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Research paper

Solar photovoltaic technology in isolated rural communities in Latin America and the Caribbean

Bárbara Liz Miravet-Sánchez [a], Alberto E. García-Rivero [b,*], Ricardo A. Yuli-Posadas [c], Luis Alberto Inostroza-Ruiz [c], Victor Fernández-Guzmán [d], Yuli Anabel Chávez-Juanito [e], José Miguel Rutti-Marin [f], José Alfonso Apesteguia-Infantes [c]

[a] *Cubaenergia, CITMA, La Habana, Cuba*
[b] *EP Geografía, Facultad de Ciencias Sociales, Universidad Nacional Mayor de San Marcos, Lima, Peru*
[c] *Universidad Nacional Mayor de San Marcos, Lima, Peru*
[d] *Graduate School of Business, ESAN University, Peru*
[e] *Universidad Nacional Autónoma de Chota, Chota, Peru*
[f] *Universidad Nacional Intercultural de la Selva Central Juan Santos Atahualpa, La Merced, Peru*

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ABSTRACT

The main characteristics of photovoltaic (PV) energy and its current development in Latin American and Caribbean countries (LAC); its impact on the electrification of homes, health institutions, and schools in isolated or difficult-to-access communities; and, the advantages thereof are presented and discussed by replacing the use of traditional fuels such as firewood and kerosene in order to improve inhabitants 'health as well as reducing CO2 emissions. Countries like Nicaragua, Peru, Brazil, Argentina, and Chile stand out for their growing PV energy development in the region. A case study of the electrification process by PV systems shows very positive changes are manifested in terms of improving the quality of life of the inhabitants, and especially their physical and mental health state. In addition, CO_2 emission reductions from electrifying 216 houses in the nine communities reach an annual amount of 2,164.19 t/yr, reducing firewood consumption by 2,123.39 t/yr and kerosene consumption by 40.80 t/yr However, LAC countries must adopt laws and regulations that regulate the use of PV energy, with an emphasis on recycling systems at the end of their life cycle.

1. Introduction

Today, the commitment to sustainable energy, which includes improving energy efficiency and the use of renewable energy sources, has become a fundamental vector of sustainable development on a global scale, as well as the main factor for achieving a global agreement on climate change, as revealed at the United Nations Conference on Sustainable Development (Rio + 20) and at the 2012 Doha Climate Change Conference.

In the final document adopted by the governments at Rio + 20, called "The Future We Want", "improving energy efficiency, increasing the proportion of renewable energy, and using less polluting and energy-efficient technologies are basic elements for sustainable development, including to address climate change" is recognized.

Another way of taking advantage of solar energy is through generating electricity by means of photo voltaic (PV) domestic system. From the very beginning, this type of alternative to meet electricity needs was recommended to the rural sector due to the high cost of fuel prices; the growing environmental impacts that the world has; and, the scarcity of primary sources of energy (Guno et al., 2021; Abdul-Wahab et al., 2019). The main objective of a PV plant is to generate electricity in direct current via PV modules, and after transforming it, it is introduced into the distribution network (Nwaigwe et al., 2019).

Unfortunately, when calculating the costs of generating electricity based on fossil fuels, environmental damage is not taken into account, among them: the price of what nature has accumulated with extremely low efficiency for millions of years; the cost of recovering the altered ecosystem; and, caring for sick people due to contamination. On the other hand, installing a 1 kW solar PV energy, avoids the average emission of fossil fuels into the atmosphere of more than 100 kg of CO_2 and saves about 400 L of water each month (Stolik, 2014). The solar PV system does

* Corresponding author at: Universidad Nacional Mayor de San Marcos, Lima, Peru.

E-mail addresses: liz@cubaenergia.cu (B.L. Miravet-Sánchez), albertoenrique.garcia@unmsm.edu.pe (A.E. García-Rivero), ryulip@unmsm.edu.pe (R.A. Yuli-Posadas), linostrozar@unmsm.edu.pe (L.A. Inostroza-Ruiz), vfernandez@esan.edu.pe (V. Fernández-Guzmán), yachavezj@unach.edu.pe (Y.A. Chávez-Juanito), jrutti@uniscjsa.edu.pe (J.M. Rutti-Marin), japesteguiai@unmsm.edu.pe (J.A. Apesteguia-Infantes).

