built using a ventilation duct to transport the heated air from the inside of the evacuated tubes to the test chamber. The ducting system used a centrifugal fan to force air into the system; thermal insulation was applied to the ducts to avoid the loss of thermal energy. Finally, the data acquisition used 14 DS18B20 temperature sensors from the Dallas semiconductor connected to an Arduino UNO board; the sensors were positioned in specific locations according to Figure 1 below.

The thermal sensors used to gather the information from the test chamber were positioned in specific locations according to Figure 1. Number 1 is the reference ambient sensor. Number 2, represented by two red dots, shows the inlet and outlet sensors for the heater. Number 3, displayed by two blue dots, depicts the sensor position from the inlet and outlet of the box. Number 4, represented by nine yellow dots, portrays the sensors used to monitor the temperature inside the chamber, which was positioned in a cube-like shape.

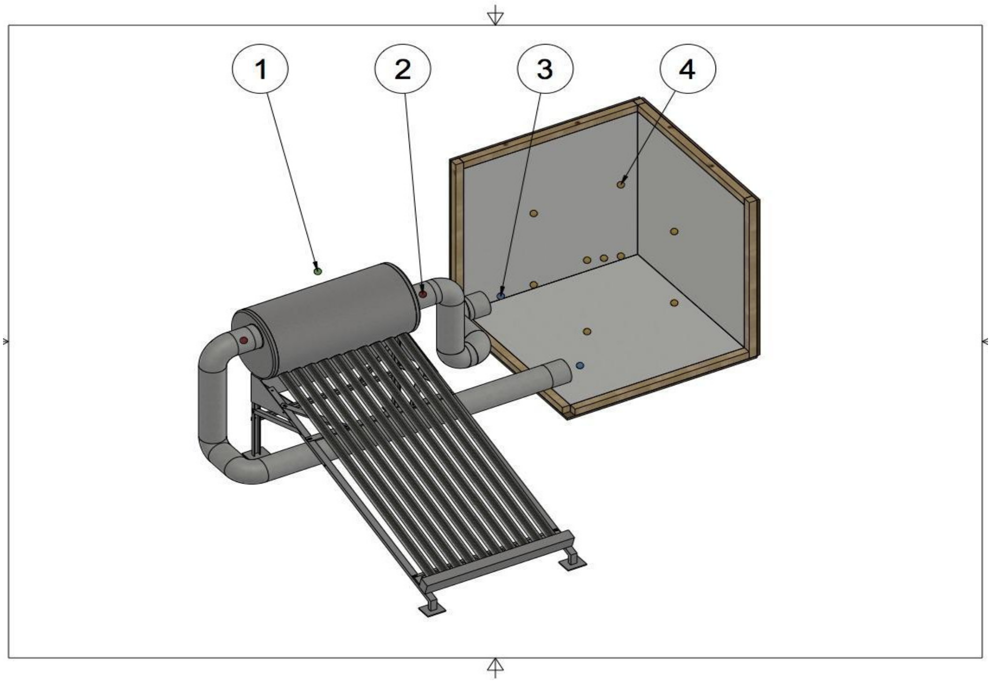

Figure 1. Experimental set. The figure above shows the four component parts of the experimental set: first, the solar air heater; second, the ducting system; third, the test chamber; and finally, the 14 temperature sensors divided into four groups.

2.3. Life Cycle Impact Assessment

A Life Cycle Impact Assessment (LCIA) was conducted to compare the environmental impacts caused by different scenarios. The three wooden materials were compared, with and without a graphene coating. The evaluation was also conducted under two heat production scenarios: the first using electricity, and the second combining the use of electric power with solar energy.

The LCIA methodology aims to collect information on the classical impact framework with a damage-oriented structure to show the midpoint and endpoint information through IMPACT 2002+. This methodology applies impact categories and their corresponding indicators in accordance with the outlines set in ISO 14040 concerning "Life Cycle Impact Assessment: Principles and Framework" [41].

Regarding the selection of wooden materials, the scope of the analysis covered the production system used in the sawmill, including the final transportation of the wood, since the wooden materials were produced in a location different from that of the sauna room. The inventory information was obtained from an investigation by the Consortium for Research on Renewable Industrial Materials (CORRIM) titled, "Cradle to Gate Life Cycle Impact Assessment of Softwood Lumber Production from the Pacific Northwest" [42].

Regarding the inventory used for the evaluation of the heat source for the sauna room, a comparison between two scenarios was made: In the first scenario, an electric sauna stove was considered as the only source of energetic consumption. In the second scenario, the same heating stove was considered, but this time with the help of a solar air heater. For the first scenario, the energy consumption from a common electric sauna stove was calculated with data from several sauna stove manufacturers. The usage of the sauna bath in this scenario was estimated to be four daily hours, with the electric stove being active for 90% of the usage time. For the second scenario, a solar air-heating installation capable of yielding 60% of the total energy needed to heat the sauna room was considered. The average annual local irradiance value in the state of Sonora was used for calculating the useful energy acquired from the sauna [43,44] along with an efficiency factor determined experimentally.

It is essential to highlight that this part of the evaluation focused only on the operational aspect of the energy consumption by the sauna room without considering either the impacts generated by the manufacturing, transportation, and distribution of the different heating units or the installation and transportation of the solar heat installation, both of which are outside the scope of this analysis. This reasoning was based around the principle that the generation of solar energy would outweigh any potential disadvantage of emitting more emissions than other heat sources beyond the operational phase. If this were not the case, then life cycle emissions would make solar air heating unfeasible.

2.4. Impact on Monetary Analysis

The methodology used to assess an applicable monetization approach that would set a pathway between environmental impacts from LCIA and monetization was given in a study presented by Weidema [33]. This investigation redefined the physical scores obtained from the LCIA's damage categories related to humans, ecosystems, and resources. The framework to monetize impact assessment reformulates the mentioned categories in terms of Quality Adjusted Life Years (QALY) for human well-being and Biodiversity Adjusted Hectare Years (BAHY) for ecosystem impacts. The units used for this methodology demonstrate the following:

- The categories related to "human well-being" are measured in QALY, which represents an identical value to DALY as used in [31], except that they represent the opposite values (1 QALY = −1 DALY).
- The categories related to "ecosystems" are defined as a damage category related to "biodiversity" set with the BAHY unit, which is similar to PDF m^2 years; except that a BAHY measures a positive state and reveals the opposite value of PDF m^2 years (1 BAHY = −10 000 PDF m^2 years), which represents damage.

Once the damage categories are set, the methodology determines a monetary value for each, which is defined from the overall budget constraint. The budget constraint is defined as "the average annual income that an average person is willing to pay for additional life years (QALY)" with a value of 74,000 EUR, or "the willingness-to-pay for additional ecosystem protection (BAHY)" with a value of 14,000 EUR [33].

3. Results

3.1. Wooden Material Evaluation

From the results obtained from the thickness swelling test, ANOVA, and Duncan multiple range tests made for the wood and graphene-based treatment variables, the following results (additional information is added in Appendix A) were generated:

ANOVA test: With a test value of 0.0188%, the statistical analysis identified a type of wood that presents a minimum thickness swelling. In the case of the protective treatments with different graphene concentrations, with a test value of 0.04%, at least one of the treatments helped to obtain minimum thickness swelling in the wood pieces. Regarding the replicates of the wood samples, it was established that the application of more than one of these replicates would not be required.

