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Carbon and Water Footprint Evaluation of 120Wp Rural Household Photovoltaic System: Case Study

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Abstract

This study uses the Life Cycle Analysis (LCA) to evaluate the magnitude of the environmental impact, in terms of global warming potential, and water footprint throughout the 20 years of useful life of a rural electrical energy concession comprised of 120Wp Households photovoltaic systems (HPS) in the isolated communities of San Martin, in the Peruvian Amazon region. On the other hand, due to the particular conditions of the system (installation, operation, maintenance, monthly tariff collection), it is necessary to know its real impact and sustainability; not only through the aforementioned environmental impact indicators, but also by energy intensity values required by the system throughout its life cycle. Therefore, this paper used the Cumulative energy demand (CED) method to determine the amount of energy taken from natural resources for each process involved in the LCA and calculated with this, *i.e.*, the Energy Payback Time (EPBT) of the whole system. Likewise, the HPS has been environmentally compared to other case studies and the Peruvian Energy Mix, revealing a lower impact in the latter case and results within the range for stand-alone systems. Besides, the HPS shows a strong relation between energy production and O&M condition. Additionally, this study allows a further promotion of the use of this type of system in isolated areas, as well as the diversification of electricity generation in Peru.

Keywords

Life Cycle Analysis, Carbon Footprint, Water Footprint, Solar Home System, Life Cycle Inventory

1. Introduction

The energy access gap represents an extremely important challenge for developing countries like Peru but, due to the geographical diversity, the remoteness of rural communities and the low purchasing power of users, bringing electricity through conventional network is very difficult. In this sense, for decades, in order to improve the quality of life of inhabitants from isolated areas and to make use of renewable energy solutions, the Peruvian government has promoted rural concession that implement Household Photovoltaic Systems (HPS) [1] that also allow reducing the emission of greenhouse gases (GHG).

However, as with any other human activity, the implementation of these systems, has an impact on the environment, although to a lesser extent [2] [3]. Therefore, it is necessary to quantify it above all, since the results depend on the equipment used, the geographical location, and its consequences on irradiation, and the particularities of the Operational and Maintenance (O&M), characteristics than differ from other studies.

The methodology used for this purpose is the Life Cycle Assessment (LCA), which; allows for estimating the cumulative environmental impacts of all stages in the life cycle [4] of a system, product or service including material production, system manufacture and assembling, services provision, maintenance, repair and final disposal; it is also, known as cradle-to-grave evaluation [5].

This study is focused on determining the kgCO_2 eq emissions of Carbon Footprint (CF) through the ILCD 2011 v1.0.10 [6] method, and the Water Footprint (WF) [7] in m^3 produced by the electricity energy supply through a 120Wp HPS located in the San Martin region in Peru.

Several LCA studies have been developed for PV modules and PV power plants and some others for Stand-alone systems with a CF range between 0.018 and 0.18 kg CO_2 eq/kWh [8] [9] [10]. Likewise, the Energy Pay-Back Time (EPBT) is between 2.1 to even more than 20 years [2] [9] [10] [11]. All these values depend on the system type, location, and the final users.

Consequently, is important to establish a starting point for further studies in stand-alone systems and compare these with photovoltaic installations in the Amazon, Andeans regions and other energy sources.

2. Case Presentation

The analysis is focused on a 120Wp Household Photovoltaic System (HPS), a Stand-alone solution from a rural concession developed since 2017 to 2018, and it is comprised of the following main components:

- 120Wp Multi-crystalline Photovoltaic module of 1.21 × 0.67 m (0.8107 m^2), model ESM, Ever Exceed. It transforms solar energy into electrical energy and it's made up of silicon cells that produce electricity through the photoelectric effect.
- Galvanized steel support structure. It is used to sustain the PV modules and is made up of profiles and tubes of steel, and has 4 meters high, which 1 meter is buried.
- 25 Ah Solar Home System (SHS), Zimpertec. Properly and efficiently man-

ages the current, coming from photovoltaic modules, towards the batteries or consumptions load. It is comprised, mainly of a solar charger controller, a battery management system (BMS), a battery and a case.

- Balance of the system (BoS).

Figure 1 shows the electrical scheme of the analyzed HPS. The 120Wp photovoltaic module is supported by a 4-meter galvanized steel structure. The Solar Home System (SHS), installed inside the household, is a compact solution composed of a 25 Ah Lithium battery, a charge controller, a BMS, two breakers, electric conductors, and a DIN rail, all of them integrated in an ABS box. In addition, the materials that complement the Photovoltaic System—cables, DC Main board, LED lightbulb, tubes, outlets, etc., are the Balance of the system (BoS).

The main service covered by the HPS is the electricity energy supply; thus, the functional unit used herein is the kWh invoiced to users. However, those systems are part of a rural concession with a fixed tariff (BT8-120-PRE) [12], both in amount of monthly energy supplied and billing. Hence, the different stages of LCA will be referenced to 10.35 kWh/month per user—an amount corresponding to the photovoltaic systems that operate in the Amazon region shown in Table 1, and 2484 kWh for the 20 years of operation analyzed in this study, time considered for the system removal.

Moreover, the company that manage the rural concession must ensure the proper functioning of the HPS and collect a monthly fee; therefore, the operators visit the households every month, a considerable activity that consists of travelling

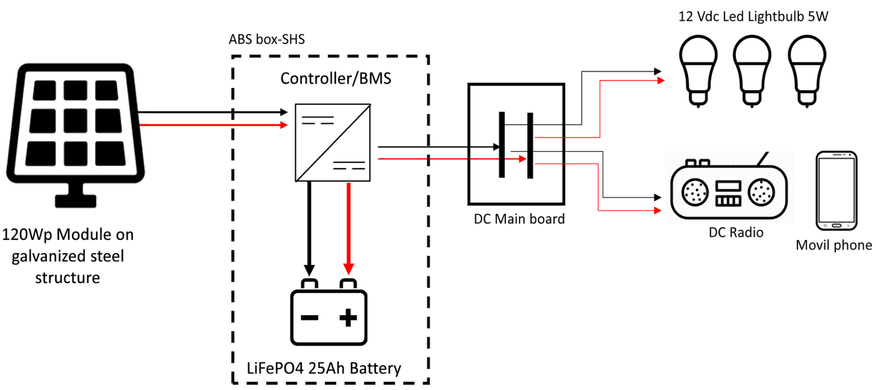

Figure 1. San martin concession's 120Wp household photovoltaic system scheme.

Table 1. Rural electricity tariff [12].

Module type	Installed capacity (Wp)	Service Voltage	Available monthly energy (kWh/month)		
			Coast	Andean	Amazon
BT8-050-PRE	50	12 Vdc	5.54	5.76	4.61
BT8-120-PRE	120	12 Vdc	12.43	12.93	10.35
BT8-240-PRE	240	220 Vac	25.37	26.39	21.12

through the Amazon region, and, also, they must establish a main office in San Martin region.

3. Methods

3.1. LCA Goal and Scope

The goal of this study is to quantitatively assess the environmental impacts of the electricity supplied, over its useful life, by a 120Wp HPS that operates in rural areas of the San Martin region, so the LCA is employed; a method to measure the potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal: it is also, known as cradle-to-grave [13].

Once the goal is defined, to ensure the accuracy of the LCA results based, it is important to establish the boundaries for the system-in this case a service- and each of its stages [14]. And, since the analysis is the cradle to the grave, all the flows of materials, products and services must be considered from the acquisition of the materials to the final disposition of the HPS. Likewise, it is necessary to establish the limits for each stage of the system, which leads to identifying the factors and details that characterize each of these, such as the type of PV module and battery employed; the kinds of transportations utilized, the method of installation and O&M used; and the final disposal to build a suitable system [10]. The project boundaries' scheme is shown in **Figure 2** and includes the processes from extraction to final disposal in the country where it is implemented. For practical purposes, the (LCA) has been divided into four stages or main processes.

1) Integration: It includes the manufacturing of all materials and components, the transport from the factories to warehouse at San Martin region, the subsequently 120Wp HPS transport from the warehouse and the installation at the user's household.

2) O&M and the Tariff collection: It corresponds to the HPS operation and maintenance; and the tariff monthly collection to the rural concession beneficiaries, which is a BT8-120-PRE price, as detailed in **Table 1**. Hence, is necessary to consider the supplies required for the management of whole rural concession: electricity and water for the office, paper for the invoices and transport of staff to the user's households.

3) Reposition: It implies the manufacture, transport, and installation of a new 25 Ah SHS when the useful life of the first SHS, comes to its end.

4) Final disposal: Disassembly, transport of the components for treatment, disposal, or recycling, as appropriate, of the whole HPS (except for the BoS, which remains in the houses to be used in the future).

