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# A New Methodology for the Development of Appropriate Technology: A Case Study for the Development of a Wood Solar Dryer

**Luis Bernardo López-Sosa [1,2], José Núñez-González [1], Alberto Beltrán [3], Mario Morales-Máximo [1,2], Mario Morales-Sánchez [4], Montserrat Serrano-Medrano [5] and Carlos A. García [1,*]**

[1] Escuela Nacional de Estudios Superiores, Unidad Morelia, Universidad Nacional Autónoma de México, Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro No. 8701, Col. Ex Hacienda de San José de la Huerta, Morelia C.P. 58190, Mexico; lbernardo.lopez@uiim.edu.mx (L.B.L.-S.); joseng@enesmorelia.unam.mx (J.N.-G.); mmoralesmaximo@gmail.com (M.M.-M.)

[2] Posgrado en Ingeniería para la Sostenibilidad Energética, Universidad Intercultural Indígena de Michoacán, Carretera Pátzcuaro-Huecorio Km3, Pátzcuaro C.P. 61614, Mexico

[3] Instituto de Investigaciones en Materiales, Unidad Morelia, Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro No. 8701, Col. Ex Hacienda de San José de la Huerta, Morelia C.P. 58190, Mexico; albem@materiales.unam.mx

[4] Grupo de Artesanos Organizados, Comunidad Indígena de San Francisco Pichátaro, San Francisco Pichátaro C.P. 60291, Mexico; moralessanchez404@gmail.com

[5] Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro No. 8701, Col. Ex Hacienda de San José de la Huerta, Morelia C.P. 58190, Mexico; mttserrano@gmail.com

* Correspondence: cgarcia@enesmorelia.unam.mx

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**Abstract:** This paper introduces a new methodology for the development of appropriate technology that allows satisfying energy needs in rural communities. The methodology integrates the technological development, taking particularly into account the assessment of environmental impacts as well as evaluation of the functionality of the technology. Therefore, it is implemented as a case study in the development of a solar wood-dryer in an artisan community in Mexico. Relevant issues were identified for the success of the methodology, which includes identifying key participants in the community, as well as the use of specialized simulation- and computer-based design tools, and a prior evaluation of the potential environmental impacts through Life-Cycle Assessment (LCA) of the solar wood-dryer. Three geometries of a solar wood-dryer prototype were proposed and analyzed with computer-based simulations, which showed better interior heat transfer than the traditional wood brick-dryer. LCA revealed that the new solar wood-dryer prototype has environmental impacts in all analyzed categories that are 5% or smaller than those of the traditional dryer. Therefore, it was demonstrated that the solar wood-dryer developed with our introduced methodology leads to less environmental impacts compared to those of the traditional wood brick-dryer previously used by the rural community.

**Keywords:** sustainable energy technologies; life cycle assessment; rural community engagement; developing countries

## 1. Introduction

The importance of reducing the lack of access to energy sources in order to meet needs in the rural sector has an increasing interest in the local technological development. In this context, universities, private initiatives, and civil society organizations can promote projects that bring technologies to marginalized communities [1]. Nowadays, the processes of development, transfer, and adoption of technology to meet energy needs in rural areas are poorly systematized or are based on fragmented approaches. Therefore, the implementation of sustainable technologies to reduce inefficient energy consumption and minimize environmental impacts requires of more inclusive and effective efforts. Similarly, it is necessary to consider overcoming the barriers that limit the access and acceptance of this type of technologies in the rural sector [2,3]. For instance, some projects related to the implementation of wood-saving stoves in rural communities lacked the environmental impact analysis of technology and the user participation [4]. There are also case studies of implementation of biodigesters, which propose methodological schemes that consider community diagnoses, identification of needs and possible impacts, construction, and training [5]; however, they do not involve users and their practices in the device design. In a project of solar ovens for rural communities, the authors considered social variables and the evaluation of the energy potential for vulnerable communities [6] but their work lacks environmental impact assessment of the technology. More recently, González et al. [7] showed more integrated processes for solar cookers that consider the development of technology and its monitoring even after its implementation, but they are not systematic in the processes of technological development and lack of an environmental impact assessment of the technology. It should be noted that the participation of the user, for whom the technology is designed, is not clearly shown. Similarly, there are efforts to develop technologies within the framework of Ecotechnology, where emphasis is placed on developing technology with the least environmental impacts [8] but these efforts do not articulate an integral scheme from the identification of needs.

It should also be noted that there has been an increasing interest in the so-called Appropriate Technologies (In this article, the definition of Appropriate technology will be used in a broad context, that is, "a way to design, develop, implement and manage technology aimed at solving social and environmental problems (energy in our case), generating social and economic dynamics of social inclusion and sustainable development" [9].), as well as their definitions and implementation processes [9–11]. The term Appropriate Technology has been widely used in the development of technologies to satisfy basic needs mainly in the rural sector [8] and actually, studies regarding the use of appropriate technologies have tipped during this decade. However, it is still necessary to systematize and document in more detail these processes, in order to optimize the development, transfer and adoption of technology; that is, that technology more often meets user's need in an affordable and sustainable manner.

Recently, methodologies have been developed that encourage the identification of technologies to address energy needs in the rural sector. For instance, MacCarty and Brynder [12] introduced a comprehensive methodological framework, although their method is not particularly focused on development of sustainable technology. In addition, Sianipar et al. [13], proposed a comprehensive framework of evaluation oriented to the development of appropriate technologies, which considers planning, conceptualization of technology, as well as design and evaluation. However, the analysis of the environmental impact of the proposed technologies and the involvement of the potential end users is not clearly appreciated.

More recently, Alvarez-Castañon et al. [14] presented a methodology and initiatives of projects for the implementation of eco-technologies, which included the following steps: detection of priority, cooperation among the actors involved, technological memory (i.e., technology available), and technological learning (i.e., ability to build by the final users). Nevertheless, in the author's opinion, the proposal does not consider the participation of the user and does not assess the environmental impact of the technology.

In the specific case of Mexico, there have been projects whose objective was the development and implementation of technologies in indigenous communities. For instance, solar thermal applications [7,15,16], the implementation and monitoring of forest biomass-saving stoves [10,17,18], and the so-called Eco Technologies [19]. In the aforementioned applications, a common action process has been suggested for the satisfaction of energy needs in rural communities which generally includes three stages: (1) identification of priority energy needs; (2) technological development and transfer; and (3) appropriation of technology. As explained by Álvarez-Castañon, et al. [14]; or Choi [20], there must always be closeness with the user. In these research works the participation of the users in the development of the technologies was fundamental, indicating the capacity of the pot for cooking, the weight of the stove for greater ease of movement and the size that it can have to fit their homes. At this point, care must also be taken in generating lower environmental impacts.

It should be highlighted that the environmental impacts of the technologies are relevant due to the negative effects that have been observed in recent times, such as the loss of biodiversity, emissions of air pollutants, the use of exhaustible resources such as minerals, emissions of greenhouse gases that cause climate change, among others [21,22]. Many of the current technologies have important environmental impacts, so the inclusion of criteria for the design and application of technologies with low negative environmental effects is an issue that has become relevant at both, theoretical and practical levels [23]. Particularly, Gerber [24] highlights that the incorporation of the evaluation of environmental impacts is essential in the development of energy technology.

The objective of the research reported in this paper is to introduce a new methodology for the development of appropriate technology that allows satisfying energy needs in rural communities. The methodology aims to integrate the technological development, device functionality evaluation, and the evaluation of the environmental impacts related to this technology. For illustration purposes, the methodology is applied to the development of a solar wood-dryer in the indigenous community of Pichátaro, in the state of Michoacán, in Mexico.