Duncan multiple range test of Duncan: The mean test for the analysis of wood species determined that of the alternatives evaluated, teak wood had a greater probability of exhibiting the least thickness swelling, while the most thickness swelling was presented by pine wood. As for the treatments, it was established that, statistically, the most effective treatment was a graphene concentration of 0.03%—this treatment presented the least thickness swelling of the wood samples evaluated. Less thickness swelling means greater sustainability, since wooden material exhibiting this characteristic would have more durability and require less exploitation of natural resources.

The results showed a positive response from the interaction between the wooden materials and the graphene treatments evaluated through the D1037 test; concerning this, Table 2 shows the percentage of swelling for the wood samples subjected to different graphene treatments. Similarly, i.e., based on the positive response shown between the materials and treatments, Table 3 shows the types of wood, the standard lifespans of wood pieces in their natural state, the responses of the wood in their natural state to the thickness swelling test, i.e., without graphene in their treatment, the best response to the thickness swelling test of the wood pieces, the most effective treatment determined by its graphene concentration, the percentage of improvement in terms of thickness swelling, and the potential extension of lifespan due to the positive responses to thickness swelling as presented in the test.

Table 2. Thickness swelling (TS) of the 36 evaluated wood samples from the humidity test.

Thickness Swelling of Wood Samples according to ASTM D1037-99 Test		
Protective Treatment based on Different Graphene Content (Graphene %)	**Mean TS Final – TS Initial (Millimeters)**	**Thickness Improvement Percentage of Thickness (%)**
0% graphene [1]	0.02072 mm [1]	100% [1]
0.01% graphene	0.01341 mm	64.72%
0.03% graphene	0.0125 mm	60.32%
0.05% graphene	0.01225 mm	59.12%

[1] A blank test was made as a reference value representing the maximum thickness swelling from the three types of wood evaluated.

Table 3. Comparison of lifespans of the wooden materials in normal conditions without graphene treatment vs. conditions augmented by graphene treatment after the thickness swelling test (TS).

Lifespan of Wooden Materials with and without Graphene Treatment							
Type of Wood	**Effective Treatment based on Graphene Concentration**	**Thickness Swelling without Graphene Treatment [2] (mm)**	**Thickness Swelling with Graphene Treatment [3] (mm)**	**Percentage of Positive Response against Thickness Swelling**	**Standard Lifespan [1] (Years)**	**Possible Lifespan Extension (Years)**	**Improved Lifespan (Years)**
Pine	C 0.03%	0.02492	0.01325	46.82%	5	2.34114	7.34
Cedar	C 0.05%	0.02567	0.01133	55.84%	10	5.58442	15.58
Teak	C 0.01%	0.01158	0.00891	23.09%	15	3.46403	18.46

[1] Standard durability lifespan established according to reference [45]. [2] All pieces, regardless of the wood species, presented the worst thickness swelling responses with the treatment of deionized water without graphene. Therefore, this natural swelling was taken as the starting point (100%) to obtain the percentages of improvement. [3] All the pieces, regardless of the wood species, presented their best thickness swelling responses with the treatments containing graphene; positive values were observed with all treatments evaluated at 0.01, 0.03, and 0.05% concentration of graphene.

3.2. Solar Energy Evaluation

To test the amount of useful heat that the solar collector can give to the air, various tests were conducted. The primary source of data was the DS18B20 thermal sensors installed on the inside of the test equipment. Also, a Campbell Scientific CMP11 Pyranometer was used to monitor solar irradiance and was positioned on a horizontal surface to measure the Global Horizontal Irradiance (GHI). The solar collector was placed on a horizontal plane with the intention of using the GHI data in the calculations. The following figures show the results from two different all-day-long tests: The first graph represents the data gathered from an almost completely clear day with occasional small clouds that correspond to sudden drops in the irradiance value in Figure 2; the second graph shows data from a completely cloudless day, which is indicated by the smoothness of the received power curve presented in Figure 3.

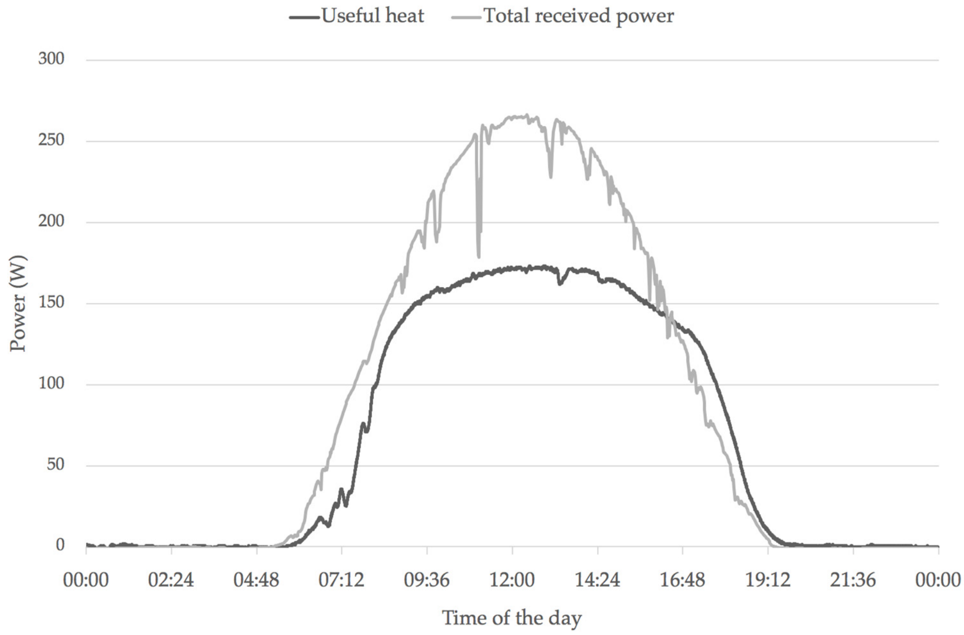

Figure 2. Test 1: total received power and useful heat produced.

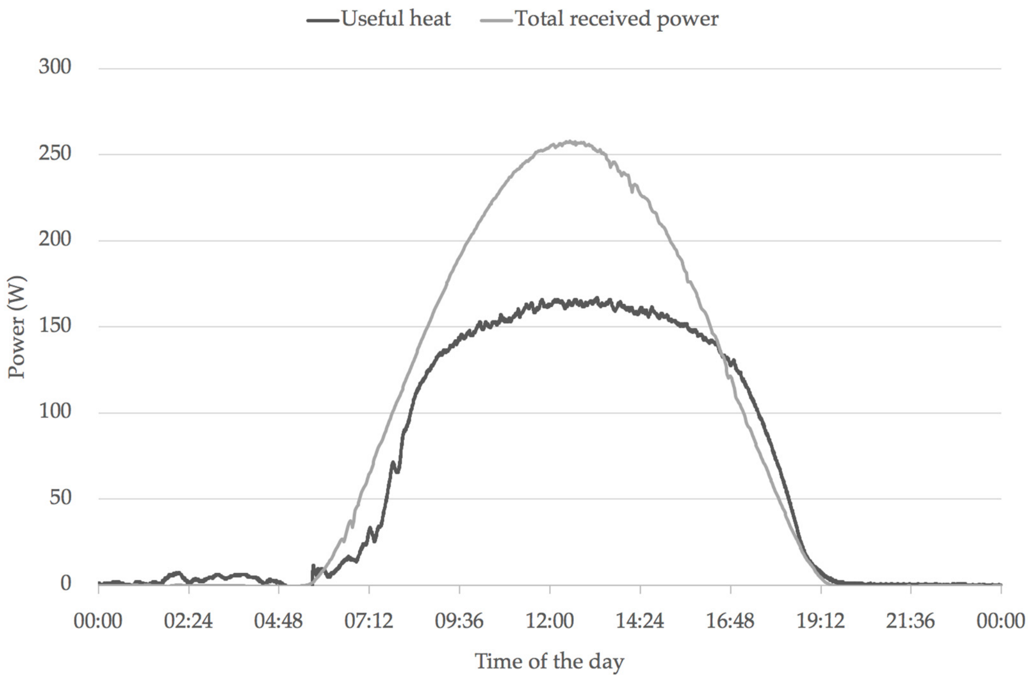

Figure 3. Test 2: total received power and useful heat.