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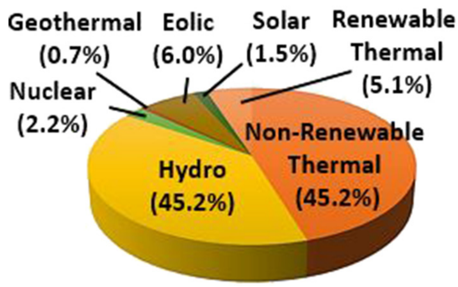

Fig. 1. Electricity generation capacity according to types of energy in LAC (2019). *Source:* Source (OLADE, 2020).

not produce harmful emissions during its operation years, while pollutant residues during manufacture are subject to controls; but, even if environmental costs are not taken into account, this energy currently competes economically with fossil fuels in terms of cost.

However, in accordance with current reality, during the life cycle of PV energy, a series of environmental impacts occur that must be taken into account and seek a progressive way to minimize them more and more (Pascualino et al., 2015; CEAC, 2020).

This article allows us to appreciate the latest developments in PV energy in selected LAC countries and exemplifies, through a case study in Cuba, how the incorporation of distributed energy, based on the incorporation of the PV module in homes, schools, and health care centers in isolated communities, in addition to substantially improving the living conditions of the inhabitants, represents a substantial reduction in CO_2 emissions, as a result of eliminating the burning of fuels such as wood and kerosene.

1.1. New energies in Latin America and the Caribbean

The last two decades witnessed a growing development of new alternative "clean" technologies for generating electricity. According to (Deloit, 2018)..."solar and wind energy have recently passed a new milestone by becoming the generation technologies with the greatest investment attractiveness. As they reach parity in prices and performance with conventional energy sources" (p. 22) and Deloit, 2018 continues to point out that these energies "are currently very close to meeting the three priorities of energy consumers: reliability, affordability, and respect for the environment" (p. 22)

For LAC, this process has manifested itself in a growing increase in installed generation capacities and energy production volumes, as shown in Fig. 1.

As can be seen, renewable energies in 2019 in LAC already constituted 13.3% of the generation capacity, which represents a potential generation volume of 213,761 GWh.

That said, if already in 2015, in the case of LAC, 97.8% of the population had access to electricity (a percentage much higher than the world average of 87.3%), the countries of the region ratified its commitment to guarantee its populations their universal access by 2030 with an affordable, reliable, sustainable, and modern energy supply by signing the resolution approved by the United Nations General Assembly. The vast majority of the 3.2% of the population lacking electricity service is the one that still lives in very isolated communities, where it becomes very difficult and expensive for conventional electricity distribution networks to provide service coverage (Ballón et al., 2019).

Faced with this problem, the incorporation of decentralized solutions, such as PV domestic system, arises as a socio-economic and environmentally viable dilemma [10, 11 *y* 12], due to small PV systems benefit less from economies of scale and therefore this market conditions may be argued to limit the full deployment of photovoltaics, in particular in the distributed residential market (Reis et al., 2019).

Hence, the main objective of this study is to address the development of PV technology in LAC, aiming to provide the geographically more isolated communities with electrical energy; allowing them to improve their standard of living, levels of health, access to new technologies; and reducing their environmental impact due to firewood and fossil fuel consumption for preparing their food and lighting. An electrification case study of a group of isolated peasant communities in an eastern mountainous region of Cuba by using a solar PV system is presented, showing, in addition to the previously mentioned benefits for the population, the level of CO_2 emission reduction, which represents the use of this new source of energy. According to (IRENA, 2021), in Cuba, PV solar energy represents 13.6% of the total renewable energy generated in 2021.

Taking into account those arguments, as (Connolly et al., 2016) has sustained, there are several reasons to consider implementing renewable energy solutions in energy systems.

1.2. The use of firewood and kerosene in rural areas. Health and environmental effects

Until the seventeenth century, at the very start of the industrial revolution, the history of fuels was essentially that of biofuels, with wood being the most widely used fuel. Once wood was replaced by charcoal, the technological revolution took place. Biomass materials can be solid and in some cases liquid. In general, solid biomass is not suitable to be directly used as fuel. It must go through a number of processes to adapt its characteristics to the intended energy use.