## 2. Methodology for the Development of Appropriate Technology

The introduced methodology was developed by a multidisciplinary group which included engineers and physicists that are experts in simulation and design, Life Cycle Analysis (LCA), and Eco Technology development with background in the implementation in indigenous communities. Similarly, it should be recall that previous studies have highlighted that potential users must participate actively, from the identification of priority energy needs, to the development of technology and its transfer processes [2,9,25–28], since it is not possible to conceive a methodology of this nature without the presence of the person who will eventually use the technology. Thus, the novelty of this work consisted in the integration of the above technical, environmental and social aspects to obtain a device which not only meet the engineering required features but also takes into account the user opinions and needs in the whole process. The integration of all these characteristics is crucial because it contributes to a successful functionality and operability of the proposed appropriate technology. For this task, an initial step is to establish links with strategic members of the community that receives the technology (i.e., identifying people that can serve as intermediaries between the community and the ecotechnologists).

For illustration purposes, Figure 1 shows a flow chart describing the stages of the methodology, which covers the development and evaluation of technology. In summary, the methodology consists of a total of 9 stages, interacting between them and where the first two stages identify the energy consumption or natural resources and the remaining stages are related to the development of the technological device.

Stage 1. Diagnosis of energy/natural resources consumption in the rural sector.

The first stage begins with a diagnosis of energy or natural resources, to identify needs in rural communities. The use of efficient tools for assessing the residential and small industry energy needs of the rural sector is very important at this stage [16,29] so, a survey was selected to obtain the diagnosis in the community.

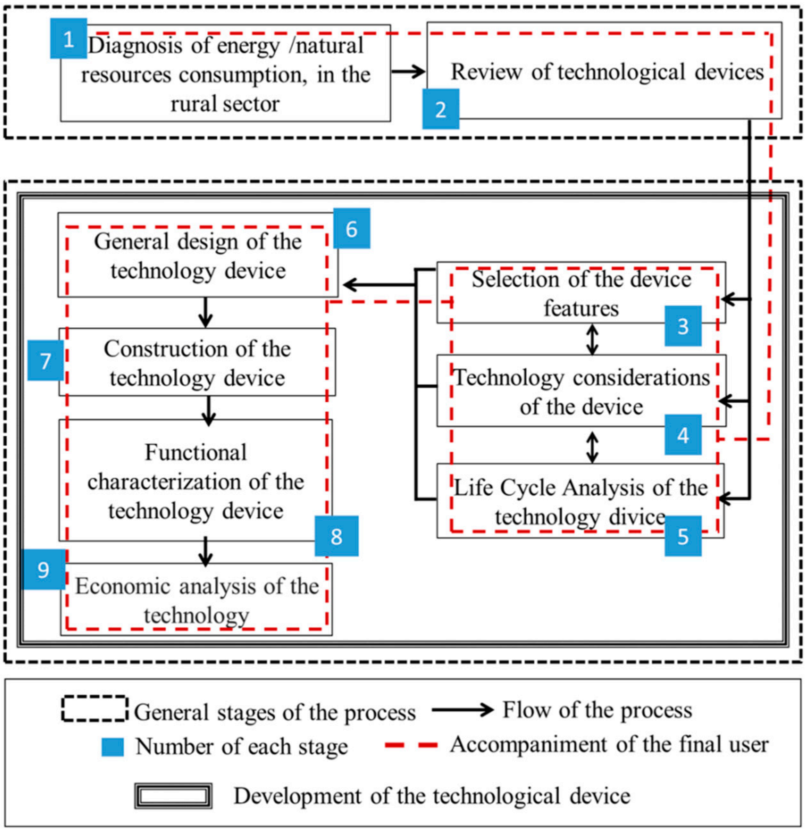

**Figure 1.** Scheme of the proposed integrated methodology for the development of Appropriate Technology where the user is involved throughout the process.

Stage 2. Review of technological devices.

In this this stage, a review of technological devices that mitigate or solve the problem that is reflected in an energy need of the community should be exercised. However, it should be noted that technological alternatives might be available in the market to satisfy certain energy needs, but these options do not necessarily have low environmental impacts, they can be adapted to the conditions of the community, or they can be appropriated by the community. For this reason, the purpose of the survey is to highlight particular aspects to develop a technology that meets specific local needs of the community where the participation of the user is a fundamental element in the conceptualization or adaptation of the first concept of a technology [13,14].

Stage 3. Selection device features.

The technological development begins with the third stage. A conceptual proposal of the device features (e.g., geometry, material, and characteristics) of the technological device according to the context where the technology will be applied is developed at this stage. For this task, computer simulations that theoretically determine the performance of the preconceived technology are very useful (e.g., using design principles and tools such as SolidWorks® [30]). This stage is particularly important since it encompasses the engineering design characteristics of the device (e.g., the inclination of a solar heater, its orientation, and the necessary height) with issues related to the future operation in situ of the device, which will depend on all the recommendations that potential users can offer (e.g., the maximum size of the technology, mass, accessible materials and complementary materials to perform a certain task).

Stage 4. Technology device considerations.

It is necessary to know aspects such as the meteorological considerations under working conditions of the device with the intention of adapting the technology to the specific context. Similarly, it is not only important to look for materials with low environmental impact to build the device, but also the device proposal must also be consistent in terms of technical and social functionality with the community [31].

Stage 5. Life-cycle assessment of the technology device.

A Life-Cycle Analysis (LCA) to quantify the lowest possible environmental impact of the candidate technological devices conforms the objective of this stage. The LCA is a well-known methodology that quantifies ecological impacts, natural resources, and human health of a product or system during its life cycle; that is, from the extraction of construction materials, through its transportation, manufacture, use, until you reach your final disposal. For this task, the ISO 14040/44 standards describe the methodology to carry out an LCA [32].

Stage 6. General design of the technology device.

This stage presents in an integrated way the conceptualization of technology to bring it to its construction. Aspects related to the review of the devices should be considered as well as characteristics according to the results of stage 1 of the methodology.

Stage 7. Construction of the technology device.

After the design stage, the construction of the technology device is carried out in the case study community. This stage is open to all inhabitants of the community for them to establish a closer link with technology device, generating feedback and joint learning [20,31]. When the proposed technology requires an irremovable structural construction, a meeting should be considered with all the participants involved in the case study project to define the initial features to be tested of the device in order to corroborate its operation and functionality. These participants may be also those who helped with the construction of the device, volunteers, or a target society sector (e.g., poor people selected based on socio-economic indicators as suggested by Rodríguez [16] and González et al. [7]). In other cases, the selection and implementation of the technology must be done after validating the operation of the device.

Stage 8. Functional characterization of the technology device.

There must be an evaluation of the technology in terms of energy and social performance to corroborate its technical functionality and that the social requirements—established at stage 4—are also met. Simultaneously, the training of selected initial users is also considered at this stage and it is important to identify if they speak an indigenous language since training on the use and maintenance of the technology device should be clear for them. The trained community members will promote the technical support and advice of the use of the technology device during the first months to improve the adoption process in the community.

Stage 9. Economic analysis of technology.

Finally, once the functionality of the proposed technological device is verified, an economic analysis of both, the prototype and, if the case, the traditional technology that should be displaced, is carried out in order to quantify the possible tradeoffs or benefits of the proposed device.

## 3. Case-Study

### 3.1. *Target Community and Consumption Diagnosis*

As a case study, the proposed methodology was applied to the development of a solar wood-dryer for the indigenous community of San Francisco Pichátaro (Latitude 19.55, Longitude −101.8) in the municipality of Tingambato of the Mexican state of Michoacán. Figure 2 displays the geographical location of the target community. San Francisco Pichátaro is an indigenous community whose main social authority is an assembly, from which derive the representation of communal goods and the authority of communal government, and then the committees and representatives of its seven neighborhoods.