The data gathered from the test were used to determine the efficiency of the solar collector as defined by the following equation:

$$\eta_g = \frac{\int_{T_1}^{T_2} m\, Cp \left(t_{f,e} - t_{f,i}\right) dT}{Ag\ \int_{T_1}^{T_2} G\, dT} \tag{1}$$

where:

η_g = efficiency of the solar collector expressed in percentage.
T_1 = start time of the test expressed in seconds.

T_2 = end time of the test expressed in seconds.
$\dot{m}$ = mass flow of the fluid expressed in kg/s.
Cp = specific heat of heat transfer fluid expressed in J/kg °C.
$t_{f,\,e}$ = transfer fluid temperature leaving the solar collector expressed in °C.
$t_{f,\,i}$ = transfer fluid temperature entering the collector expressed in °C.
Ag = area of the solar collector expressed in m^2.
G = irradiance normal to the solar collector expressed in W/m^2.

Using the data from the complete test days, the efficiency of the solar collector was calculated to be 75%, while the efficiency of the whole system, considering the ducting and the test room, was estimated to be 49%—this last calculation took into account the increase in temperature obtained inside the test room and compared it to the ambient temperature. Although the operational temperature of the sauna bath, 65 °C to 85 °C, was not reached, the overall result of the test was useful for gathering evidence of an increase in the temperature of the inside the test chamber of about 10 °C relative to the ambient temperature. This energy supplied by the solar collector can be used to preheat the air inside a sauna bath and thus reduce the electricity consumption of traditional sources of energy; additional data and temperature graphs from the tests can be found in Appendix B.

3.3. Life Cycle Impact Analysis (LCIA) and Monetization

The results obtained above suggest the possible implementation of a sustainable scenario suitable for a sauna bath, one in which a protective coating for the wooden material and the use of solar energy as the heating source can help reduce both energy and resource consumption, thereby lowering the potential environmental impacts of the sauna bath.

Tables 4 and 5 show the results of the LCIA study that integrated the environmental impacts in the four categories of final damage of the IMPACT 2002+ methodology. Table 4 presents the "business as usual" scenario, in which the traditional sauna elements were analyzed; Table 5 presents the "sustainable" scenario, in which the cleanest option for a wooden material was selected and solar energy was considered as the main source for the supply of heat, with a traditional electric stove used as a backup.

Table 4. "Business as usual" scenario, based on the IMPACT 2002+ methodology: environmental impacts of a traditional sauna constructed with wooden material without protective treatment and using an electric stove.

Category [1]	Units [2]	Impact of Teak Wood without Graphene Treatment in a 50-Year Lifespan [3]	Impact from traditional Electric Stove in a 50-Year Lifespan [4]	Total Impact of "Business as Usual" Sauna in a 50-Year Lifespan [5]
Human health	DALY	0.0039	0.2950	0.2989
Ecosystem quality	PDF*m^2*yr.	352	13,271	13,623
Climate change	kg CO_2 eq	1480	445,935	447,415
Resources	MJ primary	35,615	8,121,202	8,156,817

[1] Damage categories set by IMPACT 2002+. [2] Units of the damage categories: DALY (Disability Adjusted Life Year), PDF m^2 yr. (Potentially Disappeared Fraction of species over a certain area over a certain time), kg CO_2 eq (Carbon Dioxide Equivalent), MJ Primary (Primary Energy Use). [3] Impact values include the samples of wood evaluated in the blank test without graphene, as a protective treatment and consider the number of replacements of the wooden material needed in a 50-year lifespan. The LCIA values consider 2.40 m^3 of softwood production as needed in the case study, which includes the following stages: sawmill, heat generation, oven, planning, packaging, and final 1000-km transportation in a lorry. [4] Impacts generated by the consumption of electricity by a 15-kW electric stove considering four hours of daily use for 50 years. [5] Addition of impact values per category expressed in column 3 and 4, which represent the main factors for the construction and operation of a "business as usual" sauna bath.

Table 5. Environmental impacts from the "sustainable sauna" alternative based on construction with wooden material with protective treatment and primary solar heat supply based on the IMPACT 2002+ methodology.

Category [1]	Units [2]	Impact of Teak Wood with Graphene Treatment in a 50-Year Lifespan [3]	Impact from Electric Stove with Solar Assistance in a 50-Year Lifespan [4]	Total Impact of "Sustainable Sauna" in a 50-Year Lifespan [5]
Human health	DALY	0.0032	0.1770	0.1802
Ecosystem quality	PDF*m^2*yr.	286	7963	8249
Climate change	kg CO_2 eq	1200	267,561	268,761
Resources	MJ primary	28,940	4,872,721	4,901,661

[1] Damage categories set by IMPACT 2002+. [2] Units of the damage categories: DALY (Disability Adjusted Life Year), PDF m^2 yr. (Potentially Disappeared Fraction of species over a certain area over a certain time), kg CO_2 eq (Carbon Dioxide Equivalent), MJ Primary (Primary Energy Use). [3] Impact values include the samples of wood evaluated in the blank test without graphene as the protective treatment and consider the number of replacements of the wooden material needed in a 50-year lifespan. The LCIA values consider 2.40 m^3 of softwood production as needed in the case study, which includes the following stages: sawmill, heat generation, oven, planning, packaging, and final 1000-km transportation in a lorry. [4] Impacts generated by the consumption of electricity by a 15-kW electric stove and an air fan minus the useful heat generated by a solar collector that supplies 60% of the total heat needed in a four-hour daily usage period for 50 years. [5] Addition of impact values per category expressed in column 3 and 4, which represent the main factors for the construction and operation of a "sustainable sauna" bath.

In the sustainable scenario, teak wood with a 0.03% graphene concentration treatment represented the most effective alternative of those presented in the thickness swelling test, the impacts consider the possible replacements of material during a lapse of 50 years of standard building lifetime. Regarding the heat source, energy consumption was calculated for a sauna bath operating for four hours a day, seven days a week, during the same standard 50-year lifespan.

The information obtained from the LCIA was unified with the intention of generating a comparison of impact reduction costs. From this, the values of the damage categories can be used to assign them a monetary value, and thus the two scenarios and the evaluated damage categories can be compared. This information is presented in Table 6 and includes important data on the conversion factors and monetary values collected from an investigation related to monetization [33].