Also, it is necessary to define a unit that enables to link the stages of the system and, also to compare it with other technologies that covers the same service, e.g., the conventional electrical network. This unit is known as Functional Unit (FU), and through it is possible to quantify and present, in the same unit—the

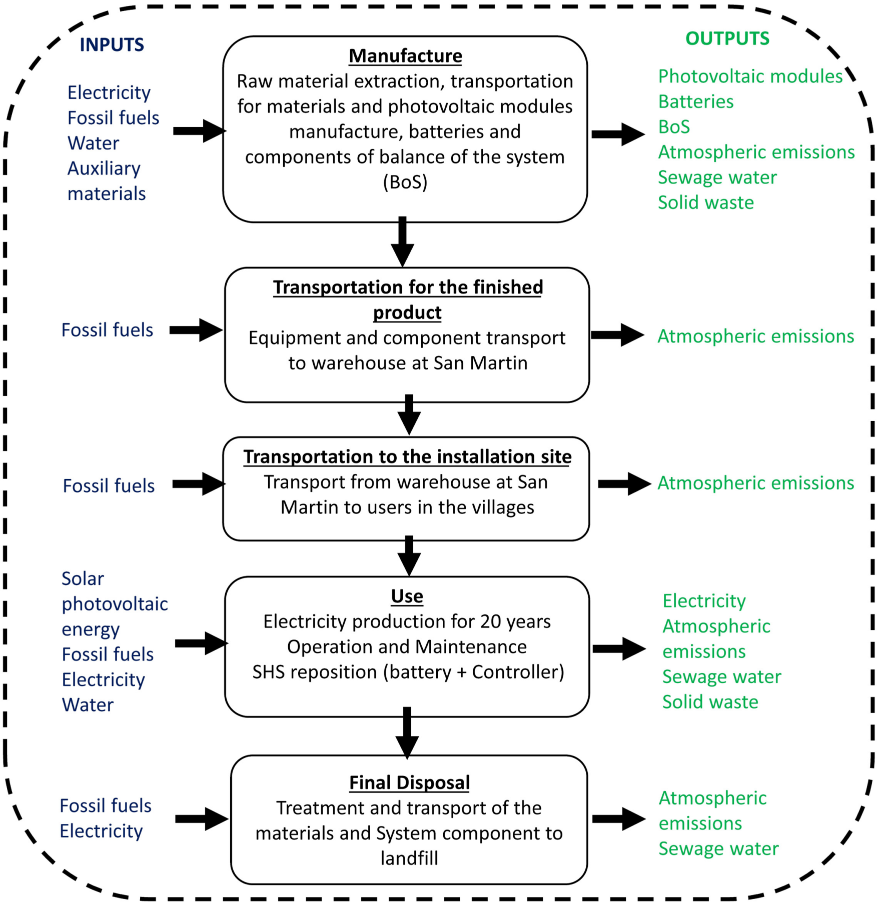

Figure 2. Project boundaries for the LCA under study [15].

stages of production that the system requires to produce the services [16], in this case the electricity supplied by the HSP. Besides, it works as the reference basis for all calculations regarding impact assessment [17] and, given that the function of the HSP is electricity production, the defined FU is the kWh of electricity generated for self-consumption from the DC-Coupled stand-alone system. As result, the CF and WF will be referenced to this unit.

3.2. Inventory Analysis

The quantification of the matter and energy flow in the LCA of a product is carried out in the inventory stage; it is called Life Cycle Inventory Analysis (LCI). Ideally, the materials and energy data collected during a LCI are fully specified. That is, the units of energy consumed (L, kWh, m^3 and kg) and the specific consumption of material (kg) are indicated [5] [18]. For this reason, this study focused on collecting all the material, transport, water and energy consumed data for a product manufacture or service within the system boundaries shown in **Figure 2**, which are necessaries to produce 1 kWh of electricity through HPS.

As well, the data collected was used as an input for the corresponding processes e.g., the PV module manufacture or PV module transport to San Martin region. Additionally, these processes were grouped into the four stages or main process mentioned above (integration, O&M and collection, reposition and final disposal) as shown in **Figure 3**.

On the other hand, this study used the Open-Source Life Cycle Assessment (open LCA v.1.10.3), a software created by the Germany company GreenDelta GmbH, a tool with an extensive database supported by several institutions throughout the world (NEEDs, LCA, Environmental Footprints). It also includes a complete package of impact assessment methods, which can be used along with many databases such as Ecoinvent 3, GaBi and ELCD.

3.2.1. Integration Process

Is a first stage carried out for the development of the rural concession and it includes the manufacture of all materials and products required by the system at the first year, as well as the transport and the installation of the system in rural dwellings.

For practical purposes the processes listed below, from A to F, were grouped as sub-processes of the Integration stage or process.

1) Photovoltaic module manufacturing

The 120Wp Multi-Crystalline Photovoltaic Module comes from the city of Shenzhen in China. Therefore, for purposes of the LCA, the data of the unit process for a 1 m^2 photovoltaic module manufactured in that country was taken into account, based on "Life Cycle Inventories and Life Cycle Assessments of Photovoltaic systems 2020" [19] report of the International Energy Agency (IEA) PVPS, task 12 which appears in **Table 2**. These values were introduced as inputs and outputs, as appropriate, for the 1 m^2 photovoltaic module manufacturing process.

2) Solar Home System Manufacture

The SHS is a product integrated by different equipment, such as the $LiFePO_4$ battery, BMS, solar charger, cables, breakers, and minor components (rail DIN), all installed inside an ABS box.

Given that the total weight of the product (7.3 kg) is available, calculations were made based on the measurements of the components in order to obtain the kg of each of them (electrical conductors, DIN rail and ABS casing). The lithium battery analyzed with the weight indicated in its technical sheet. On the other hand, the weight of the breakers is not available in the database; therefore, it was

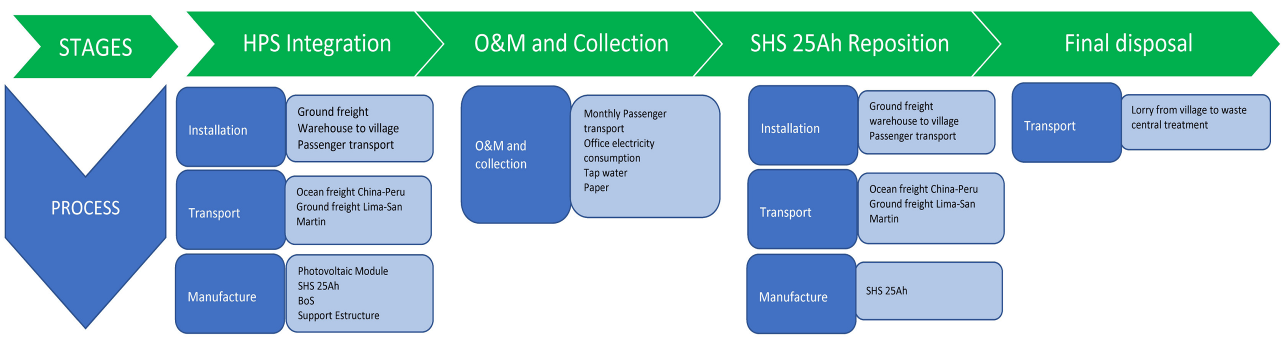

Figure 3. Stage and process for a 1 kWh HPS production.

Table 2. LCI data of the unitary process for the manufacture of 1 m^2 of photovoltaic module [19].

OpenLCA Inputs	Location	Unit	Amount
Photovoltaic cell, Multi-Si, at plant	CN	m^2	9.35E−01
Aluminium alloy, $AlMg_3$, at plant	RER	kg	2.13E+00
Wire drawing, copper	RER	kg	1.03E+01
Diode, unspecified, at plant	RER	kg	1.03E+01
Silicone product, at plant	GLO	kg	2.81E−03
Tin, at regional storage	RER	kg	1.22E−01
Lead, at regional storage	RER	kg	1.29E−02
Solar glass, low-iron, at regional storage	RER	kg	7.25E−04
Tempering, flat glass	RER	kg	8.81E+00
Glass fiber reinforcer plastic, polyamide, injection moulding, at plant	RER	kg	2.95E−01
Polyethylene terephthalate, granulate, amorphous, at plant	RER	kg	3.46E−01
Polyethylene, HDPE, granulate, at plant	RER	kg	2.38E−02
Ethyl vinyl acetate, foil, at plant	RER	kg	8.75E−01
Polyvinyl fluoride film, at plant	US	kg	1.12E−01
Tap water, water balance according to MoeK 2013, at user	CN	kg	5.03E+00
Hydrogen fluoride, at plant	GLO	kg	6.24E−02
1-propanol, at plant	RER	kg	1.59E−02
Isopropanol, at plant	RER	kg	1.47E−04
Potassium hydroxide, at regional storage	RER	kg	5.14E−02
Soap, at plant	RER	kg	1.16E−02
Corrugated board, mixed fiber, single wall, at plant	RER	kg	7.63E−01
EUR-flat pallet	RER	unit	5.00E−02
Electricity, medium voltage, at grid	CN	kWh	1.40E+01
Diesel, burden in building machine, average	CN	MJ	8.75E−03
Transport, freight, lorry, fleet average	RER	t·km	3.01E+00
Transport, freight, rail	RER	t·km	1.66E+01
Disposal, municipal solid waste, 22.9% water, to municipal incineration	CN	kg	3.00E−02
Disposal, polyvinylfluoride, 0.2% water, to municipal incineration	CN	kg	4.29E−03
Disposal, plastic, mixture, 15.3% water, to hazardous waste incineration	CN	kg	2.81E−02
Disposal, used mineral oil, 10% water, to hazardous waste incineration	CN	kg	1.61E−03
Treatment, sewage, from residence to wastewater treatment, class 2	CN	m^3	4.53E−03
Heat, waste	-	MJ	5.03E+01
NMVOC, non-methane volatile organic compounds, unspecified origin	-	kg	8.06E−03
Carbon dioxide, fossil	-	kg	2.18E−02
Water, CN	-	kg	5.03E−01

CN: China.

decided to introduce the material that makes up the shell (polypropylene) and equal it to the total weight of the breaker (0.243 kg). The cardboard box that packs the equipment and the plate that makes up the BMS were also added [19].