Firewood is considered a primary energy source, which means that it is obtained directly from nature, specifically from forest resources. It includes the tree trunks and branches, but excludes wastes from logging activities (Sierra et al., 2011). According to Singer "Wood is the oldest heat source used by man, which is perhaps due to the fact that it is much more accessible than other fuels as it easily. It is due to this accessibility that even today it continues to burn in homes according to traditional methods. The result cannot be other than intense consumption" (Singer, 1961) (p. 4).

Wood basically consists of: 49% Carbon, 6% Hydrogen, and 45% Oxygen, with slight variations. The energy contained in wood, with 20% humidity, is 15 GJ/ton or 10 GJ/m^3. For the most part, firewood is produced and is still consumed locally. The difficulty in collecting reliable data in countries is that firewood is used mainly in homes and its trade is often informal. Moreover, as firewood is cheap in most countries, its economic importance in the fuel sector is very little and resources are not allocated for collecting statistical data. The fact is that many countries lack the financial resources to carry out this type of work, as countries where firewood is used the most are often also the poorest in general. Another factor influencing the lack of reliable statistics is illegal logging, which causes the figures to be underestimated (Mejía, 2011).

The authors in Malyshev (2009) warns how just over a decade ago there were approximately 2.6 billion people using firewood, charcoal, or agricultural residues to supply their energy needs for cooking and heating, and, according to projections, by 2030, the figure will rise to 2.7 billion inhabitants. In addition, he reported that there were more than 1.6 billion people without access to electricity, which corresponds to a quarter of the world's population.

Direct firewood combustion is the best-known process and is currently used to obtain almost all of the energy from this resource, developed at temperatures that vary between 590 °C needed to maintain secondary combustion and 660 °C, where finally complete combustion is reached. Obtaining these temperatures and burning efficiency will depend on the type and condition of the firewood and the type of stove that each household has.

The principle of operating the traditional kitchen is based on the incomplete combustion of firewood by means of which the potential energy of the fuel is converted into heat energy, and this energy is transmitted to the pot or the room in where the food is cooked by heat transfer processes, whereby smoke is expelled into the surroundings while polluting the indoor environment where cooking is taking place. This situation is very dangerous for children who run the risk of suffering burns due to accidents.

These everyday practices satisfy the population's vital needs. However, they also generate greenhouse gas emissions while at the same time negatively impacting the population's health and the environment.

On the other hand, like the burning of wood, the use of kerosene contributes to the emission of greenhouse gases (GHG) into the atmosphere and black carbon associated with fine $PM_{2.5}$ particles. Combustion does not only generate CO_2, it also generates other gases with much greater potential for global warming effects, such as: CO and different nitrogen oxides (NOx). In addition, kerosene is highly toxic to humans and its limited exposure can cause irritation to the skin, eyes, and mucous membranes. Long-term exposure can cause advanced toxicity symptoms such as vomiting, nausea, and headaches; people can die if they are prolongly exposed to high concentrations or if the fumes are inhaled; and, it is also potentially carcinogenic due to prolonged exposures (Curto et al., 2019).

1.3. Photovoltaic systems in isolated rural areas in LAC

As mentioned previously, most of the families that still have no access to electricity in their homes are located in rural communities that are very isolated and far away from the large electricity distribution lines. In many cases, connection to these lines are unfeasible due to high levels of practical difficulty and high costs.

In the interventions to provide electricity in rural areas in LAC from 1970 to the present, the Dealer model, implemented in Bolivia, through the Decentralized Infrastructure Program for Rural Transformation (IDTR) (Banal-Estañol et al., 2017); the Concessionary model introduced in the 1990s in countries such as Argentina, Bolivia, Chile and Peru (Barnes and Halpern, 2001), where this auction mechanism has been widely used in Latin America, for example, in Argentina with the Energías Project Renewables in Rural Markets, in Peru with the National Rural Electrification Plan and in Brazil with the Luz Para Todos Program (Barnes and Halpern, 2001); and, finally, the Community-led model, which is a decentralized version of the Concessionary model, directed to expanding the supply of off-grid and mini-grid electricity, which has been applied in Chile since 1994 through the Rural Electrification Program (PER), the Rural and Social Energization Program (PERYS), the Micro Network Project of Huatacondo, or in the Coquimbo Regional Photovoltaic Project (Kruckenberg, 2014); stand out.