Table 6. Comparison of environmental impacts and their monetary values between a "business as usual" sauna bath and a "sustainable sauna" bath in a lifespan of 50 years.

Category [1]	Units [2]	Total Impact "Business as Usual" Sauna in 50 Years [3]	Total Impact of "Sustainable Sauna" in 50 Years [4]	Monetary Value (Eur/Units) [5]	Monetary Value of Total Impact from "Business as Usual" Sauna in 50 Years	Monetary Value of Total Impact from "Sustainable Sauna" in 50 Years
Human health	QALY	0.2989	0.1802	74,000	$22,118	$13,332
Ecosystem quality	BAHLY	1.3623	0.8249	1400	$1907	$1155
Climate change	kg CO_2 eq	447,415	268,761	0.0800	$35,793	$21,501
Resources	MJ primary	8,156,817	4,901,661	0.0040	$32,627	$19,607
				TOTAL	$92,446	$55,594

[1] Damage categories set by IMPACT 2002+. [2] Units of the damage categories: QALY (Quality Adjusted Life Year), BAHY (Biodiversity Adjusted Hectare Year), kg CO2 eq (Carbon Dioxide Equivalent), MJ Primary (Primary Energy Use). [3] Information gathered from Table 4. [4] Information gathered from Table 5. [5] Specific conversion factors.

After the integration of the LCIA´s results and the coefficient values to determine a common comparable factor, which in this case is money, the final results derived from the presented scenarios demonstrate a reduction in the impact in terms of monetary values by 61%. This value exhibits the monetization of possible costs involved in counteracting morbidity, mortality, loss of endangered species, or ecosystem deterioration. The "sustainable sauna" scenario embraces the same quality of wooden materials and similar operative technical characteristics of the "business as usual" scenario but with different environmental impacts and subsequent consequences to the biosphere.

4. Discussion

4.1. Experimental Stages of Wooden Interior Construction and Solar Heating

Thickness swelling, which was selected as a variable to determine the durability of wooden materials, represents one of the most important properties of timber products [46]. In this study, according to the results obtained from the used methodology, teak wood is proposed as the timber product with the smallest thickness swelling compared to cedar and pine wood. It was also established that the treatment with the greatest effectiveness against deformation is graphene and deionized water at a concentration of 0.03%, followed by treatments at 0.05% and 0.01% graphene; comparable results were obtained by a similar study on wooden materials and graphene [47]. Therefore, the optimal alternative is teak wood with a preservative treatment of 0.03% graphene concentration.

The deformation of wood, as shown in the test materials, as well as in other analyses of volumetric variations [47], is affected by natural properties that can significantly influence the material's response to swelling and subsequent structural changes. These natural properties, such as the number of extractives and woody tissue, intrinsic moisture content, and density, vary by species [48,49].

The effectiveness of the preservative treatment of wood is supported by different investigations that have confirmed that the presence of graphene as a treatment does not affect the adhesion interface between the substrate (wood) and matrix (treatment) [50]. Thus, graphene generates a stable coating with high potential interaction, aiding efforts to develop treatment alternatives for wooden materials that do not involve toxic components and are environmentally friendly, especially when contained in closed spaces with high humidity and high temperature.

Despite the fact that the effectiveness of the protective treatment was confirmed, i.e., its potential to protect the material and prolong its useful life, the analysis of wood production performed at the sawmill demonstrated no considerable impact within the four final impact categories analyzed. Nevertheless, one of the external factors of the manufacturing system that has a strong impact on environmental load is the final transport stage, from the place of production to the place of usage. This fact means that those wood species near to the place of final usage are favorable, since these species involve lower transportation costs and thus reduced consumption of fossil fuels.

The second investigated factor regarding the sauna bath was its operation, for which new ways to harness clean energy were sought. This pursuit should be considered a priority to combat the effects of climate change and to mitigate the impact of greenhouse gas emissions on the climate [29,30]. The solar air heater used in this work is still a developing technology, in contrast to evacuated tubes for water heating, about which extensive information exists [51–54]. However, the use of evacuated tube technology to heat air is not well documented, even though this application could have both economic and technical benefits [55,56]. Since existing publications on clean energy seem to ignore this alternative use of evacuated tubes for air heating, it can be considered an innovative application. The development of air-heating appliances has great market potential, since at present these devices represent less than 1% of the market share for solar technologies [29].

The overall efficiency of the solar collector in this test was calculated to be 58%. This value represents the relationship between total incident irradiation and the useful heat obtained, a relationship which is key for the characterization of a solar heater [57]. The calculated efficiency coincides with related data from the literature, where efficiencies were reported to be around 75% to 75% in evacuated tubes while heating water [29,30,53,58]. Although these tests referred to the use of water as a working fluid, it was considered that this range is also relevant for solar energy technology.

As for wooden materials, it is important to keep in mind that renewables are dependent on the availability of the resource, thus making solar heaters reliant on climatic conditions, which in turn requires the development of hybrid systems that can use solar energy when it is available and traditional equipment when it is not [26]. In contrast, human processes are rarely tied to climatic conditions. Therefore, the installation of hybrid equipment for the satisfaction of energy needs can be viewed as the most flexible option. The objective in hybridization is that conventional systems are only used to compensate for the energy that the solar heat system failed to generate, thus taking advantage of the solar resource when it is available while simultaneously allowing for the use of the system at full capacity all the time [58]. Because of the modular nature of solar equipment, the size of any installation can be adapted to the desired energy supply, with the main constraint being the higher upfront investment cost compared to traditional thermal energies [33]. For this reason, an economic evaluation of such projects comprising a cost–benefit analysis of the expected profit that can be obtained is necessary.

4.2. Integration of Environmental Impacts through Monetization

The impact values analyzed in the present study were derived from the IMPACT 2002+ methodology, which uses three important subjects—humans, ecosystems, and resources—through the application of an endpoint framework based on the LCIA method, ReCiPe [31], and Eco-indicator 99 [31]. A method to define the damage categories and access the monetary cost for a QALY and BAHY unit in terms of an overall budget constraint was applied [33]. This approach sets all the impact values in terms of common and standard information applicable and understandable globally, which is monetary units. Particularly, these data are derived from the average annual income of a person and his or her willingness to pay for additional life years (QALY) or for the conservation of endangered natural species (BAHY), establishing this concept as part of the proportion of human economic production [33].

The methodology used in this publication establishes the LCIA impact values in terms not only of natural resources and ecosystem damage, as most LCIAs do, but also in terms of social impacts and comparable monetary units. The monetization or conversion of social and environmental impacts into monetary units assists in the translation of impacts from non-market goods into market goods [33], which are sometimes conceived as free and inexhaustible, such as clean air, water, and soil.

Even though these types of methodologies are dependent on various economic scenarios, such as materials and energy flows, the Gross Domestic Product (GDP) of countries, economic growth rates, and regulatory schemes, they are still accurate that may be applicable to the economic enrollment that is lived nowadays. The monetization approach used in this investigation contains less uncertainty and helps in the communication of LCIA analysis, which has the benefit of converting information from a conceptual level into an applicable one [33].