All these components have been referenced to the city of the Shandong in China, place of manufacture of the SHS. The inputs are shown in **Table 3**.

3) Supporting structure

The supporting structure was made for steel galvanized profiles, so the inventory analysis included the calculation of the weight of materials and the m^2 of zinc coating, as well as the transport from the workshops, which have been considered at Lima, Peru, to the main warehouse in San Martin region.

The total weight of the Support structure is 21.5 kg and the distance from Lima to San Martin warehouse is 1228 km. The inputs are shown in **Table 4**.

4) Balance of System (BoS)

These are minor components that complement the HPS. They include the LED lightbulbs manufactured in Shandong, in China, to which the sea freight to Lima, Peru, was added. The other materials that make up the BoS were considered global processes for the city of Lima in Peru. Subsequently, the t·km to the main warehouse at San Martin were calculated, taking into account the total weight (14.47 kg) of the BoS and the kilometers from Lima to the warehouse (1228 km), distance calculated by Google Maps [20]. Finally, both the manufacture and t·km were considered as inputs in the process, and they are shown in **Table 5**.

Table 3. Inputs for the 25 Ah SHS production, in China.

OpenLCA Inputs	Unit	Quantities
Add Acrylonitrile Butadiene Styrene (ABS) GLO	kg	3.05
Battery, Li-ion, rechargeable, prismatic {GLO}|market for	kg	3.00
Cable, unspecified {GLO}|	kg	0.03
Printed wiring board, through-hole mounted, unspecified, Pb free GLO	kg	0.08
Steel Sheet part	kg	0.13
Polypropylene, granulate {GLO}| market for	kg	0.49
Carton board box production {GLO}| market for	kg	0.12

GLO: Global.

Table 4. Inputs to produce a 120Wp HPS support structure, transporting to warehouseat San Martin, Peru.

OpenLCA Inputs	Unit	Quantities
Steel, low alloyed {GLO}| market for	kg	21.5
Zinc coat, pieces	m^2	1.96
Transport, freight, lorry 16 - 32 metric ton, EURO 3 {GLO}| market for	t·km	26.40

Table 5. Inputs, BoS for one 120Wp HPS.

OpenLCA Inputs	Unit	Quantities
Cables, unspecified {GLO}| production	kg	4.18
Extrusion, plastic pipes {GLO} market for	kg	5.29
Polyvinyl chloride, bulk polymerized {GLO}| market for	kg	0.55
Steel cold rolled coil	kg	0.75
Add imported Taiwanese Galvanized Steel Bolt Screw	kg	0.40
Indoor LED lamp, 3 - 5 W, at Lima	item	1.00
Transport, freight, lorry 16 - 32 metric ton, EURO5 {GLO}|market for	t·km	14.47

5) Transports

Since the specific information related to raw material transport for SHS manufacture is not available, this study used ECOINVENT, World steel and ELCD databases, considering that materials were obtained in China.

Then, the weight of photovoltaic module and SHS, as well as the kilometers of sea and land transport from the factories in China to seaports (both Peru and China), and from these to the main warehouse located in San Martin were calculated. For travelled sea distances, Searates [21] was used. The route is shown in Figure 4.

As well, given that the multi-crystalline photovoltaic module manufacturing process is referred for a 1 m^2 and the 120Wp module employed for the studied HPS has 0.81 m^2, it is necessary to indicate this amount as an input for the new process. Thus, the environmental impact related to the manufacture of 120Wp module can be define, and with the addition of the t·km involved in all the route, from China to San Martin region, the impact of locating this module at the main warehouse is established. Table 6 shows the inputs for the process of a 120Wp photovoltaic module at warehouse in San Martin. On the other hand, Table 7 shows the inputs for a process of a 25 Ah SHS located at San Martin's warehouse.

6) Installation

This stage encompasses every aspect related to the installation of the HPS, including the transport of materials from the main warehouse to the users' households and the transfer of personnel.

Given that the beneficiary' villages are located in isolated areas difficult to access, to determine the tons per km transported from the main warehouse, the km traveled have been calculated based on the monthly movement of O&M crews. This value amounts to 2843.6 km and, on the other hand, the total weight of the 120Wp HPS is 49.59 kg (photovoltaic module, 25 Ah SHS, support structure and BoS equipment). Likewise, the transfer of staff employed during the project was obtained with the average distance traveled by the O&M team registered by the concessionary. The inputs are shown in Table 8.

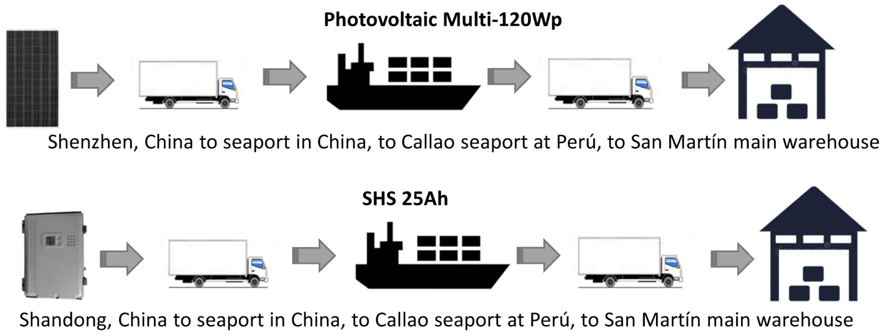

Figure 4. Transport scheme used.

Table 6. Inputs for a process of a 120Wp Photovoltaic module at warehouse in San Martin.

OpenLCA Inputs	Unit	Quantities
Photovoltaic Multi-Si panel, production, at plant CN-GD	m^2	0.81
Transport, freight, lorry >32 metric ton, EURO4 {GLO}|market for	t·km	0.47
Transport, freight, sea, transoceanic ship {GLO}| market for	t·km	169.20
Transport, freight, lorry >32 metric ton, EURO3 {GLO}| market for	t·km	8.81

N-GD: Guangdong in China.

Table 7. Inputs for SHS at warehouse in San Martin.

OpenLCA Inputs	Unit	Quantities
SHS 25 Ah, production at plant-CN-SD	Item	1
Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for	t·km	0.0073
Transport, freight, sea, transoceanic ship {GLO}| market for	t·km	130.45
Transport, freight, lorry >32 metric ton, EURO3 {GLO}| market for	t·km	7.15

CN-SD: Shandong in China.

Table 8. Inputs for installation process.

OpenLCA Inputs	Unit	Quantities
Transport, freight, lorry, unspecified {GLO}| market for	t·km	140.99
Transport, passenger car, medium size, diesel, EURO 4 {GLO}| market for	m	473.88

Finally, all abovementioned processes—photovoltaic module manufacture, SHS manufacture, supporting structure—are sub processes that make up the HPS integration process in the village's household, as shown in Table 9.

Table 9. Inputs for Integration process.

OpenLCA Inputs	Unit	Quantities
Installation, 120Wp HPS, at San Martin-PE	Item	1
BoS, SFD 120Wp, at San Martin-PE	Item	1
Panel Support Structure, 120Wp module, at San Martin-PE	Item	1
SHS 25 Ah, at San Martin-PE	Item	1

PE: Peru.

3.2.2. O&M and Tariff Collection Process

This stage includes the Operation and Maintenance (O&M) works and the monthly collection to the users for being a rural concession. For this, it is important to consider the management input, that is: the electrical energy of the office; receipt paper; staff transportation; and water for consumption and cleaning. The information has been provided by a concessionary company and the quantities calculated for 20 years of a 120Wp HPS operation. The inputs are shown in Table 10.

3.2.3. Reposition Process

The SHS includes components with a 10-year useful life and, since the analysis horizon is 20 years, these components are eventually refitted. Thus, the transport of a new SHS from China to the main warehouse at San Martin and the installation must be considered. It is important to note that the SHS can be transported with the installation staff, a passenger car, from the main warehouse to the users' households. Table 11 shows the inputs for this process.