In view of this situation, many LAC countries are expanding by introducing small PV systems or modules that allow for individually providing a certain amount of electricity to isolated houses or small groups of houses.

There are several examples regarding the development of this electro-energy variant in different countries. As an example, different projects are presented in Table 1.

1.4. Case study. Rural electrification project with solar PV technology in isolated areas of the Province of Guantá namo, Cuba

In Cuba's southeastern coastal region, government agencies and civil society have been working for several years now to solve specific energy sustainability problems, by using renewable sources and by caring for the environment, water supply, food production, rescue of biodiversity, and stability of the necessary workforce. It is in the government's interest to integrate the development of these sources in these areas of the country into a single program at all levels. The project covers the second rural electrification cap, extending services to rural farmers.

In April 2018, 100% of the country was electrified using isolated photovoltaic systems, bringing electricity to homes located in rural areas that are difficult to access and where power lines are not justified due to high transmission costs. A 300 Watt system was then installed for each house.

After the first phase of the electrification project in isolated rural areas, a total of 17,061 solar PV systems had been installed in the country, where the largest number of beneficiaries coincide are the provinces with a more complicated geography product of the relief and the configuration of national electricity distribution networks (Fig. 2)

With the aim of expanding the possibilities of using this energy in 2021, the second phase of this project began in the province of Guantánamo and in this study an assessment of the contribution of the current electrification project in nine isolated rural communities from the municipalities of Imías, Yateras, and San Antonio del Sur in the province of Guantánamo, with the co-financing of the Spanish Agency for International Collaboration (Fig. 3). This phase permits the reduction of the use of firewood, kerosene, and CO_2 emission and the substantial improvement of the living conditions of this important sector of the Cuban population, reducing their exodus to the cities; and, to increase food production by promoting life in the countryside (Miravet, 2015).

2. Materials and methods

2.1. Characteristics of the solar PV system to be installed

In Cuba, continuing with the second stage of the rural electrification program in the country, the plan is to install 300 solar PV systems of 1.92 kW as a pilot project, which will provide a greater benefit to dispersed peasant households, unlike the previous system.

These solar PV systems, to be installed in isolated homes of the National Electric System (NES), will consist of six 320 Wp PV panels; a 40 A 150 V charge regulator; a 24 VDC, 110 VAC ± 3% 60 inverter Hz; 1.92 kW, four 160 Ah 12 V batteries; a cabinet; the interconnection conductors, and their corresponding grounding system. Table 2 shows the module of equipment and accessories that it is recommended to install powered by this system, as well as the operating hours of each one. These systems will autonomously work to up to 36 h, given the conditions and distances in which the communities are located and foreseeing adverse weather conditions.

Once in operation, these systems will allow the nine communities to be electrified thereby stopping them from using firewood and/or kerosene as fuels for cooking food and lighting, while consequently reducing CO_2 emissions into the atmosphere.

According to several scientific reports (Miravet, 2015; Ramírez and Taborda, 2014; Hernández, 2014; Valderrama and Linares, 2008; Muro et al., 2011; Masera et al., 1997; Bustos and Ferrada, 2017) an inhabitant of the Latin America region daily consumes between 2 and 5.5 kg of firewood to cook their food, the values