The main productive activities of the community are the agriculture and the production of wood furniture for sale. For the latter activity, pine wood is the raw material used to make the furniture.

Some years ago, there were about 312 workshops, but due to the low sale of furniture and the excessive prices of wood, so far only about 100 workshops remain open and in continuous operation.

**Figure 2.** Target community San Francisco Pichátaro and its geographical location.

The community representatives in this project were a "craftsman leader" and an "artisan engineer" instead of the authorities and a community technician because of their technical knowledge.

(i) The "craftsman leader" (so-called because there is no concept to name an actor with the characteristics of the one identified) facilitated the communication between ecotechnologists and artisans. For instance, the craftsman leader carried out informal public consultations with the other artisans that facilitated the generation of concrete proposals within both groups, the ecotechnologists and the artisans, regarding the characteristics of the technology.

(ii) The "artisan engineer" has technical professional knowledge on the design and construction of technologies and joined the group of ecotechnologists. This participant facilitated and participated in the application of the methodology. He also served as a "translator" of the technical issues to the community leader. His knowledge of the community, his experience in the development of technology and his craft perspective, were characteristics difficult to find in a regular community technician. Thus, the "artisan engineer" complements the craftsman leader abilities and benefits the stages described in the methodology.

### 3.1.1. Diagnosis of Consumption of Natural Resources for the Construction of Furniture

Stage 1 of the introduced methodology was carried out through a survey, which included: (a) types of wood used by artisans, (b) time of wood drying outdoors, (c) activities in artisan workshops, (d) weekly consumption of wood of boards with different thicknesses. Figure 3 shows the results of this survey which also serve to determine the size of the proposed technology. Subsequent analysis of the surveys revealed that pine is the most common type of wood used as forest biomass for furniture production (Figure 3a). The time allocated for drying wood outdoors is from 1 to 6 months (Figure 3b). In addition, it was identified that most of the workshops carry out activities of wood carving and brushing, assembling and painting furniture, drying and cutting wood (Figure 3c). The most common types of wood boards used per week have thickness between 0.5 and 2 inches (Figure 3d). Similarly, it was recorded that one of the main difficulties of local artisans is the drying of wood. That is, the manufacture of furniture with wet wood impacts on its quality, as it can be deformed or cracked, which translates into furniture of poor quality that the customer is not willing to buy. Therefore, the furniture manufactured with dry wood represents an alternative to generate added value to the products of the final sale. However, acquiring dry wood increases the costs of the necessary raw wood, which decreases the profits of the artisans.

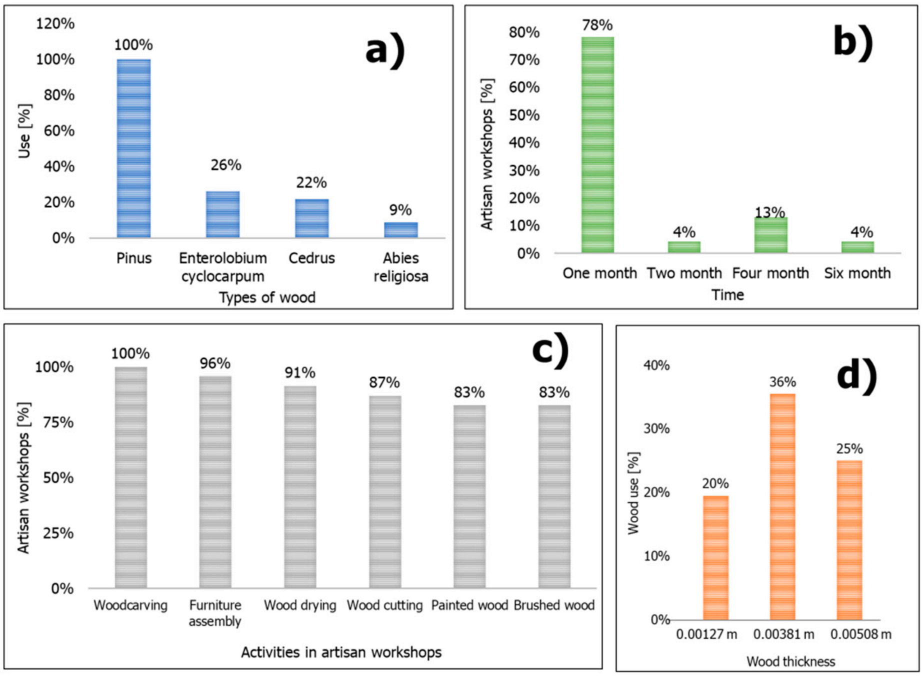

**Figure 3.** Results of community participatory diagnosis: (**a**) types of wood used by artisans, (**b**) time of wood drying outdoors, (**c**) activities in artisan workshops, (**d**) percentage of wood boards with different thicknesses used per week.

The diagnosis also allowed to determine that the humidity of the wood, before and after the outdoors drying process, was around 54% and 21% respectively. Likewise, it was identified that only five artisans have wood-dryers that operate with forest residues, which are made of hand-made brick units and a reinforced concrete roof as shown in Figure 4. The capacity in usable resource area that can be dried in these dryer's ranges, on average, between one and two cubic meters of wood (Figure 4a). The wood is placed on the walls inside the dryer and in the center forest biomass is combusted (Figure 4b). It is evident that this form of drying is not only polluting due to the emissions produced by the traditional combustion of forest biomass, but it can also represent a risk for the user and the wood to be dried. Therefore, it was identified that wood drying is a priority need for artisans.

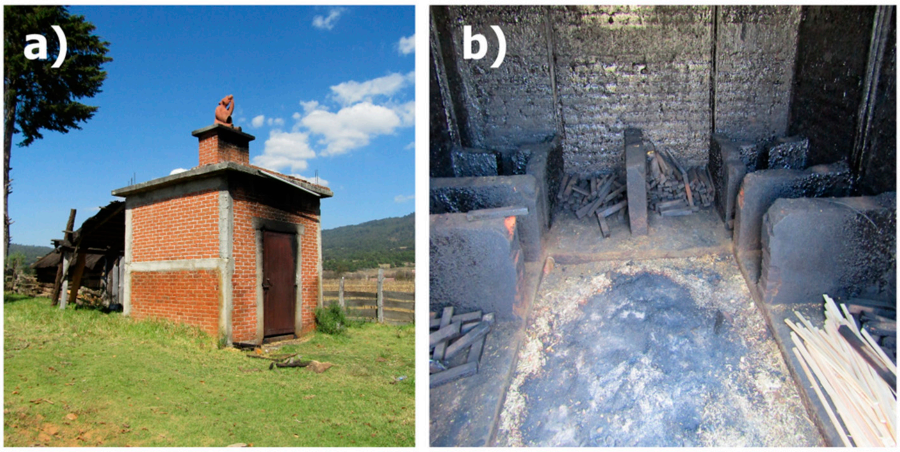

**Figure 4.** Exterior (**a**) and interior (**b**) view of the hand-made brick drier.

An informative meeting was held with artisans and ecotechnologists with the purpose of discussing the results of the diagnosis. It was agreed to make a technological proposal, with low environmental negative impacts, to achieve total or partial drying of wood. The community also agreed with the approach presented and the community council even offered to finance the construction of the drier presented at the project level. However, it was decided to wait in order to (1) have a valid and functional design, (2) characterize the dryer to later empower the artisans, and (3) the adoption and reproducibility of this technology was already set within the community.

### 3.1.2. Review of Technological Devices (Stage 2)

The design of a solar dryer usually includes the following components: roof, collector, drying chamber, thermal smoothing, fans, and vents. Each of these components helps to ensure a proper operation and guarantees the efficiency and quality during the drying process [33]. These elements can be designed in different ways so they can be part of different solar drying equipment [34]. The roof is a component through which solar energy is captured to heat the indoor air of the chamber in order to dry the wood. The collector is where solar radiation heats the air and it must be located between the roof and the pile of wood. The drying chamber is the area where the product is dehydrated by the heated air. The average air velocity passing through the pile of wood to be dried must be between 1.0 and 2.0 m/s [35].