In the area in which the study was conducted, natural resources, particularly softwoods, are not part of existing regional products and must therefore be imported. This characteristic makes these wooden materials highly impactful because of transportation costs, infrastructure requirements, and fossil fuel usage. In addition to the appropriate selection of materials, it is also important to implement practices that make use of resources and natural characteristics endemic to a given region, such as solar energy in regions within the Sun Belt. Particularly, in this case study, northwest México, which is a geographical area within the Sun Belt, was analyzed as an ideal location for solar energy utilization.

The results of the impact analysis of the sauna bath show a higher contribution of operational phases than the wooden materials used in the interior construction. In particular, the data reveal a high impact in categories of climate change and resource depletion as a consequence of fuel consumption (coal, oil, gas, and petroleum) [44]. Furthermore, the investigation strongly suggests the evaluation and analysis of the resources available in a region in order to make efficient use of the relevant materials and energy. This in turn highlights the urgency of the responsible consumption and production of goods, the need for innovative and sustainable systems that are both powerful and adaptable, and the need to shift from fossil fuels to renewable energy, all of which are important objectives established by the UN and promoted by governments worldwide.

The value of this study lies in its quantitative evaluation of the two environmental sustainability practices as applied in the context of a sauna bath, which is usually unsustainable. In the scientific literature on saunas, health benefits are often discussed rather than environmental benefits; in addition, most extant studies do not provide quantitative data drawn from empirical studies, a gap this study sought to remedy.

5. Conclusions

From the integration of the thickness swelling test, the energy efficiency test, and the LCIA, it can be concluded that there are conditions that may reduce costs due to environmental impacts during the 50-year lifespan of the sauna bath. The above goal was achieved with the application and selection of teak wood with a graphene-based treatment at a concentration of 0.03%, confirming a reduction of wood deformation by 60% in comparison with the worst alternative, pine wood without graphene. The efficiency of implementing solar collectors was also demonstrated, with a calculated efficiency of 75% and an overall efficiency of the test chamber with the solar heater of 49%. These percentages are promising for the implementation of these practices, particularly the positive response observed in wooden materials, which relates to two important factors: the wood species, which sets its natural durability and the protective treatment needed to prevent premature degradation; and the application of heaters in areas where hot air is needed and solar energy is available. These innovative applications will help in many industrial processes to satisfy material and energy needs. That said, the implementation of the technologies requires a cost–benefit analysis to truly assess the scope of economic improvements.

Furthermore, the impact values of the interior construction and operation of the sauna bath were monetized, thereby making them comparable and helpful in the determination of the most impactful phases of the system. It was found that the operational phase presents a much higher impact in comparison to the use of wooden material, even including the replacement of wood after a 50-year lifespan. Nevertheless, adapting innovative systems in terms of the availability of native resources and a commitment to modifying consumption patterns to promote the use of renewable resources are urgently needed. Remarkably, a contrast of the two scenarios—the "business as usual" sauna and the "sustainable" sauna—demonstrated a monetized impact reduction of 61% in all aggregated impact categories, confirming the positive response of the proposed sustainable practices and a notable reduction of environmental impacts in contrast to traditional sauna practices. These impacts were translated into costs, but these costs are not paid by either the producer or the final of the sauna; instead, they are an externalization that the whole biosphere must pay.

Finally, although several studies have evaluated the benefits of sauna baths for human health and well-being, which are of course important from social sustainability, their environmental sustainability has not been well documented, and therefore quantitative data are often lacking. For this reason, the findings of this study can contribute to the expansion of knowledge with regard to the promotion of sustainable saunas.

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Appendix A

Table A1. Analysis of Variance (ANOVA) of the results obtained in the thickness swelling test.

Variation Origin	Degrees of Freedom	Sum of Squares	Mean Sum of Squares	F_c	*p* (Value of the Evidence)
Wood type	2	0.000423	0.0002115	4.59	0.0188
Graphene-based treatment	3	0.000438	0.000146	3.16	0.04
Replica	2	0.00005643	0.000028215	0.6124	0.55
Error	28	0.00129	0.00004607		
Total	35	0.00221			

Table A2. Duncan multiple range test results presenting the type of wood and its thickness swelling variation from the moisture test. Means with a common letter are not significantly different ($p > 0.05$).

Duncan´s Multiple Range Test for Wood Type Alpha = 0.05			
Wood Type	**Thickness Swelling Means (mm)**	**N**	**Means Tests (A/B)**
Teak	0.010164	12	A
Cedar	0.01562	12	A B
Pine	0.01837	12	B

Table A3. Duncan multiple range test results presenting the type of treatment with different concentrations of graphene and its variation in thickness swelling from the moisture test.

Duncan´s Multiple Range Test for Graphene Treatment			
Graphene Treatment	**Thickness Swelling Means (mm)**	**N**	**Means Tests (A/B) Alpha = 0.05**
C 0.03%	0.01225	9	A
C 0.05%	0.0125	9	A
C 0.01%	0.01341	9	A
C 0.0%	0.02072	2	B

Means with a common letter are not significantly different ($p > 0.05$).

Appendix B

Solar Air Heater Test Data Graphs

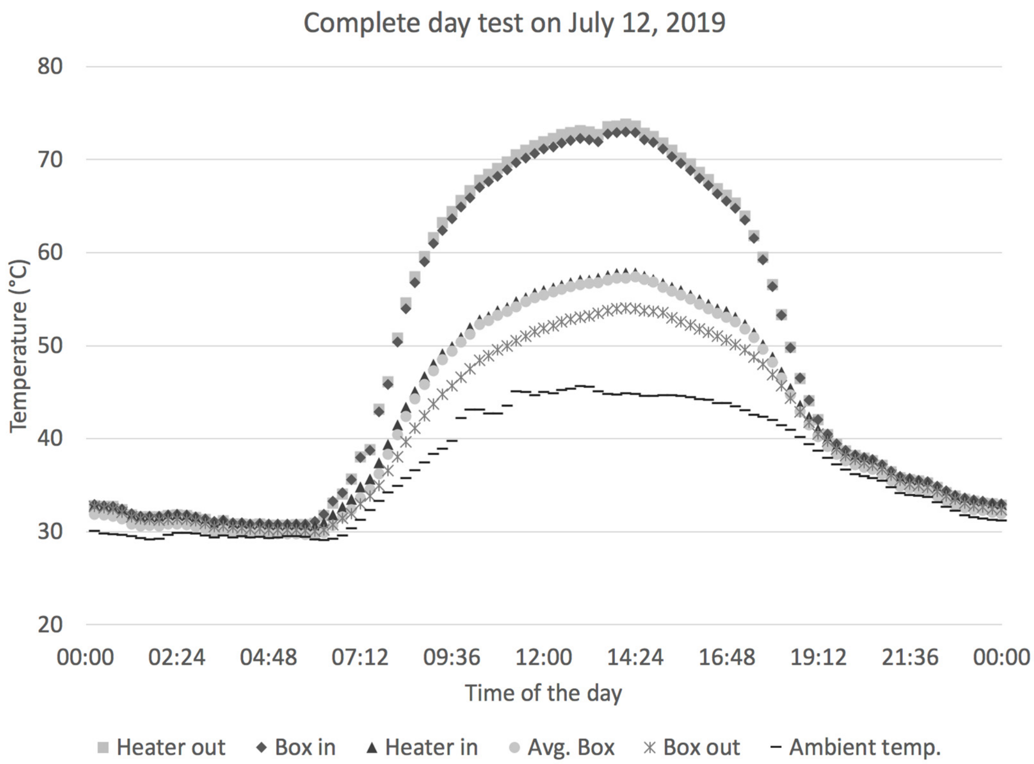

Figure A1. Complete test data acquired from experimentation on 12 July 2019.