3.2.4. Final Disposal Process

It covers the "end of life" stage and implies the HPS total dismantling and the transport of components for treatment, disposal or recycle, as appropriate. Therefore, it takes in account all the environmental impact resulting from the removal, transport to a treatment plant and final disposal of the HPS components; for this case, the study considers a treatment plant located in Tarapoto, a district in San Martin region, 6.4 km from main warehouse.

According to the PVPS Task 12, in silicon modules, only 75% of glass, 21.8% of non-ferrous metals are recovered [19]. On the other hand, the SHS will be disposed in the waste center in two cases: the galvanized steel support structures are 100% recovered and the materials that make up the BoS will remain in the households because they can be reused for a new system, or for a future connection to the conventional electrical network—with the exception of 5 W LED lighting which only casing aluminum will be recycled. For this reason, the materials that will be transported to the treatment plant are the same as those shown in Table 2 and Table 3, manufacturing of photovoltaic module and SHS, considering glass and non-ferrous metals recovering mentioned above (according PVPS Task 12) and the amount of m^2 corresponding to a 120Wp PV module and the reposition of 25 SHS. Then, given that the installation had a route of

Table 10. Inputs for O&M and monthly tariff collection process.

OpenLCA Inputs	Unit	Quantities
Electricity, low voltage {PE}| market for	kWh	10.025
Paper	kg	0.8
Transport, passenger car, medium size, diesel, EURO 4 {GLO}| market for	m	113.73
Tap water {GLO}| market group for	kg	5.48
Water	kg	0.013

Table 11. Inputs for SHS reposition.

OpenLCA Inputs	Unit	Quantities
SHS 25 Ah, production at plant-CN-SD	item	1
Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for	t·km	0.0073
Transport, freight, sea, transoceanic ship {GLO}| market for	t·km	130.45
Transport, freight, lorry >32 metric ton, EURO3 {GLO}| market for	t·km	7.15
Transport, passenger car, medium size, diesel, EURO 4 {GLO}| market for	m	473.88

2843.6 km the traveling for disposal will be 2850 km.

In the case of steel, the transportation of the structures to the disposal site was considered (21.5 kg), but, due to the possibility to reuse it with no additional processing, its treatment was not. All the transport inputs are shown in Table 12, and it obtained 6.14E−02 total t·km.

4. Analysis Methodology

As a part of the systematic LCA, it is necessary to carry out an impact assessment on the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis [22]. Therefore, it is necessary to establish a methodology that allows defining, understanding, and evaluating the environmental implications of the process inputs and outputs, based on the selected environmental impact category [15].

The purpose of this study is to obtain the amount of equivalent CO_2 emissions produced by the 120Wp HPS rural concession in San Martin region. Therefore, the global warning potential (GWP) category must be used, according to the ILCD midpoint 2011 method [23]. The pollutants associated to the entire process can be represented quantitatively in units corresponding to the studied impact category, *i.e.*, kg CO_2 eq [24], of so-called Carbon Footprint (CF), see Table 13.

On the other hand, the Water Footprint (WF) is the amount of the human freshwater appropriation. This is measured in terms of water volume consumed

Table 12. Transport inputs for a 120Wp HPS waste treatment.

Waste	OpenLCA Inputs	t·km
Glass	Transport, freight, lorry, unspecified {GLO}| market for	1.02E+01
Silicon	Transport, freight, lorry, unspecified {GLO}| market for	2.44E+00
Aluminum	Transport, freight, lorry, unspecified {GLO}| market for	5.39E+00
Copper	Transport, freight, lorry, unspecified {GLO}| market for	3.74E+00
Plastics	Transport, freight, lorry, unspecified {GLO}| market for	2.04E+01
Polyethylene	Transport, freight, lorry, unspecified {GLO}| market for	8.50E+01
Tin	Transport, freight, lorry, unspecified {GLO}| market for	2.33E−02
Lead	Transport, freight, lorry, unspecified {GLO}| market for	1.31E−03
Electronic Material	Transport, freight, lorry, unspecified {GLO}| market for	6.30E−01
Polypropylene	Transport, freight, lorry, unspecified {GLO}| market for	2.79E+00
Steel	Transport, freight, lorry, unspecified {GLO}| market for	6.20E−01

Table 13. Impact category and acronyms used in ILCD midpoint 2011 [23].

Impact Category	Acronym	Unit	
Global warming potential	GWP	kg CO_2 eq	kilograms of carbon dioxide equivalent
Particulate matter	PM	kg PM2.5 eq	kilograms of particulate matter suspended of less than 2.5 microns
Human toxicity, non-cancer effects	HTNCE	CTUh	comparative toxic units for human toxicity
Photochemical ozone formation	POF	kg NMVOC eq	kilograms of non-methane volatile organic compounds equivalent
Marine eutrophication	EUTM	kg N eq	kilograms of nitrogen equivalent.
Terrestrial eutrophication	EUTT	molc N eq	moles of nitrogen equivalent
Freshwater ecotoxicity	FRWTOX	CTUe	comparative toxic units for aquatic ecotoxicity
Ozone depletion	QDP	kg CFC-11 eq	kilograms of trichlorofluoromethane equivalent
Ionizing radiation E (interim)	IRE	CTUe	comparative toxic units for aquatic ecotoxicity
Ionizing radiation HH	IRHH	kBq U235 eq	kilobecquerel of uranium 235 for ionizing radiation
Acidification	AC	molc H^+ eq	moles of hydrogen ion equivalent
Human toxicity, cancer effects	HTCE	CTUh	comparative toxic units for human toxicity
Water resource depletion	WD	m^3 water eq	cubic meters of water equivalent
Freshwater eutrophication	EUTF	kg P eq	kilograms of phosphorus equivalent
Mineral, fossil & ren resource depletion	MFRRD	kg Sb eq	kilograms of antimony equivalent
Land use	LU	kg C deficit	kg of carbon deficit

(evaporated or incorporated into a product) or polluted per unit of time [25]. For this reason, carrying out the LCA of a product and determining its potential environmental impact is not enough, but it is also necessary to know both the consumption and pollution of water that has been derived from its manufacture, transport, installation, operation, and final disposal. This study used, the Berger *et al.* 2014 method [7] [26] focused on water scarcity.

5. Results

The entire analysis is composed by different main processes (stages) and sub-processes. The main processes are Integration, O&M, reposition of the 25 SHS and final disposal of the material; each of these processes is considered to produce electricity for 20 years, which according to the **Table 1** defined by Peruvian government, the total amount of energy delivered will be 2484 kWh. Therefore, the production of 1 kWh of energy by the studied 120Wp HPS requires 4.026E−04 units of each stage, or main processes is shown in **Table 14**.

It is important to clarify that the amount of energy (2484 kWh) is a value stablished by the BT8 tariff fixed by the government. It does not take into account the real production capacity of a 120Wp system, which is around 3036 kWh considering a 0.82 PR, 1651.11 kWh/m^2 yr [27] and 0.8% of annual degradation instead of the 1262 kWh/m^2 yr deemed by the government.

Table 14. Inputs for a 1 kwh electricity production through 120Wp HPD.

OpenLCA Inputs	Unit	Quantities
120Wp HPS Integration process	item	4.026E−04
O&M and tariff monthly collection process	Item	4.026E−04
25 Ah SHS reposition process	Item	4.026E−04
Final disposal process	t·km	6.14E−02

5.1. Carbon Footprint

For each kWh produced by the HPS a 0.14616 kg CO_2 was obtained; in this case, the most prevalent stage is Integration, with a 0.10145 kg CO_2 eq (69.41%), since it includes the manufacture of all the components, transport, and installation. The second most prevalent stage is Reposition with a 0.02084 kg CO_2 eq (14.26%), followed by O&M stage, with 0.01582 kg CO_2 eq. (10.82%) and final disposal stage, with 0.00805 kg CO_2 eq (5.51%). The result for each stage and the sub-processes it comprises appears in **Table 15**.

Besides, the entire international and national transport sub-process, used across the 20 years of useful HPS, contributes 0.03513 kg CO_2 eq (24.04%); and the 120Wp PV module and 25 Ah SHS manufacturing, including reposition, contribute 0.02804 (19.2%) and 0.03986 (27.3%) kg CO_2 eq., respectively. The BoS contributes 0.02183 (14.94%) and the supporting structure 0.01945 (13.31%).

The Sankey diagram for CF is shown in **Figure 5** and the contribution, in percentage, of main sub processes of each stage is shown in **Figure 6**.

Table 15. GWP for each subprocess and stage.