Some types of solar wood-dryers are mentioned below for more details see [36]. We identified several types of solar wood-dryers that could meet the needs detected during the diagnosis phase. For instance, a dryer developed by the company Wood-Mizer of Canada developed the "SD3000" dryer with a capacity of 3000 feet of wood boards. This dryer was designed to be built by the user and includes a passive solar collector, with three insulated walls, concrete floor, a transparent plastic roof with a 45° slope, oriented south or north depending on the hemisphere. The disadvantage of this solar wood-dryer is that it is only suitable for locations above 40° north latitude.

In Australia, a dryer with a greenhouse structure has been proposed [37] and it is essentially a rectangular compartment painted in matt black with corrugated iron sheets used as a collector and a greenhouse-type structure with a transparent plastic cover. This dryer also includes an additional heating system for cloudy days. Also, the company "Solar Dryers of Australia" [38], developed a rectangular hybrid dryer (solar-natural gas) built with aluminum structure, stainless steel, and galvanized steel. This dryer uses natural gas to heat the water passing through the radiators inside the chamber and it only uses solar energy as a complement to heat the water by means of collectors placed on the top of the dryer. It has a capacity of 10 m and it requires a 240 V electrical power to operate the fans. However, the information regarding the drying time and the operation of the devices is missing.

In Resistencia, Argentina, Reuss et al. [39] developed a dryer design based on computational modeling. The program predicts temperatures and humidity contents. For its validation, a prototype with a capacity of 12 m and a data acquisition system to monitor the drying process was built. The operating temperature was 40 °C, and its efficiency varied from 40 to 60%, depending on the radiation value (between 150 and 750 W/m). The drying time of the product also varied from 30 to 51 days.

The Center for Research in Integration Forest Industry (CIIBI), of the Technological Institute of Costa Rica, developed a dryer prototype with a capacity of 6.6 $m^3$ built of wood walls, doors, and windows as the main structure. As an external and internal lining, galvanized iron was recommended and as a thermal insulator, glass wool, that was placed between the spaces of the internal and external linings was used and the roof was made of glass and the solar collector consisted of a black 4 mm-thick iron sheet. In Mexico, Martinez [40] and Fuentes-Salinas et al. [41] developed box-type wood dryers in which the indoor area was heated by means of a greenhouse effect.

We considered several designs and technical aspects from the dryers previously reviewed while designing and constructing our proposed wood solar dryer, but we had to adapt our prototype in order to obtain an innovative locally-suitable device as it is described in the following development process:

## *3.2. Technology Development*

### 3.2.1. Technology Proposal: Selection of the Device Features (Stage 3)

The technology proposal for this case study was the development of a solar wood dryer. As shown in Figure 5, three different geometries were studied from a numerical point of view: (a) G0 corresponds to a simple square cavity, (b) G1 considers that the roof of the dryer is inclined at a latitude corresponding to the latitude of the community of Picháтало (latitude 19° North), and (c) G2 considers that the roof is formed by two plates at two different angles, one of them also corresponding to the latitude of the community.

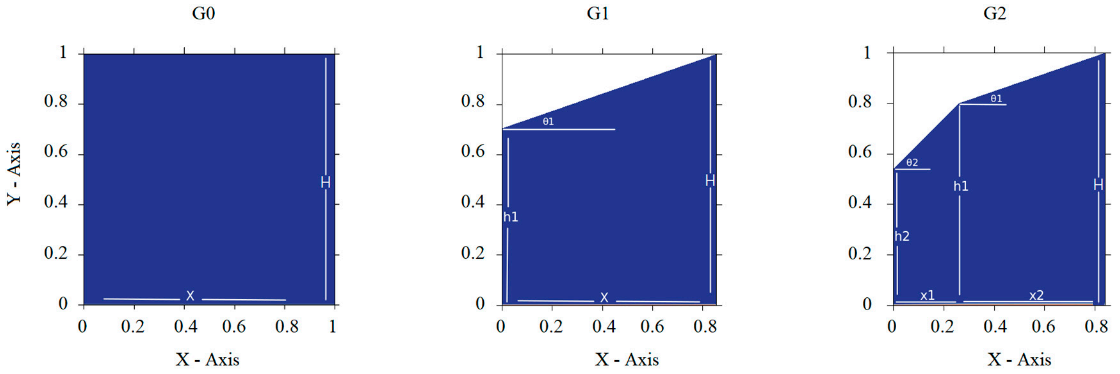

**Figure 5.** Side view of the geometries considered for solar wood dryers. Main dimensions are shown: height, H, length, X, and angles, θ.

In order to select the geometry with the best heat transfer performance, numerical simulations were performed using the open source CFD library OpenFOAM [42] to obtain and compare the velocity and temperature fields, as well as some other global parameters within the three proposed geometries. The analysis of natural convection in our geometries is based on the mass, momentum, and energy conservation equations, by using the Boussinesq approximation. These equations are commonly expressed in a dimensionless form [43] as follows:

$$\nabla\bullet\vec{u} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + (\vec{u}\bullet\nabla)u = -\frac{\partial p}{\partial x} + \left(\frac{Pr}{Ra}\right)^{\frac{1}{2}}\nabla^2\, u \tag{2}$$

$$\frac{\partial v}{\partial t} + (\vec{u}\bullet\nabla)v = -\frac{\partial p}{\partial y} + \left(\frac{Pr}{Ra}\right)^{\frac{1}{2}}\nabla^2\, v + T \tag{3}$$

$$\frac{\partial T}{\partial t} + (\vec{u}\bullet\nabla)T = \left(\frac{1}{PrRa}\right)^{\frac{1}{2}}\nabla^2 T \tag{4}$$

where $x$, $y$, are spatial dimensions, t, $\vec{u} = (u,v)$ are the time and the velocity vector, and p and T, are the pressure and the temperature scalar fields, respectively. For the dimensionless variables, we use as a characteristic dimension the height of the cavity L, the temperature difference $\Delta T = TH - TC$ and the thermal diffusive velocity, $uc = \alpha/L$, with $\alpha$ being the thermal diffusivity.

Associated boundary conditions are assumed as:

(i) Constant temperature:

$$T = 1 \text{ on bottom wall, } T = 0 \text{ on top wall} \tag{5}$$

(ii) thermal insulation:

$$\frac{\partial T}{\partial x} = 0 \; on\; left\; and\; right\; walls \tag{6}$$

(iii) and the no-slip condition for the velocity:

$$\vec{u} = 0 \; \textit{on all boundaries} \tag{7}$$

The following initial conditions are considered:

$$T(x, y, t = 0) = 0.5, \; \vec{u} = 0 \tag{8}$$

As it can be seen from the Equations (1)–(4), the flow is characterized by two dimensionless parameters, the Rayleigh number, Ra, and the Prandtl number, Pr, which are defined as

$$Ra = \frac{g\beta \Delta T L^3}{\nu\alpha}, \; Pr \; = \; \frac{\nu}{\alpha} \tag{9}$$

where $g$ is the gravity constant, $\nu$ is the kinematic viscosity and $\beta$ is the volumetric thermal expansion coefficient. The Ra number is the ratio of buoyancy and viscosity forces; whereas, the *Pr* number is the ratio of momentum diffusivity to thermal diffusivity. Simulations were run for *Ra* = 104, 105 and 106, and *Pr* = 0.71 (air). As it can be seen in Figure 6, the temperature field and isotherms are different for each of the three geometries. Interestingly, geometry G2 shows a better temperature distribution in the whole cavity (for all the values of *Ra*) than geometries G0 and G1, which can be explained by a detachment of the boundary layers in each of the two sections of the roof.