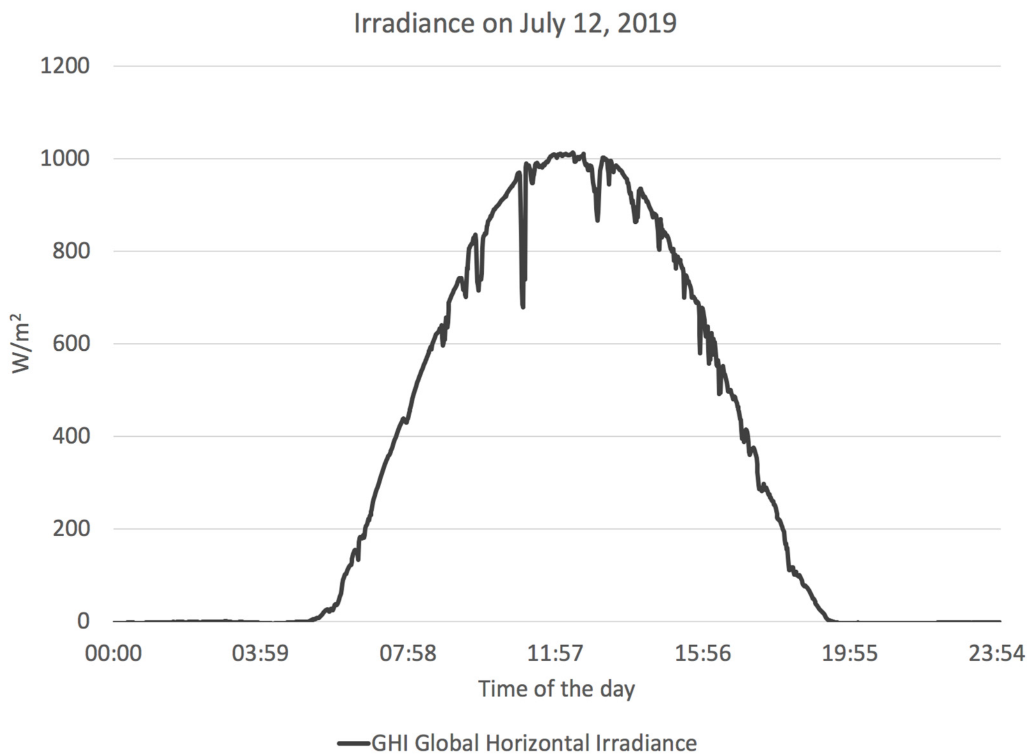

Figure A2. Irradiance data gathered from Campbell Scientific CMP11 Pyranometer on 12 July 2019.

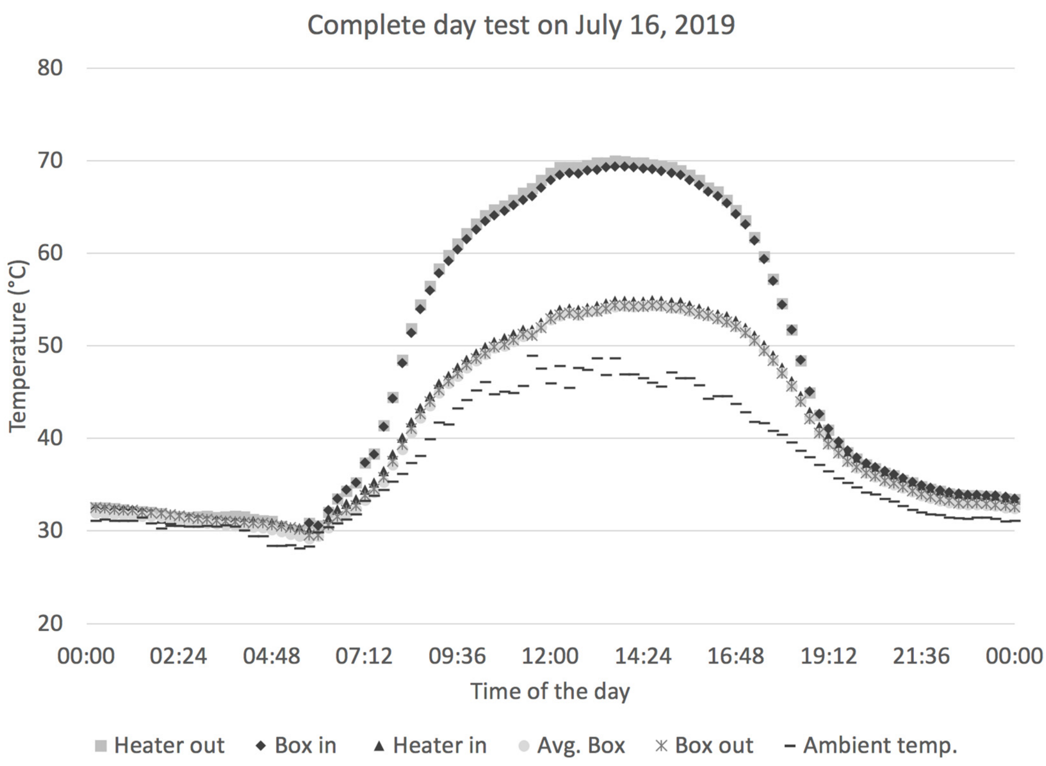

Figure A3. Complete test data acquired from experimentation on 16 July 2019.

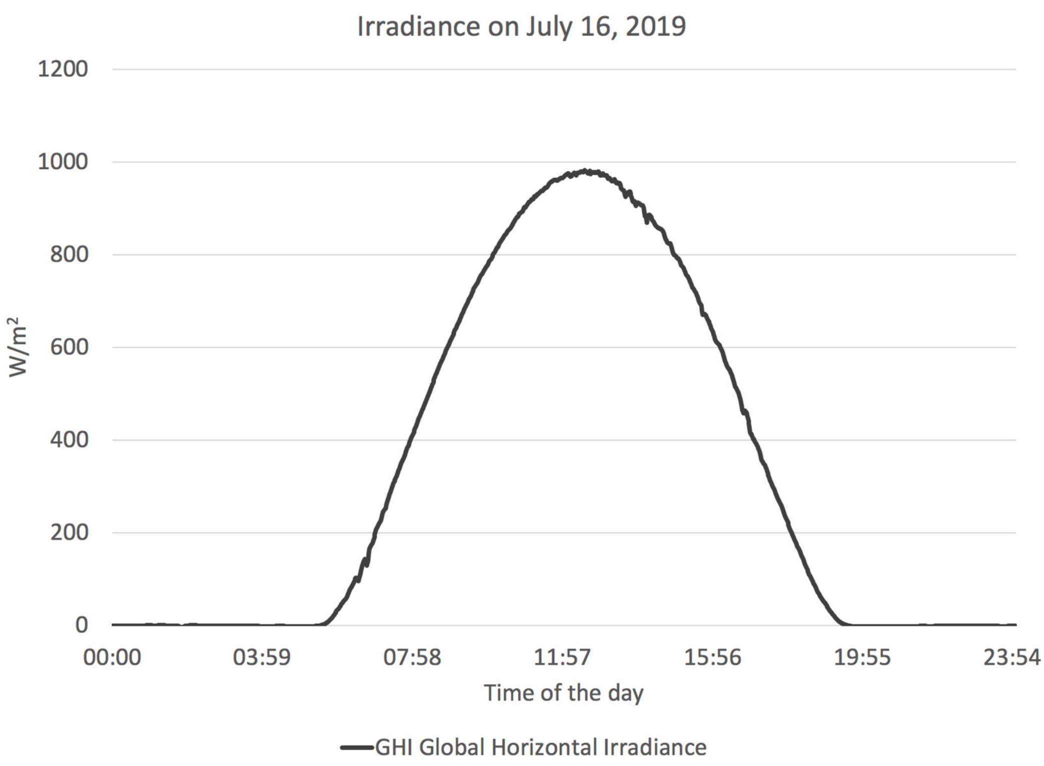

Figure A4. Irradiance data gathered from Campbell Scientific CMP11 Pyranometer on 16 July 2019.