Sub processes	GWP (kg CO_2 eq)
120Wp HPS, integration, at San Martin-PE	**0.10145**
Photovoltaic Multi-Si panel, production, at plant-CN-GD	0.02804
SHS 25Ah, production at plant-CN-SD	0.01993
Market for steel, low-alloyed-GLO	0.01399
Steel Cold rolled coil Global, production mix	0.01275
Market for transport, freight, lorry, unspecified-GLO	0.00744
Cable production, unspecified-GLO	0.00624
Zinc coating, pieces-RER	0.00546
Market for transport freight, lorry 16 - 32 metric ton, EURO3-GLO	0.00274
Market for transport freight, sea, transoceanic ship-GLO	0.00136
Indoor LED Lamp, 3 - 5 W, at Lima	0.00114
Market for extrusion, plastic pipe-GLO	0.00083
Market for transport, freight, lorry >32 metric ton. EURO 3-GLO	0.00058
Market for polyvinylchloride, bulk polymerized-GLO	0.00048
Add Imported Taiwanese Galvanized Steel Bolt Screw	0.00039
Market for transport freight, lorry >32 metric ton, EURO4-GLO	1.7089E−05
Market for transport, passenger car, medium size, diesel, EURO 4-GLO	5.82346E−05
25 Ah SHS Reposition, at San Martin-PE	**0.02084**
SHS 25 Ah, production at plant-CN-SD	0.01993
Market for transport freight, sea, transoceanic ship-GLO	0.00059
Market for transport freight, lorry >32 metric ton, EURO3-GLO	0.00026
Market for transport freight, lorry >32 metric ton, EURO4-GLO	2.51649E−07
Market for transport, passenger car, medium size, diesel, EURO 4-GLO	5.82346E−05
O&M and tariff monthly collection, 120Wp HPS, at San Martin-PE	**0.01583**
Market for transport, passenger car, medium size, diesel, EURO 4-GLO	0.01398
Market for electricity, low voltage-PE	0.00157
Paper	0.00028
Market for tap water-RoW	1.49E−06
Market for transport, freight, lorry, unspecified-GLO	**0.00805**

RER: Europe, RoW: Rest of the World.

5.2. Water Footprint

To produce 1 kWh of electricity via a 120Wp HPS a 0.00053 m^3 of water was determined as necessary. As in CF, Integration is the prevalent stage with 3.8264E−04 m^3 (72.38%) but O&M is most predominant than Reposition, with 8.0471E−05 m^3 (15.22%) versus 5.3957E−05 m^3 (10.21%). Finally, the Final

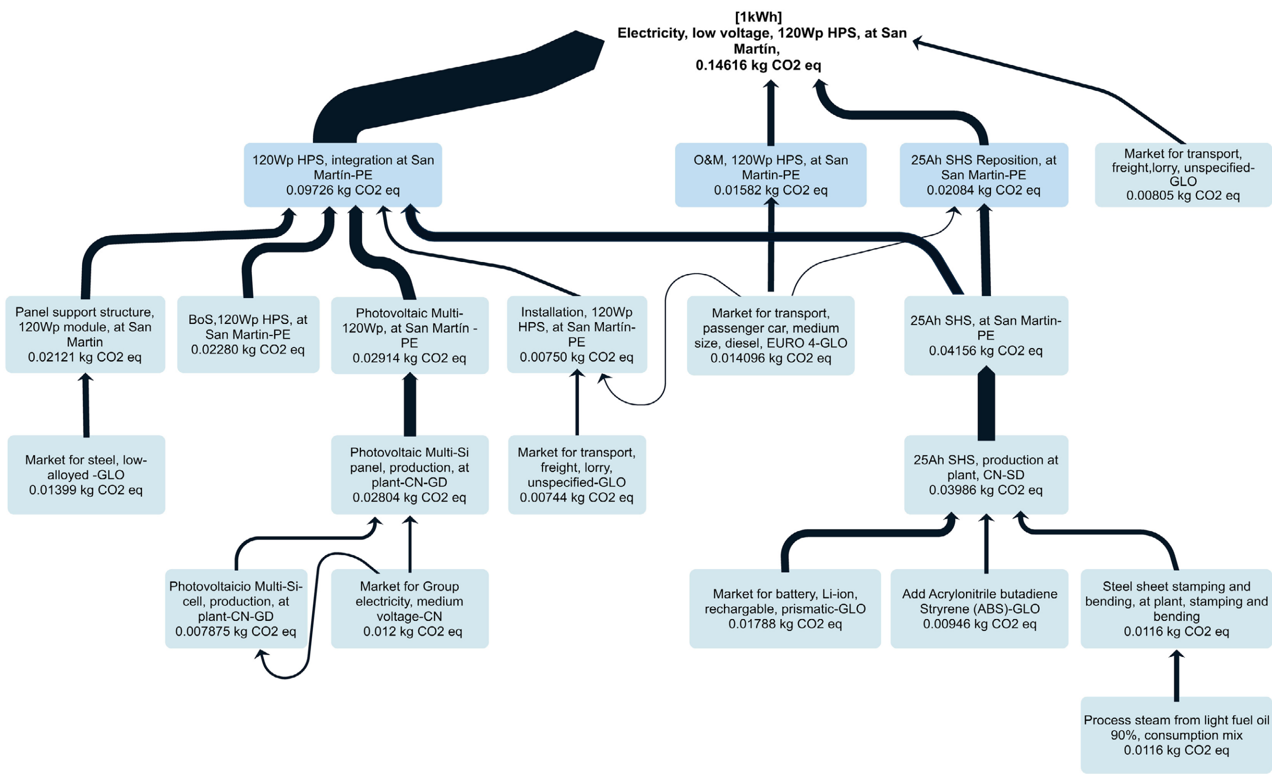

Figure 5. Sankey diagram for climate change category for the production of 1 kWh of electricity using 120Wp HPS.

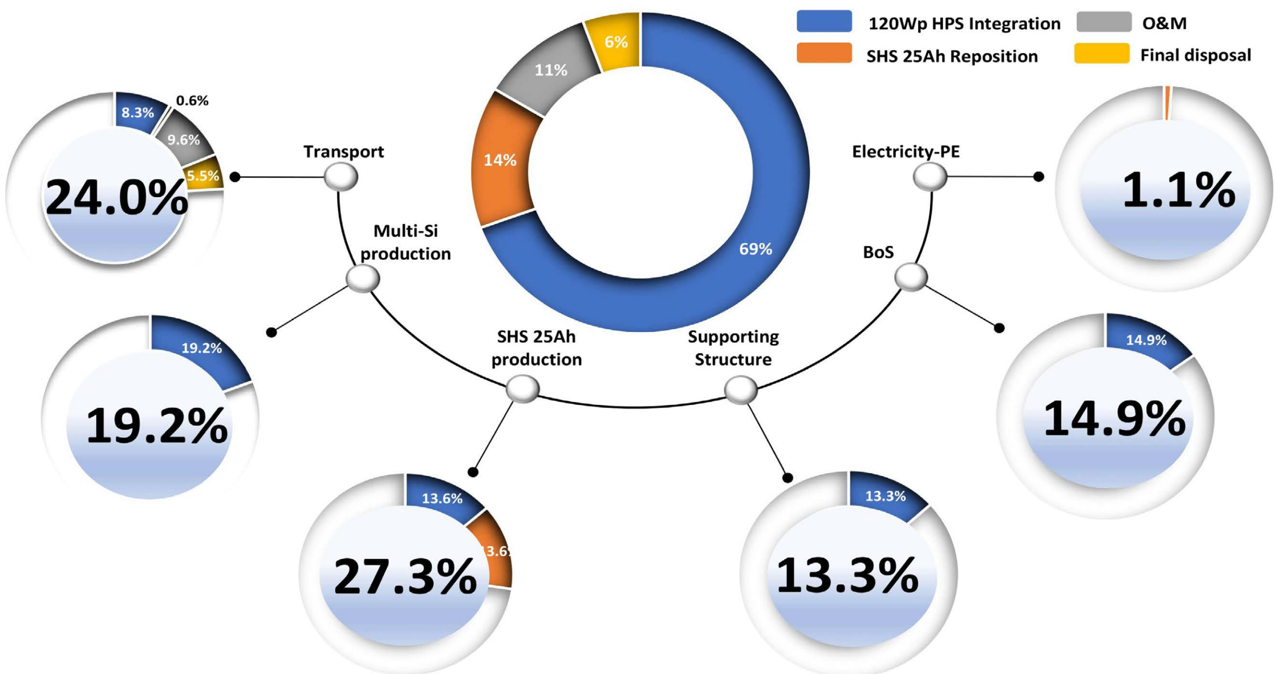

Figure 6. Carbon footprint distribution for each process involved for the production of 1 kWh of electricity using 120Wp HPS.

disposal only contributes with 1.1587E−05 m^3 (2.19%). These results are shown in Table 16.

Unlike the CF results, the 120Wp HPS manufacture presents a higher impact

Table 16. Water footprint for each subprocess and stage.