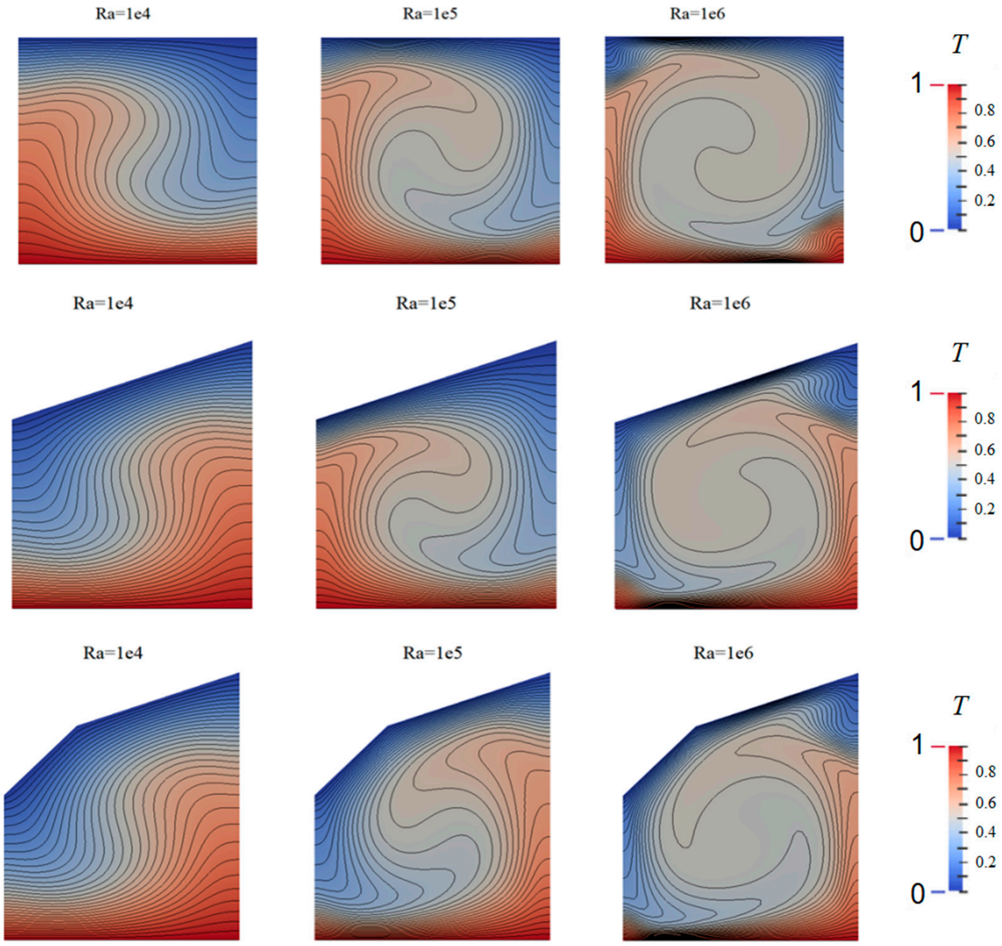

**Figure 6.** Temperature field and isotherms for the different geometries. The Raleigh number is considered in the range of 1e4–1e6 ($1 \times 10^4$–$1 \times 10^6$) for each geometry. Dimensionless temperature is in the range of 0–1.

In order to have a parameter that allows to evaluate the heat transfer in the three different cavities, the mean Nusselt ($Nu$) number is evaluated on the bottom wall, it is defined as:

$$Nu = \int_0^1 Nu_L dx,\ where\ Nu_L = -\frac{\partial T}{\partial y}|_{y=0} \tag{10}$$

The higher the $Nu$ number the greater is the heat transfer in the cavity, which therefore is better for the wood boards drying. Results of the $Nu$ number vs. the Ra number are shown in Figure 7. Interestingly, the G2 configuration shows (for all values of Ra) the highest values of the $Nu$ number.

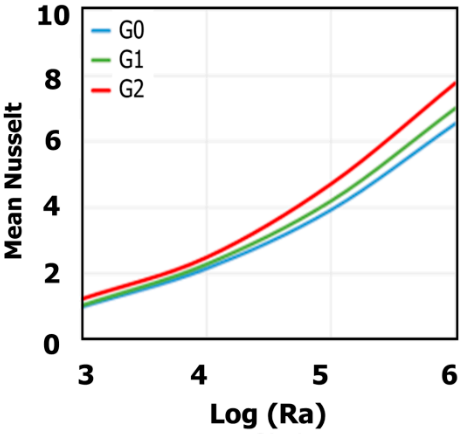

**Figure 7.** Mean Nusselt number vs. Rayleigh number for the three different geometries.

Therefore, the numerical results revealed that geometry G2 was the best candidate. However, before its construction, it was decided to corroborate the simulation results through the construction of two prototypes. This decision arises since the development of a technology device is an uncertain process, which does not always determine the functioning of the devices on a real scale [44]. Furthermore, it was necessary to demonstrate the proposed geometry due to the uncertainty of the artisans to successfully use the proposed dry wood.

Figure 8a shows the two scale-models of geometries G1 and G2, which has less than one square-meter of solar collection area. From the scale-models, it was possible to obtain information about the thermographic characterization, the temperature, and humidity percentage of in wooden specimens in dryer prototypes. Figure 8b,c show that the performance of solar energy use and the thermal accumulation in the drying chamber, respectively, is better for the solar dryer G2 than that for G1, which confirms the simulation results. In addition, a batch of 6 samples was placed in each dryer (all of dimensions of 5 cm × 15 cm × 2.54 cm) to evaluate the efficiency of wood drying. It should be noted that specimens with a higher moisture content were deliberately included in the dryer with two inclinations. Figure 8d shows the results of the kinetics of drying during 7 days of sun exposure, which reveals that the drying efficiency is also better in the dryer with two roof inclinations than that with one roof inclination.

### 3.2.2. Technology Considerations of the Device (Stage 4)

During the workshops held in the community, the artisans expressed that the device must have specific characteristics. For instance, the area of the device must be less than 10 $m^2$, it must be located avoiding any shade, and the access must be wide enough to place the wood in and out of the chamber. These characteristics conditioned that the effective-area for solar collection of the device must be less than 6 $m^2$. Finally, by means of the diagnosis of wood consumption, we also defined that the device should have one cubic meter of load capacity. These considerations were contemplated to define the size of the dryer.

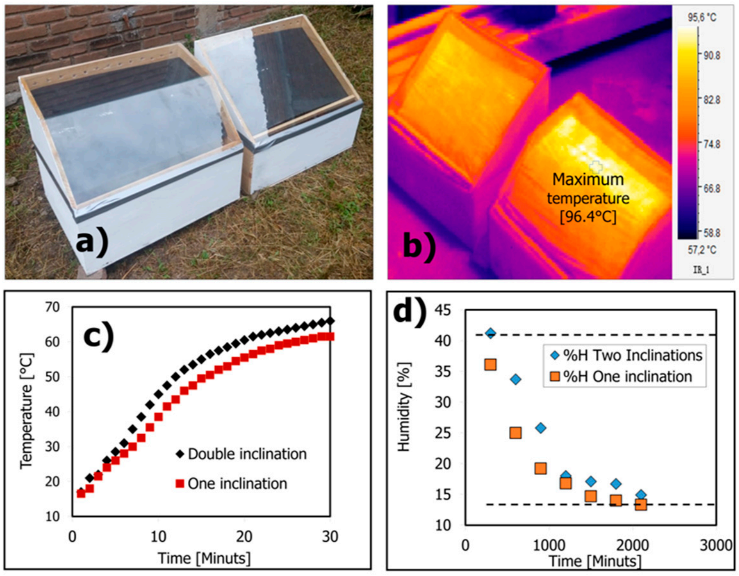

**Figure 8.** (**a**) Scale dryer models, (**b**) thermographic characterization, (**c**) thermal evaluation of the drying chamber and (**d**) drying kinetics of wooden specimens within the scale dryers.