References

1. Pilch, W.; Szygula, Z.; Palka, T.; Pilch, P.; Cison, T.; Wiecha, S. Comparison of physiological reactions and physiological strain in healthy men under heat stress in dry and steam heat saunas. *Biol. Sport* **2014**, *31*, 145. [CrossRef] [PubMed]
2. Tsonis, J. Sauna Studies as an Academic Field: A New Agenda for International Research. *Lit. Aesthet.* **2017**, *26*, 41–82.
3. Sustainable Development Goals. Available online: https://www.un.org/sustainabledevelopment (accessed on 8 May 2019).
4. Aguilar, A. Building Materials Recycling [Reciclado de materiales de construcción]. *Boletín CF+ S* **2016**, *2*, 8–11.
5. Barrera, G.M.; Zaragoza, J.B.H.; Lara, T.L.; Campos, C.M. *Sustainable and Recycled Materials in Construction [Materiales Sustentables y Reciclados en la Construcción]*; OmniaScience: Terrassa, Spain, 2015.
6. Falk, B. Wood as a sustainable building material. *For. Prod. J.* **2009**, *59*, 6–12.
7. Jakes, J.E.; Arzola, X.; Bergman, R.; Ciesielski, P.; Hunt, C.G.; Rahbar, N.; Zelinka, S.L. Not just lumber—using wood in the sustainable future of materials, chemicals, and fuels. *JOM* **2016**, *68*, 2395–2404. [CrossRef]
8. Santi, S.; Pierobon, F.; Corradini, G.; Cavalli, R.; Zanetti, M. Massive wood material for sustainable building design: The Massiv–Holz–Mauer wall system. *J. Wood Sci.* **2016**, *62*, 416–428. [CrossRef]
9. Viluma, A. The situation with use of wood constructions in contemporary latvian architecture. *Moksl. Liet. Ateitis* **2017**, *9*, 9–15. [CrossRef]
10. Goto, Y.K.; Ostermeyer, T.; Ando, N.F.; Wallbaum, H. Preliminary investigation of a vapor-open envelope tailored for subtropical climate. *Build. Environ.* **2011**, *46*, 719–728. [CrossRef]
11. Coulson, J. *Sustainable Use of Wood in Construction*, 1st ed.; Wiley-Blackwell: Hoboken, NJ, USA, 2015.
12. Jara, M.V. Design of a Pilot Plant to Obtain Plastic Wood Pellets from Recycled Polyethylene with Lignocellulosic Particles (Sawdust) [Diseño de una Planta Piloto para la Obtención de Granza de Madera Plástica a Partir de Polietileno Reciclado con Partículas Lignocelulósicas (Aserrín)]. Bachelor's Thesis, Escuela Politécnica Nacional, Quito, Ecuador, 2015.
13. Biofusta Ecological House. Available online: http://www.casa-ecologica.com (accessed on 5 January 2018).
14. Chipa, M.A. Comparative advantages in the Physical-Chemical, mechanical and environmental properties of polychloroprene adhesives in aqueous dispersion and solvent base [Ventajas comparativas en las propiedades Físico-Químicas, mecánicas y medioambientales de los adhesivos de policloropreno en dispersión acuosa y en base solvente]. Master's Thesis, Universidad Nacional del Callao, Callao, Perú, 2015.
15. Alarcón, J.; Parra, X.; Droguett, C. Boards based on barley waste from the agri-food industry and natural adhesives: Experience of perceived quality. [Tableros en base a residuos de cebada de la industria agroalimentaria y adhesivos naturales: Experiencia de una calidad percibida]. *Interciencia* **2017**, *42*, 364–369.
16. Lei, H.; Pizzi, A.; Navarrete, P.; Rigolet, S.; Redl, A.; Wagner, A. Gluten protein adhesives for wood panels. *J. Adhes. Sci. Technol.* **2010**, *24*, 1583–1596. [CrossRef]
17. Ibáñez, C.; Mantero, C.; Silva, L.; Rabinovich, M.; Escudero, R.; Franco, J. Preservation of wood treated with Zn and Mn and effectiveness of anti-leaching treatment with borax [Preservación de madera tratada con Zn y Mn y efectividad de tratamiento anti lixiviante con bórax]. *Maderas Cienc. Tecnol.* **2012**, *14*, 165–174. [CrossRef]
18. Graphenstone Home Page. Available online: https://www.graphenstone.com/ (accessed on 8 Februrary 2018).
19. Wang, J.; Sun, Q.; Sun, F.; Zhang, Q.; Jin, C. Layer-by-layer self-assembly of reduced graphene oxide on bamboo timber surface with improved decay resistance. *Eur. J. Wood Wood Prod.* **2018**, *76*, 1223–1231. [CrossRef]
20. Broekhuizen, P.; Broekhuizen, F.; Cornelissen, R.; Reijnders, L. Use of nanomaterials in the European construction industry and some occupational health aspects. *J. Nanopart. Res.* **2011**, *13*, 447–462. [CrossRef]
21. De la Peña, A.; García, S. Nanotechnological design of surfaces with antibacterial properties: Graphene [Diseño nanotecnológico de superficies con propiedades antibacterianas: El grafeno]. *Revista Ingeniería de Construcción* **2016**, *31*, 201–207. [CrossRef]
22. Huang, X.; Yin, Z.; Wu, S.; Qi, X.; He, Q.; Zhang, Q.; Zhang, H. Graphene-based materials: Synthesis, characterization, properties, and applications. *Small* **2011**, *7*, 1876–1902. [CrossRef] [PubMed]