Sub processes	Water footprint (m^3)
120Wp HPS integration, at San Martin-PE	3.8264E−04
Photovoltaic Multi-Si panel, production, at plant-CN-GD	1.5000E−04
SHS 25 Ah, production at plant-CN-SD	5.2690E−05
Market for steel, low-alloyed-GLO	5.2330E−05
Cable production, unspecified-GLO	4.9591E−05
Zinc coating, pieces-RER	2.2974E−05
Market for polyvinylchloride, bulk polymerized-GLO	2.2493E−05
Market for extrusion, plastic pipe-GLO	1.1139E−05
Market for transport, freight, lorry, unspecified-GLO	1.0712E−05
Indoor LED Lamp, 3 - 5 W, at Lima	4.2516E−06
Market for transport, freight, lorry 16 - 32 metric ton. EURO3-GLO	3.7030E−06
Market for transport freight, sea, transoceanic ship-GLO	1.7217E−06
Market for transport freight, lorry >32 metric ton, EURO3-GLO	8.9862E−07
Market for transport, passenger car, medium size, diesel, EURO 4-GLO	1.1515E−07
Market for transport freight, lorry >32 metric ton, EURO4-GLO	2.65E−08
O&M and tariff monthly collection 120Wp HPS at San Martin-PE	**8.0471E−05**
Market for electricity, low voltage-PE	5.1321E−05
Market for transport, passenger car, medium size, diesel, EURO 4-GLO	2.7635E−05
Market for tap water-RoW	1.3072E−06
Paper	2.0832E−07
25 Ah SHS Reposition at San Martin-PE	**5.3957E−05**
SHS 25 Ah, production at plant-CN-SD	5.2690E−05
Market for transport freight, sea, transoceanic ship-GLO	7.4999E−07
Market for transport freight, lorry >32 metric ton, EURO3-GLO	4.0245E−07
Market for transport freight, lorry >32 metric ton, EURO4-GLO	4.07E−10
Market for transport, passenger car, medium size, diesel, EURO 4-GLO	1.1515E−07
Market for transport, freight, lorry, unspecified -GLO	**1.1587E−05**

than the 25 Ah SHS manufacture, each one has 1.5E−04 m^3 (28.4%) and 1.0538E−04 m^3 (19.93%), respectively followed by the BoS 8.7474E−05 (16.55%), the Supporting structure, 7.5304E−05 (14.24%) and all the transport, 5.77E−05 m^3 (10.91%).

The Sankey diagram for Water Footprint is shown in Figure 7 and Figure 8 shows the percentage of contributions of the most significant processes according to each impact category.

5.3. Comparison

The Peruvian energy mix is composed by 55.20% of hydric sources and 40.50%

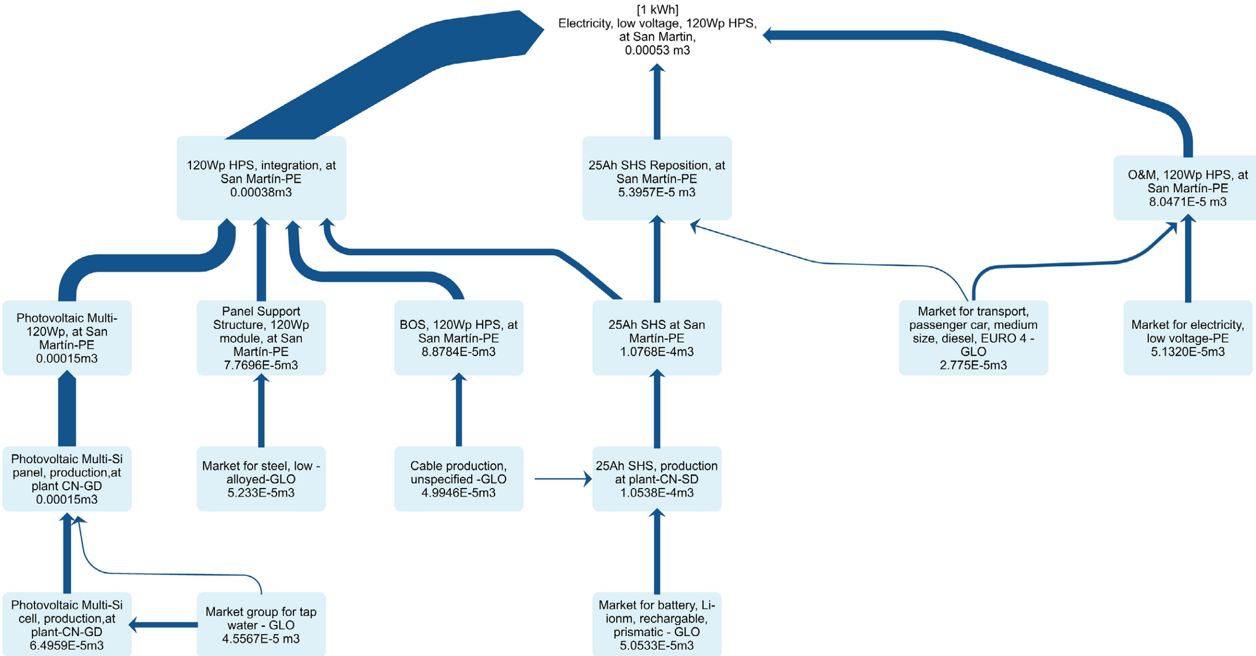

Figure 7. Sankey diagram of water footprint category for the production of 1 kWh of electricity using 120Wp HPS.

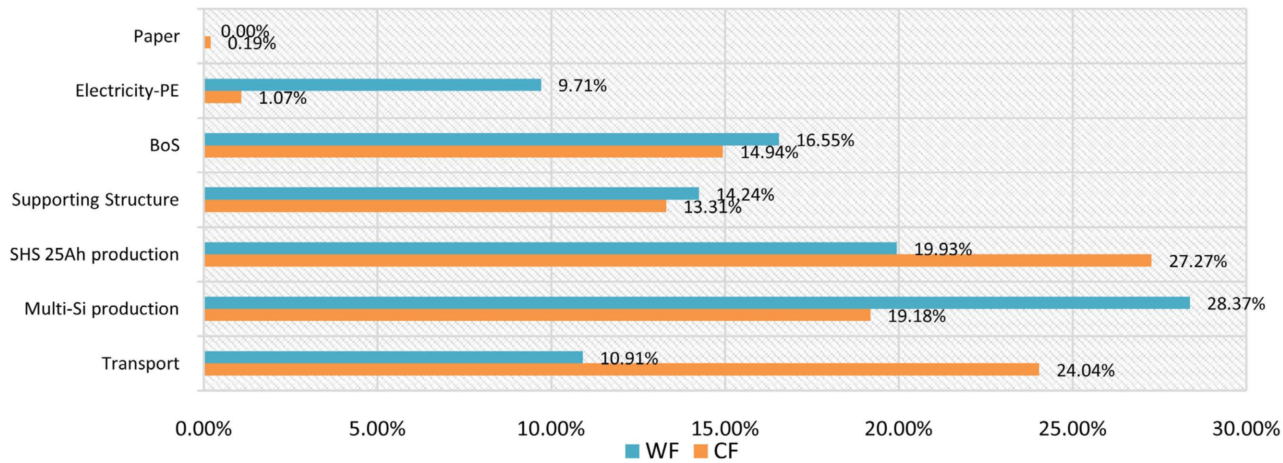

Figure 8. Contributions percentage of the most significant processes according to each impact category.

of fossil fuels [28] and presents a 0.4119 kg CO_2 eq/kWh of carbon footprint of electrical energy for residential uses [29]. The water footprint was obtained via Open LCA simulation, using the ECOINVENT databases, for a low voltage production and the value is 0.01272 m^3. Thus, it is possible to compare the results obtained from the HPS within the country's mix, which is shown in Figure 9.

5.4. Energy Payback Time (EPBT)

The energy payback time is a value that indicates the time required by the photovoltaic system, as a whole, to produce the same amount of energy used for its manufacturing [30], and due to the characteristics of the study, it also includes the O&M and the transport for final disposal. Therefore, for EPBT should

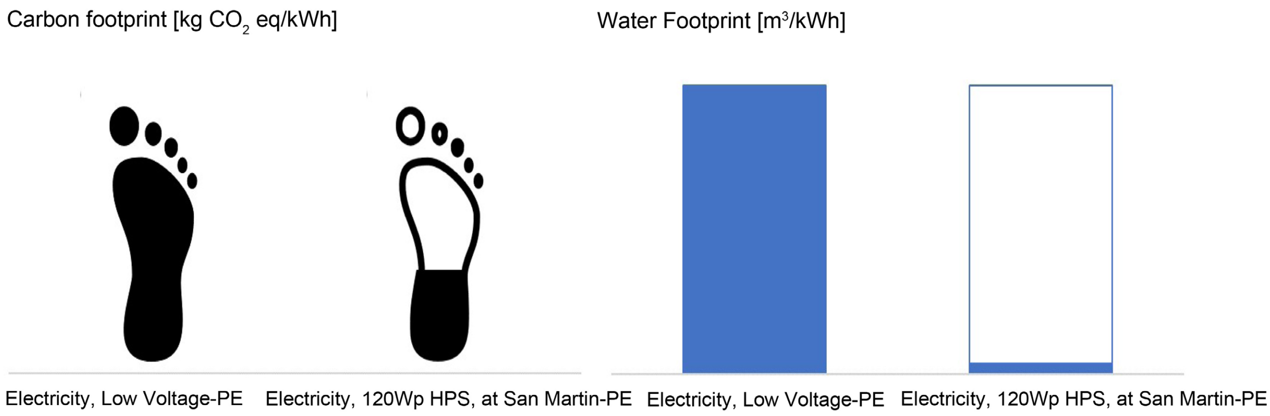

Figure 9. Carbon and water footprint comparison between Peruvian energy mix and 120Wp HSP.

compare the total primary energy content of the system, "Etot", with the corresponding average annual energy produced by it, "Ey", as shown in Equation (1) [31].

$$\text{EPBT} = \frac{\text{Etot}}{\text{Ey}} \quad (1)$$

Consequently, to obtain the amount of primary energy demanded by the 120Wp HPS throughout its 20 years of life (Etot), the Cumulative Energy Demand (CED) method, developed by Ecoinvent, was applied. This is a tool widely applied to investigate the energy use throughout the life cycle of a good or service [32]. The CED-indicator is split into eight subcategories, showing in **Table 17** (fossil, nuclear, primary forest, biomass, wind, solar, geothermal and water), for the Ecoinvent database, and have an intrinsic value determined by the amount of energy withdrawn from nature expressed in MJ-equivalents. [33].