### 3.2.3. Life-Cycle Assessment of the Technology Device (Stage 5)

To determine the potential environmental impacts of the wood dryer, a Life Cycle Assessment (LCA) was carried out for the design of the dryer, following the methodology described in the ISO 14040/44 standards [32]. The system boundary to analyze includes the materials for the construction of the dryer as well as the energy for its operation (in this case, solar energy). The functional unit was defined as 3 $m^3$ of dry wood. To carry out the inventory, the dryer design was used in SolidWorks® to determine the quantities of materials needed to build the device. For the inventory of secondary data, the Ecoinvent version 3.5 database was used [45]. The theoretical solar energy required for wood drying was also calculated considering the water mass that must be evaporated (the latter was calculated from initial and final moisture measurements of a wood sample). The method for impact evaluation was the CML Baseline/World 2000 where 11 impact categories were included. For comparative purposes and using the same method and scope, an analysis of the traditional wood drying system was also carried out, which consists of a quarter of brick and concrete with a steel door, which uses biomass as fuel for wood drying.

As indicated in Stage 5 of the methodology, a Life-Cycle Assessment (LCA) of the traditional artisan dryer and the proposed wood-dryer was carried out and the results are reported in Table 1. It should be highlighted that the proposed solar dryer design has impacts equal to or less than 5% of the impacts of the traditional dryer. Particularly, the stage of use in the traditional dryer is the one that contributes with more than 90% in all the categories of impact. This situation arises due to the combustion of biomass for drying. The rest of the impacts are due to the construction of the traditional dryer, mainly hand-made brick (from 60 to 90%), followed by cement (30%), and the rest for the steel and the iron of the rods and the door. As examples of the impacts, in the categories of global warming and human toxicity which have a much greater impact in the conventional furnace, this is due to the use stage where the energy required by the burning of biomass generates greenhouse gases, besides particles. Therefore, there is an impact on climate change and human health. For the category of abiotic degradation, the biggest impact was the extraction of the clay to make the brick. For this same category of impact, in terms of concrete, the impacts of cement manufacturing and gravel extraction stood out.

**Table 1.** Quantitative comparison of selected environmental impacts generated between the conventional oven and the proposed technology (CML-Base Line/World200 Method).

| Impact Category | Unit | Traditional Drier (Bricks and Cement) | Solar Dryer | % Impact Solar Dryer VS. Traditional Dryer |
|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 0.0635 | 0.0032 | 5% |
| Abiotic depletion (fossil fuels) | MJ | 385,322.7 | 8389.5 | 2% |
| Global warming (GWP100a) | kg $CO_2$ eq | 36,451.5 | 899.0 | 2% |
| Ozone layer depletion (ODP) | kg CFC-11 eq | 0.00301 | 6.76E-05 | 2% |
| Human toxicity | kg 1,4-DB eq | 25,799.2 | 556.4 | 2% |
| Fresh water aquatic ecotox. | kg 1,4-DB eq | 12,303.8 | 195.2 | 2% |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 31,933,493.6 | 852,103.5 | 3% |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 280.6 | −0.09 | −0.03% * |
| Photochemical oxidation | kg $C_2H_4$ eq | 90.7 | 0.3 | 0.31% |
| Acidification | kg $SO_2$ eq | 410.3 | 2.6 | 1% |
| Eutrophication | kg $PO_4$ eq | 148.7 | 0.9 | 1% |

* For the terrestrial ecotoxicity category, steel has a negative value which indicates an impact reduction. This reduction is mainly achieved because we considered the use of recyclable material and, therefore, new raw material is not being extracted. Thus, the inventory data used in the analysis (Ecoinvent 3.5, Steel, unalloyed {RoW} | steel production, converter, unalloyed | Conseq, U), reflected this reduction.

Figure 9 depicts that all the impacts derived from the proposed wood solar dryer, from the LCA analysis are due to the materials with which the dryer is built, since the drying process is performed by means of solar energy. The steel plate has the greatest impacts in most of the categories analyzed, followed by glass, and to a lesser extent, the concrete used for the base and the wood for the walls.

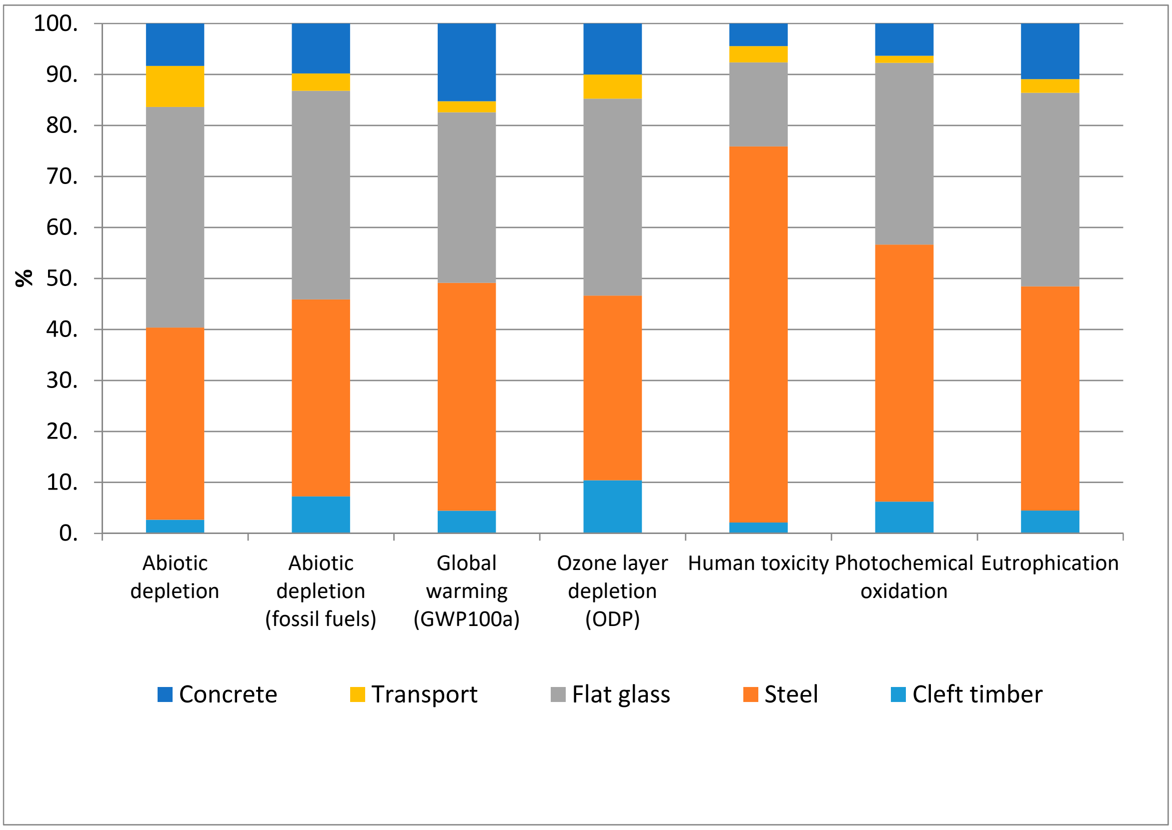

**Figure 9.** Selected aggregate environmental impacts (in percentage) generated by alternative technology construction materials (CML-Base Line/World200 method).