23. Jin, Z. Concentrated Solar Power Generation. Bachelor's Thesis, Arizona State University, Tempe, AZ, USA, 2013.
24. Askari, I.B.; Ameri, M. The application of Linear Fresnel and Parabolic Trough solar fields as thermal source to produce electricity and fresh water. *Desalination* **2017**, *415*, 90–103. [CrossRef]
25. Tyagi, H.; Kumar, A.; Chakraborty, P.; Powar, S. *Applications of Solar Energy, Environment, and Sustainability*; Springer Nature: Singapore, 2018.
26. IEA. *Technology Roadmap: Solar Heating and Cooling*; International Energy Agency: Paris, France, 2012.
27. Bolaji, B.O.; Abiala, I. Theoretical and experimental analyses of heat transfer in a flat-plate solar collector. *Walailak J. Sci. Technol.* **2012**, *9*, 239–248.
28. Santiago, R.; Emmanuel, N. The photothermal and photovoltaic industries in Mexico [La industria solar fotovoltaica y fototérmica en México]. *ProMéxico* **2017**, 170–172.
29. García Valladares, O.; Pilatowsky Figueroa, I. *Thermal Applications of Solar Energy in Residential, Industrial and Service Sectors [Aplicaciones Térmicas de la Energía solar: En los Sectores Residencial, Servicios e Industrial]*, 1st ed.; Universidad Nacional Autónoma de México: Ciudad de México, México, 2017.
30. Psomopoulos, S.C. Solar Energy: Harvesting the Sun's Energy for Sustainable Future. In *Handbook of Sustainable Engineering*, 1st ed.; Kauffman, J., Kun-Mo, L., Eds.; Springer Netherlands: Dordrecht, The Netherlands, 2013; pp. 1065–1107.
31. IMPACT 2002+ UserGuide. Available online: https://www.quantis-intl.com/pdf/IMPACT2002_UserGuide_for_vQ2.21.pdf (accessed on 5 May 2019).
32. Pizzol, M.; Weidema, B.; Brandão, M.; Osset, P. Monetary evaluation in life cycle assessment: A review. *J. Clean. Prod.* **2015**, *86*, 170–179. [CrossRef]
33. Weidema, B.P. Using the budget constraint to monetarise impact assessment results. *Ecol. Econ.* **2009**, *68*, 1591–1598. [CrossRef]
34. Sokka, L.; Sinkko, T.; Holma, A.; Manninen, K.; Pasanen, K.; Rantala, M.; Leskinen, P. Environmental Impacts of the National Renewable Energy Targets—A Case Study from Finland. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1599–1610. [CrossRef]
35. Siponen, T.; Yli-Tuomi, T.; Tiittanen, P.; Taimisto, P.; Pekkanen, J.; Salonen, R.O.; Lanki, T. Wood Stove Use and Other Determinants of Personal and Indoor Exposures to Particulate Air Pollution and Ozone among Elderly Persons in a Northern Suburb. *Indoor Air* **2019**, *29*, 413–422. [CrossRef] [PubMed]
36. Tissari, J.; Hytönen, K.; Sippula, O.; Jokiniemi, J. The Effects of Operating Conditions on Emissions from Masonry Heaters and Sauna Stoves. *Biomass Bioenerg.* **2009**, *33*, 513–520. [CrossRef]
37. Camillis, C.; Raggi, A.; Petti, L. Life cycle assessment in the framework of sustainable tourism: A preliminary examination of its effectiveness and challenges. *J. Ind. Ecol.* **2010**, *7*, 205–218. [CrossRef]
38. Heinonen, J.; Säynäjoki, A.; Junnonen, J.M.; Pöyry, A.; Junnila, S. Pre-Use Phase LCA of a Multi-Story Residential Building: Can Greenhouse Gas Emissions Be Used as a More General Environmental Performance Indicator? *Build. Environ.* **2016**, *95*, 116–125. [CrossRef]
39. ASTM. *ASTM D1037-99 Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials*; ASTM International: West Conshohocken, PA, USA, 1999.
40. NORMEX. *NMX-ES-001-NORMEX-2005*; Sociedad Mexicana de Normalización y Certificación S.C: Ciudad de México, México, 2005.
41. ISO 14040. 2006. Available online: www.iso.org (accessed on 15 March 2019).
42. Puettmann, M.; Oneil, E.; Bergman, R. *Cradle to Gate Life Cycle Assessment of Softwood Lumber Production from the Northeast-North Central*, 1st ed.; CORRIM: Seattle, WA, USA, 2013.
43. Smartenergy Sonora. *Sonora State Energy Route Map [Mapa de Ruta de Energía de Sonora]*, 1st ed.; ProMéxico: Hermosillo, México, 2017.
44. Comisión Nacional para el Uso Eficiente de la Energía. *Thermal solar energy for industrial processes in Mexico: A market study [Energía solar térmica para procesos industriales en México: Estudio base de mercado]*, 1st ed.; CONUEE: Ciudad de México, México, 2018.
45. Data Sheet about Technological Characteristics and Uses of Wood in Mexico [Ficha Técnicas Sobre Características Tecnológicas y usos de Maderas Comercializadas en México]. Available online: centro.paot.org.mx/documentos/conafor/catalogo_maderas.pdf (accessed on 10 April 2018).
46. Kojima, Y.; Suzuki, S. Evaluation of wood-based panel durability using bending properties after accelerated aging treatments. *J. Wood Sci.* **2011**, *57*, 126–133. [CrossRef]

47. Yang, T.; Wang, J.; Sheng, N.; Ma, E. Comparison of dynamic sorption and hygroexpansion of wood by different cyclic hygrothermal changing effects II. *J. Build. Phys.* **2018**, *5041*, 360–376. [CrossRef]
48. Stuckenberg, P.; Wenderdel, C.; Zauer, M. Determination of the swelling velocity of different wood species and tissues depending on the cutting direction on microtome section level. *Results Phys.* **2018**, *9*, 1388–1390. [CrossRef]
49. Absorption in Wood [Absorción en Madera]. Available online: https://www.inia.es (accessed on 10 March 2019).
50. Monetta, T.; Acquesta, A.; Carangelo, A.; Bellucci, F. Considering the effect of graphene loading in water-based epoxy coatings. *J Coat. Technol. Res.* **2018**, *15*, 923–931. [CrossRef]
51. Asif, M.; Muneer, T. Life cycle assessment of built-in-storage solar water heaters in Pakistan. *Build. Serv. Eng. Res. Technol.* **2006**, *27*, 63–69. [CrossRef]
52. Cao, F.; Zhao, L.; Zhang, F.; Guo, L. Redesign of a water heating system using evacuated tube solar collectors: Trnsys simulation and techno-economic evaluation. *Heat Transf. Eng.* **2014**, *35*, 556–566. [CrossRef]
53. Kocer, A.; Atmaca, I.; Ertekin, C.A. Comparison of Flat Plate and Evacuated Tube Solar Collectors with F-Chart Method. *Isi Bilimi Ve Teknigi Dergisi* **2015**, *35*, 77–86.
54. Porras-Prieto, C.J.; Benedicto-Schönemann, S.; Mazarrón, F.R.; Benavente, R.M. Profitability variations of a solar system with an evacuated tube collector according to schedules and frequency of hot water demand. *Energies* **2016**, *9*, 1053. [CrossRef]
55. Paradis, P.L.; Rousse, D.R.; Hallé, S.; Lamarche, L.; Quesada, G. Thermal modeling of evacuated tube solar air collectors. *Sol. Energy* **2015**, *115*, 708–721. [CrossRef]
56. Mehla, N.; Yadav, A. Experimental investigation of a desiccant dehumidifier based on evacuated tube solar collector with a PCM storage unit. *Dry. Technol.* **2017**, *35*, 417–432. [CrossRef]
57. Goswami, Y.D. *Principles of Solar Engineering*, 3rd ed.; CRC Press: Boca Ratón, FL, USA, 2015.
58. IEA. *Renewable Energy Essentials: Solar Heating and Cooling*, 1st ed.; IEA: Paris, France, 2009.