Figure 10 illustrates the energy demand by subcategories used on each process, obtained by OpenLCA simulation through CED method. Non-renewable energy is the one with the highest demand, since the photovoltaic modules and SHS were produced in China, which energy mix is 55% coal [34], in addition to the stronger dependence to the transport during the entire project useful life.

CED value, is 1.27626 MJ/kWh and as mentioned before, the total produced energy of a 120Wp HPS throughout the useful life (20 years) is 2484 kWh whit is equal to an annual average (Ey) of 124.2 kWh/year (447.12 MJ). Therefore, to determine "Etot", Equation (2) is applied:

$$\text{Etot} = 1.27626 \frac{\text{MJ}}{\text{kWh}} \times 2484 \text{ kWh} = 3170.24\text{MJ} \quad (2)$$

Replacement "Etot" and "Ey" in Equation (1)

$$\text{EBPT} = \frac{\text{Etot}}{\text{Ey}} = \frac{3170.24 \text{ MJ}}{447.12 \text{ MJ/year}} = 7.09 \text{ years}$$

Hence, the energy retribution calculated is 7.09 years, time the HSP will take to produce the same value of energy employed to manufacture, transport, install and operate the entire system, including the SHS reposition. Likewise, total

Table 17. Impact assessment method Cumulative Energy Demand (CED) implemented in Ecoinvent [33].

Category	Subcategory	Includes
Non-renewable resources	Fossil	Hard coal, lignite, crude oil, natural gas, coal mining off gas, peat
	Nuclear	Uranium
	Primary forest	Wood and biomass from primary forests
Renewable resources	Biomass	Wood, food products, biomass from agriculture, e.g., straw
	Wind	Wind energy
	Solar	Solar energy (used for heats & electricity)
	Geothermal	Geothermal energy (shallow 100 - 300 m)
	Water	Run-of-river hydro power, reservoir hydro power

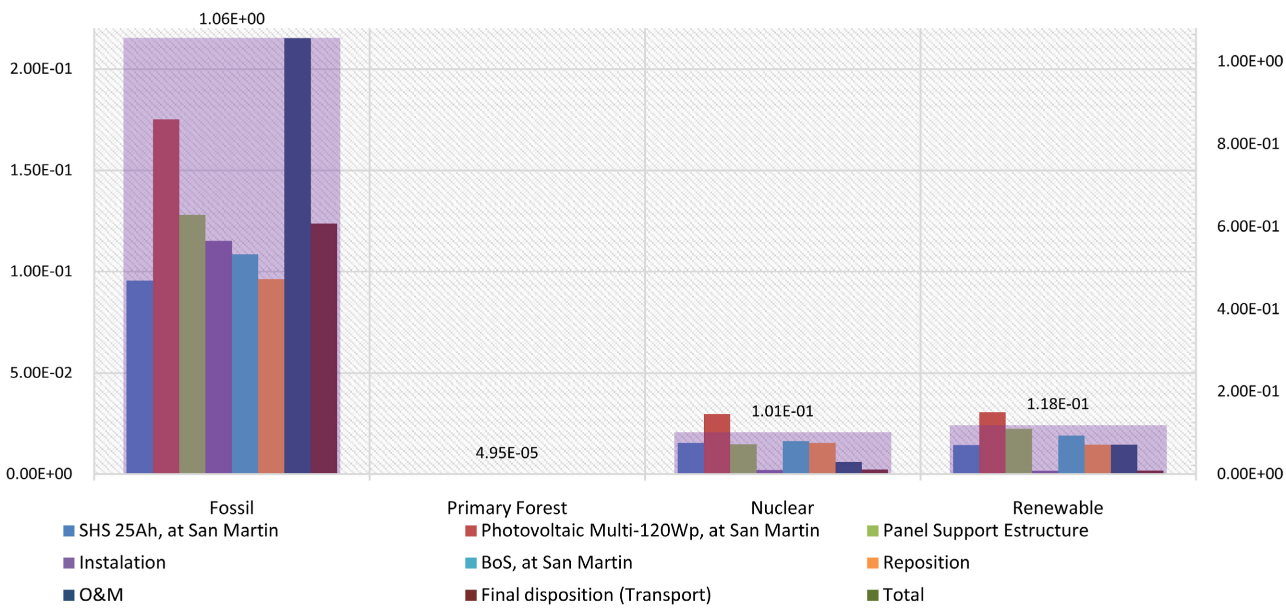

Figure 10. CED (MJ) by subcategories used on each process.

amount of primary energy required for a 120Wp HPS across the useful life is 3170.24 MJ.

Nevertheless, as stated before the energy deemed in the calculation is a value fixed by the government and does not take into account the real production capacity, so the EPBT decreases if the entire energy production of the PV generator is absorbed [31], since it depends on electricity production [35]. The two cases are presented in Table 18.

6. Discussion

The HSP has a 0.14616 kgCO_2 eq/kWh that represents a 34.11% of the carbon footprint for low voltage electricity delivered to the final users in Peru (0.4119 kg CO_2 eq/kWh). Likewise, the 0.00053 m^3 of HPS water footprint represents the 3.95% of the Peruvian energy mix (0.1272 m^3). Both values are compared in Figure 9.

Table 18. EPBT comparison for different 120Wp HPS energy production.

E20 (kWh)	kWh/kWp	CED	Etot (MJ)	Ey (MJ)	EPBT
2484	1035	1.27626	3170.24	447.12	7.09
3036	1265	1.06734	3240.45	546.48	5.93

E20: Total cumulative energy produced at year 20th.

Figure 5 and Figure 7, demonstrate that the highest CO_2 emissions and water footprint contributions occur in the integration stage 69% for CF (0.09726 of 0.14616 kg CO_2 eq/kWh) and 71% for WF (0.00038 of 0.00053 m^3).

On the other hand, in relation to CF, the entire transport involved contributes 24%; the manufacturing of batteries, including their replacement, 27.3%; and the photovoltaic module manufacture, 19.2%. Altogether they sum up 70.5% and it is mainly due to the material transfer from the port of Callao to the communities (where the end users are located), the change of batteries at year 10, and the predominance of fossil fuels in the energy source of the country where the devices were manufactured. This is also shown in Figure 10.

The WF results are quite similar to those obtained for CF. For them, the main contributors are the manufacturing and transport except for the Electricity during the O&M and collection stage, since it corresponds to the energy consumption of the HPS concessionaire office. It is important to explain, due to systems location in the Peruvian Amazon, water resources are not required for the photovoltaic modules' maintenance.

The resultant emission value is much higher than the average for photovoltaic plants at utility scale between 0.014 - 0.045 kg CO_2 eq/kWh [10] [36]. Nevertheless, due to the particular conditions of the rural concession of this study, such as transport, O&M, the inclusion of a SHS and its reposition, and the capacity of the HPS, which is made up of only one photovoltaic module, in contrast to a photovoltaic plant made up of thousands of them. On the contrary, the HPS values are below natural gas and coal carbon footprint, as shown in Figure 11. Besides, the results for CF are in the range of other Stand-alone systems, even rooftop or small-scale PV plants. See Table 19.

The calculation of the CF and WF was carried out in the same way that the EPBT, with a simulation of the real value of energy produced by the system; the values obtained were, 0.1204 kg CO_2 eq/kWh (17.62%) and 0.00044 m^3 (16.98%), respectively for each indicator. This is shown in Table 20.

The results in Table 20 shown the close relation between the energy delivered to users and the CF and WF impact category, which is inversely proportional [3] [11] [16] [38] [42].

Moreover, unlike other studies, where transportation has a contribution lower than 3.2% of CF [4] [9] [16] [42] [43], the case study presents a value of 24%. This proves the particularity of the analyzed system, where the distance and the monthly travels for the operation, maintenance, and billing of each HPS have an impact on the results.