### 3.2.4. General Design of the Technology Device (Stage 6)

Based on the results of both the numerical simulations and the testing prototypes, a biomass dryer was designed in Solidworks® [30] considering geometry G2. The dryer, indirect-box type [46], consists of a wooden structure with a cover formed by two glass plates at different angles at the roof as shown in Figure 10.

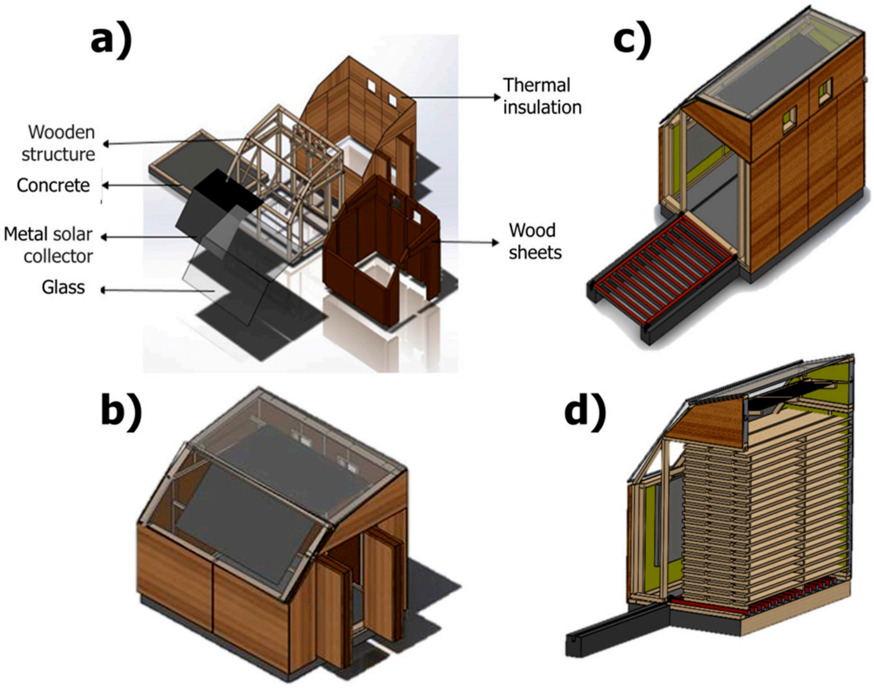

**Figure 10.** (**a**) structural system of the proposed wood-dryer, (**b**) isometric view of the dryer, (**c**) cross-section of the dryer with wood content, and (**d**) top view.

The design considers walls of three sections to the outside and inside sheets of wood with phenolic coating, and between these a thermal insulator to avoid the losses of heat transfer. It should be noted that the structure and coatings were decided to be constructed of wood because the community has availability of this resource. The collector has a metal cover and an absorbent coating with low environmental impact [47]. Figure 10a shows the parts of the wood solar dryer to be assembled, while Figure 10b displays an isometric view of the dryer. Additionally, Figure 10c illustrates the access door to the solar wood-dryer through a sliding metal structure, and Figure 10d displays a cross-section showing the wood placement inside the dryer. This design was made considering the loading capacity of the brick and concrete kilns, as well as the amount of wood dried per workshop in a month. Additionally, the availability of space to place devices of this type in the workshops was evaluated, so the dimensions are $2 \times 2\ \mathrm{m}^2$. These considerations represent stage 4 of the proposed methodology, which conclude with the design of the device.

### 3.2.5. Construction of the Wood Solar Dryer (Stage 7)

From the favorable evaluation, in technical and environmental terms, the proposed wood dryer was built according to the design described previously. For this task, it was necessary to determine the ideal place to install the device in the community, to select the space where it would be built, and to define the potential users that would receive the dryer. The ecotechnologists left that decision in the hands of the artisan group, which determined, through an assembly, a benefit for all. That is, they decided that the dryer should be built in a community space, which belongs to the entire population, so that, in this way, all artisans had access to the drying of wood in this new technology. Therefore, Figure 11 shows different construction stages of the proposed wood solar dryer.

**Figure 11.** Construction of the solar dryer: (**a**) structure, (**b**) cover walls, (**c**) Finished construction.

### 3.2.6. Functional Characterization of the Technology Device (Stage 8)

After the construction, tests of the thermal behavior of the proposed solar wood-dryer have been carried with the purpose of evaluating the cover of the collector and the internal temperature during an average day. For this task, "Stove Use Monitors" thermometers [48], a UNI-T UTi160B thermographic camera, an environmental thermometer Beurer HM16, and a Piranometer with datalogger LP02, were used. The results of the thermal analysis showed that the collector cover has good absorption of solar energy (Figure 12), reaching temperatures of approximately 100 ° C to the solar medium as shown in Figure 12b. Additionally, the drying chamber managed to reach temperatures above 50 °C even with reference to low ambient temperatures. Finally, although there was no high irradiance because the tests were carried out in a month of rain, the absorption capacity of the collector led to an acceptable thermal accumulation for wood drying as shown in Figure 12c.

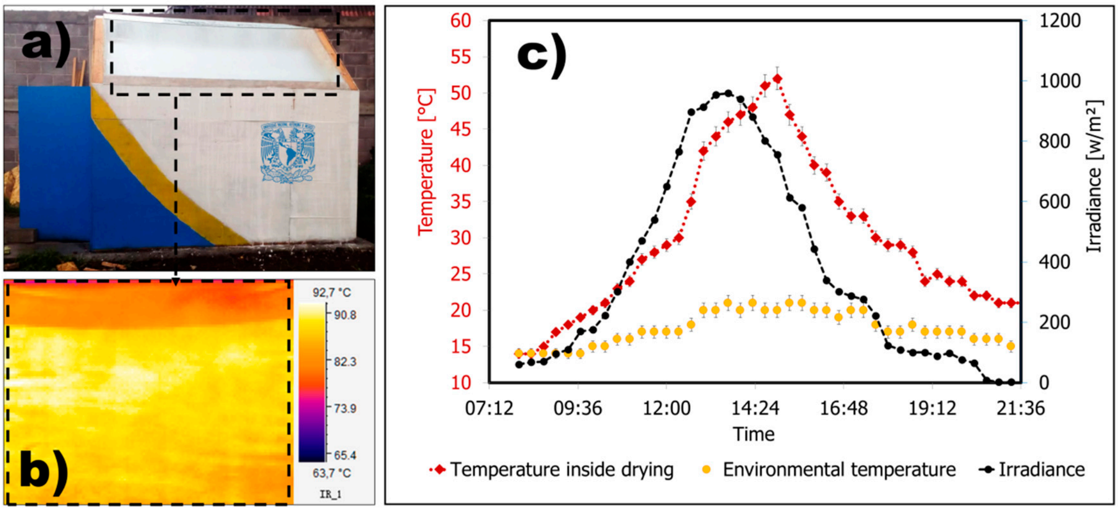

**Figure 12.** (**a**) Solar dryer, (**b**) thermographic analysis of the solar collector, (**c**) results of thermal behavior of the drying chamber.

The evaluation of the drying process of the proposed wood-dryer was also carried out after its construction. For this purpose, a system for monitoring the mass of wood was developed to determine the loss of moisture during the stay of the wood in the dryer. Thus, 200 tables (with dimensions of

1.5 cm thick, 15 cm wide, and 200 cm long) were introduced in such a way that the distance between them allowed air circulation as shown in Figure 13.

**Figure 13.** Craftsman placing wood for drying.

The drying tests were conducted in a time interval of 15 days and the results are depicted in Figure 14 where subsection (a) shows the irradiance analysis during the days of wood drying; subsection (b) shows the peaks of room temperature, and the loss of wood mass (due to the drying process); and subsection (c) shows the wind speed along the solar absorption plate. Finally, the wind temperatures at different distances from the vents during different times of the day (i.e., in the morning, at mid-day and in the afternoon) are shown in subsection (d). It is evident that the highest temperature gradient was reached at noon and at shorter distances from the vents, which are also close to the absorber plate.