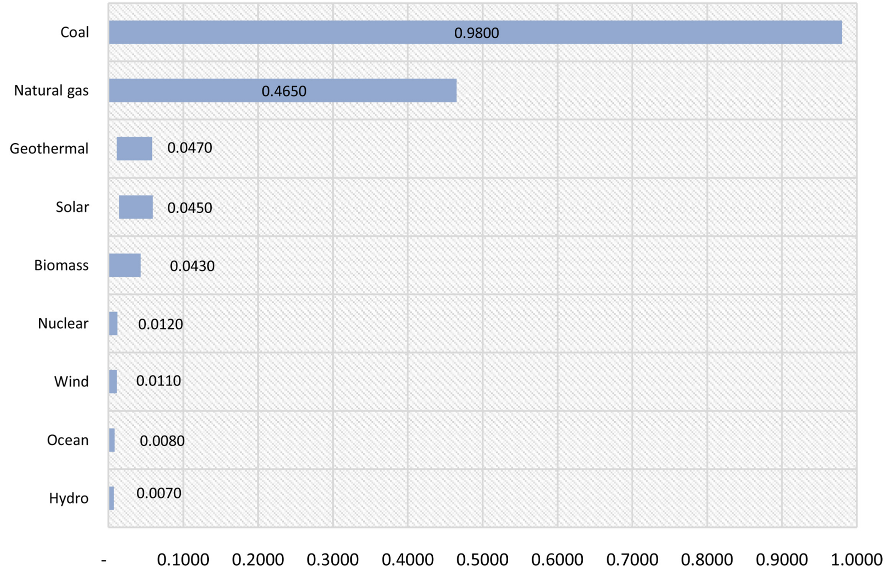

Figure 11. Estimated Carbon Footprint of energy sourcekg CO_2 eq/kWh [36].

Table 19. CF for photovoltaic systems.

Type	kg CO_2 eq/kWh	kWp	kWh/m²/yr	Reference
VLS-PV	0.052 - 0.071	10E5	2017	[10]
Rooftop	0.0364	3500	1700	[37]
-	0.053	3	1150	[16]
Stand-alone	0.029 - 0.068	12	1733	[38]
Rooftop	0.083	3	1427	[39]
Stand-alone	0.131	4.2	1932	[9]
Case study	0.1461	0.12	1262	
Stand-alone	0.173	3.6	1752	[40]
Rooftop	0.217	2.7	-	[41]
Stand-alone	0.583	0.049	1533	[42]
Stand-alone	0.6 - 1.2	-	1700	[11]

VLS-PV: Very large scale photovoltaic.

Table 20. CF and WF comparison for different 120Wp HPS energy production.

E20 (kWh)	kWh/kWp	WF (m^3)	CF (kgCO_2 eq/kWh)
2484	1035	0.00053	0.14616
3036	1265	0.00044	0.12104

On the other hand, unlike the CF result, the WF value is lower than other study cases, as shown in Figure 12. This difference is because the 120 HPS were installed in the Amazon Region, which presents abundant rainfall all season [44], so the hydric resource is not necessary during the O&M works.

Finally, regarding to the EBPT value obtained for the studied system, is higher than those found for large-scale and small-scale PV plants (1.2 kWp to 10 GWp), this does not occur when compared to Stand-alone PV systems, where the payback periods are between 3.5 to 15 years, as indicated in Table 21.

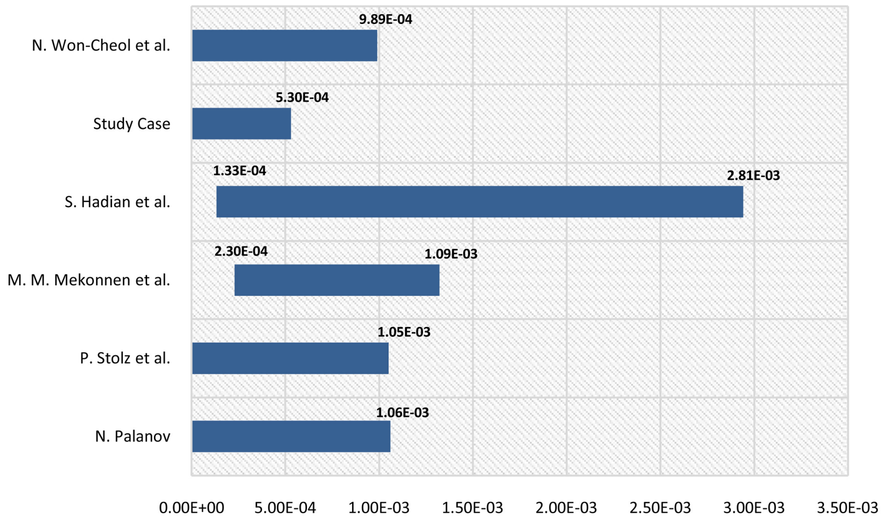

Figure 12. Comparison WF [m^3/kWh] between studies. N. Won Cheol *et al.* [45]; S. Hadian *et al.* [46], N. M. Mekonnen *et al.* [47], P. Stolz *et al.* [48], Palanov *et al.* [16].

Table 21. EPBT for photovoltaic systems.

Type	EPBT (yr)	kWp	kWh/m²/yr	Reference
VLS-PV	2.1 - 2.8	10E5	2017	[10]
Rooftop	2.2	3500	1700	[37]
-	2.3	3	1150	[16]
Rooftop	2.47 - 3.13	1.2	1506 - 1935	[43]
Stand-alone	3.5 - 6		1700	[31]
Stand-alone	4.61	3.4	1686	[49]
Stand-alone	5.34	3.6	1752	[40]
Rooftop	5.87 - 6.74	2.7	-	[41]
Stand-alone	9.08	4.2	1932	[9]
Case study	7.09	0.12	1262	
Rooftop	11.8	3	1427	[39]
Stand-alone	12	1	944.44	[50]
Thailand	15	720	1772	[2]

Consequently, the EPBT is a value related to irradiation, materials employed, transportation, installation and O&M method and electricity delivered to the users. However, although the payback time indicates the system efficiency to produce the amount of energy required during its useful life, the HPS and Stand-Alone Systems not only produce a cleaner energy but they provide a service scarce in rural areas. Therefore, the EPBT is a less meaningful indicator because the HPS are not primarily installed for the energy they produce but rather for the service they provide [11]. Likewise, calculated in relation to the source to be replaced, such as candles or kerosene lamps, the payback time will be different [42].

7. Conclusions

Throughout the stages of manufacturing, transportation, installation and 20 years of Operation, maintenance, and billing, the analyzed HPS presents environmental impacts in climate change category in amount of 0.14616 kg CO_2 eq/kWh and a 0.00053 m^3/kWh of water footprint. However, the use of these systems, compared to the electrical energy produced by Peruvian mix, reduces the emissions by approximately 659.99 kg CO_2 eq, and 30.27 m^3 of water consumption, considering the 2484 kWh delivered to users through 20 years.

On the other hand, the HPS requires 3,170.24 MJ of energy across its entire life useful and reaches this amount in 7.09 years.

Many factors influence the CF and WF, and, in this study, the particular conditions of the systems such as the equipment used, the site located far from the users and the energy delivered. For these reasons, the transportation process implies ~24% of the CF, while in other studies it only reaches 3.2%; or 11%, that implies the development of the O&M and tariff collection stage. Is the same case of energy provided, since taking into account the irradiance of the region, it is possible to obtain better results, but due to the user's characterization defined by the government, the value of delivered energy is limited. As is shown in the current study the simulation carried out improved the CF, WF and EB's results by around 17%, this demonstrates the close relation between the energy delivered to users and the impact category, which is inversely proportional.

Other factors to consider are the energy sources of the country where the devices were manufactured, both the panels and the batteries come from China where the energy matrix heavily depends on fossil fuels.

Additionally, this study establishes a point of comparison for others CF and WF analysis of an electrical rural concession operating through a PV Standalone system, and it could be interpolated to systems installed in different regions, like the Andes, and with different power. Also, could help the Peruvian government to promote the implementation of higher-power HPS, since it is an energy supply with lower impact on environment and a solution to the lack of basic services access. This will improve the life quality of inhabitants and will reduce the pollution inside homes caused by using candles. Besides, these systems will diversify the electricity generation in Peru.

Data Availability Statement

The data used in this study can be obtained by contacting the correspondence author.

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Data Availability Statement

The data used in this study can be obtained by contacting the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this manuscript.

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Abbreviations

BoS	Balance of System
BMS	Battery Management System
CED	Cumulative Energy Demanda
CF	CarbonFootprint
CN	China (region code)
CN-GD	Guangdong in China (region code)
CN-SD	Shandong in China (region code)
EPBT	Energy Payback Time
E20	Total produced energy at year 20th
FU	Functional Unit
GHG	Greenhouse Gases
GLO	Global (region code)
HPS	Household photovoltaic system
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
O&M	Operation and Maintenance
PE	Peru (region code)
RER	Europe (region code)
RoW	Rest of the World (region code)
SHS	Solar Home System
VLS-PV	Very large scale Photovoltaic
WF	Water Footprint