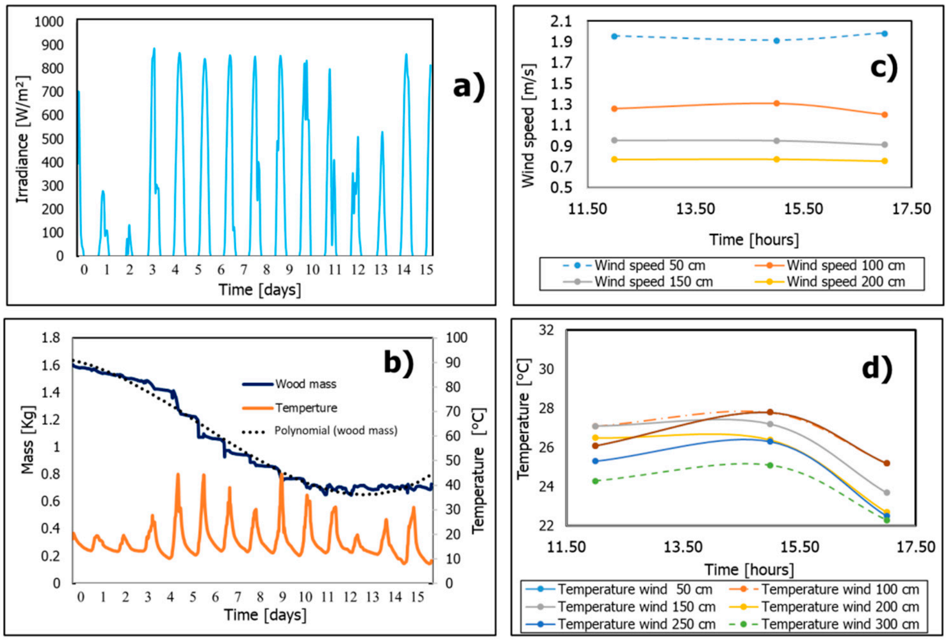

**Figure 14.** Drying tests: (**a**) solar irradiance, (**b**) temperature inside the dryer and drying kinetics of the wood specimens, (**c**) wind speed in the drying chamber at different distances from the vents, (**d**) Temperature of the wind at different distances from the vents during different times of the day.

The drying process allowed to reduce the mass of the wood by 30% with the resulting reduction of 40 to 12% of moisture content. The wood used to evaluate the kinetics of drying was provided by artisans from the community, who had received preliminary training on the operation of the dryer, which allowed them to have a first approach with the technology. Finally, we followed the approach suggested by Chavan et al. [49] to evaluate the drying efficiency of the developed technological device using the equation:

$$\eta = \frac{\mathrm{WL}}{\mathrm{IA}} \quad (11)$$

where $W$ is mass loss of the wood [Kg], L is the latent heat of water vaporization [KJ/Kg], I is the solar energy during the process [kWh/m$^2$], and A is the collector area [m$^2$]. Evaluation of Equation (11) during the drying process yielded an efficiency of 20.5%.

Stage 9. Economic Analysis.

Table 2 shows the results of the economic analysis performed to compare the cost to dry a cubic meter of wood (Equation (12)) in the traditional dryer and the proposed solar wood-dryer over a lifespan of 30 years. In this analysis, we considered the costs of the materials and the fuel for drying for the traditional drier and only the materials for the solar wood-drier.

$$C_d = \frac{C_m + C_f}{C_l} \quad (12)$$

where $C_d$ = *Cost of dried wood*; $C_m$ = costs of the materials for the construction of the dryer; $C_f$ = costs of the fuel for drying over a lifespan of 30 years; $C_l$ = dried wood during a lifespan of 30 years.

**Table 2.** Economic analysis data.

| Concept | Traditional Dryer | Solar Wood-Dryer |
|---|---|---|
| Materials (USD) | 967 | 599 |
| Fuel (USD/m$^3$ DM) | 0/22.1 ** | 0 |
| Dried Wood capacity—(m$^3$ DM)/year * | 32 | 12 |

* Cubic meters of dry matter (DM) ** To estimate the related costs of the traditional dryer we run two scenarios: one assuming zero fuel cost (this is the current situation in the community due to the artisans use the sawdust residues from their work activities), and the other assuming 22.1 USD/m$^3$ of dried wood (the price in the community of the sawdust used as fuel, despite the artisans are not currently buying it). We also assumed an exchange rate of MX$19.7/USD. The labor required for the operation of the dryers is developed by the artisans.

The economic analysis showed that for the scenario where we assumed zero fuel costs, the cost to dry a m$^3$ of wood is about 1 USD and 1.7 USD for the traditional and the proposed solar wood-dryer, respectively. For the second scenario, where we assumed the cost of buying sawdust, the cost to dry a m$^3$ of wood is about 22 USD for the traditional dryer. These drying costs are indeed low when compared to the 126 USD/m$^3$ that it would cost the artisans to dry their wood boards in existing industrial kilns in other nearby communities. Thus, the proposed technology could be attractive to artisans, given its lower implementation cost compared to traditional technology.

## 4. Summary and Conclusions

A new methodology is proposed for the development of appropriate technology that allows satisfying energy needs in rural communities. Thus, the novelty of this work consisted in the integration of the technical, environmental and social aspects to obtain a device, which not only met the engineering required features but also takes into account the user opinions and needs in the whole process. The integration of all these characteristics is crucial because it contributes to a successful functionality and operability of the proposed appropriate technology. The introduced methodology included several stages grouped in a process that consists of two parts: (a) Identification of energy consumption or natural resources, and (b) development of appropriate technology.

The methodology is implemented in a case study for the development of a solar wood-dryer in the artisan community of the indigenous population of Pichátaro, in the Mexican state of Michoacán. The key results and findings from this investigation are as follows:

- Three geometries of a solar wood-dryer prototype were proposed and analyzed with the computer software Open FOAM [42]. All proposed geometries showed better interior heat transfer than the traditional wood-brick dryer.
- A Life-Cycle Analysis (LCA) of the proposed solar wood-dryer was carried out as part of the methodology. The results showed that the new solar wood-dryer prototype has environmental impacts in all analyzed categories that are 5% or smaller than those of the traditional dryer. Particularly, global warming potential figures decreased by about 98% with the use of the proposed solar wood-dryer. Due to the aim of this study was to compare our proposed solar wood-dryer with the traditional dryer it was immediately displacing, we omitted comparisons with other devices in the market.
- Based on the designed geometries, the LCA, and the considerations proposed by the artisans of the community, a solar wood-dryer was developed which has 20% efficiency. The design, construction, and energy evaluation of this device, incorporated the technical and operational requirements requested by the artisans in the community.
- The functionality of the solar wood-dryer was checked to meet an identified need based on a diagnosis of consumption of timber resources. The dryer met the purpose for which it was designed, and it will be delivered to artisans for frequent use.
- It was identified that the accompaniment of artisans during all stages of the methodology was essential to facilitate the construction and functionality evaluation. The information that they provided at each stage represented an exercise in co-design and technology development that covered their needs and motivated its possible adoption. Therefore, it should be noted that accompaniment is a key factor since we believe that technology should always suits the user and not vice versa. Finally, it is envisioned that the systematic way of developing appropriate technology should be energy efficient, socially acceptable, and economic and environmentally viable as suggested in this methodology.

It is well known that the way to check the impact of the appropriate technology is through monitoring that evaluates the transfer and adoption of it. Therefore, the monitoring process will be discussed in a follow-up work.

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