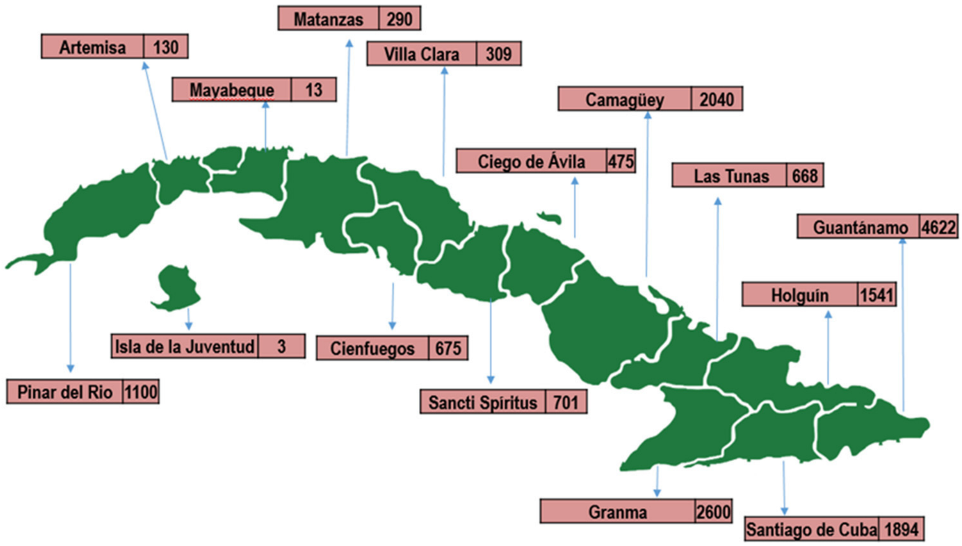

Fig. 2. Location by Provinces of the solar PV systems installed in the First Phase of the Electrification Project of Isolated Rural Areas.

Table 1
Examples of Different PV Projects in the LAC Region.

Subregion Country	Main Characteristics of the Projects	References
Central America Nicaragua	In 2020, "4,200 PV systems were installed in the same number of homes, communal houses, health posts and churches" at isolated rural communities on its Caribbean Coast.	ENERGIA LIMPIA XXI (2020)
	Some 270 inhabitants of San Nicolás and Río San Juan in Estelí benefited from the SPVS installation.	Canal2TVNoticias (2021)
Andean Community of Nations Peru	The Peruvian State developed a Massive Photovoltaic Program in two stages, which includes modular systems for homes, health centers, and educational institution. By the end of 2020, 213,443 users should be benefited.	Ministerio de Energía y Minas-República del Perú (2020)
	The acciona.org Foundation has recently completed the third phase of the Luz en Casa Amazonía project, which already benefits approximately 7,400 people in the Amazon region of Loreto.	pvmagazine (2021)
Southern Cone Brazil	"More Light for the Amazon (MLA)" Program in 2020, which will install SFV to approximately 70 thousand families in different regions until 2022.	pvmagazine (2020)
Southern Cone Argentina	Through the Renewable Energy in Rural Markets Project (PERMER), the Government is facilitating access to renewable energy sources in homes, rural schools, agglomerate communities, and small productive enterprises for the rural population, delivering and installing Solar Home Kits (3G Kits) and solar lanterns.	(de Argentina, 2021) Government of Argentina, 2021
Southern Cone Chile	Inaugurated in April 2021, the Sonnedix Atacama Photovoltaic Plant, will produce around 470Gwh of clean electricity per year, providing more than 200,000 Chilean homes with electricity.	Sonnedi (2021)
	The Energy Access Fund (FAE) 2018–2019, contemplated USD 515 million for projects to provide PV energy to rural, isolated or vulnerable sectors.	Guía Chile Energía (2021)

Table 2
Equipment and accessories recommended to be connected to the PV systems installed in each of the homes.

Type of equipment or device	Amount of equipment	Nominal level of electricity consumption (W/h)	Daily wear time	Electricity consumption (W/h/day)
Luminaires	6	20	5	600
TV	1	70	6	420
Refrigerator	1	167	18	3006
Domestic fan	2	40	10	800
Mobile phone charger	1	5	2	10
Audio–video system	1	50	2	100
Electric pot	1	800	2	1600

fluctuate depending on the availability or price of firewood, the type of kitchen they use, eating habits and climate characteristics (mainly temperature and humidity). In most cases the firewood comes from natural vegetation, which aggravates global deforestation and desertification in some sensitive areas. In addition, collecting wood is a job that requires considerable effort and time. Women and children often walk for hours to extract or collect firewood. Furthermore, the smoke resulting from the combustion of wood-burning causes serious health problems for thousands of people each year.

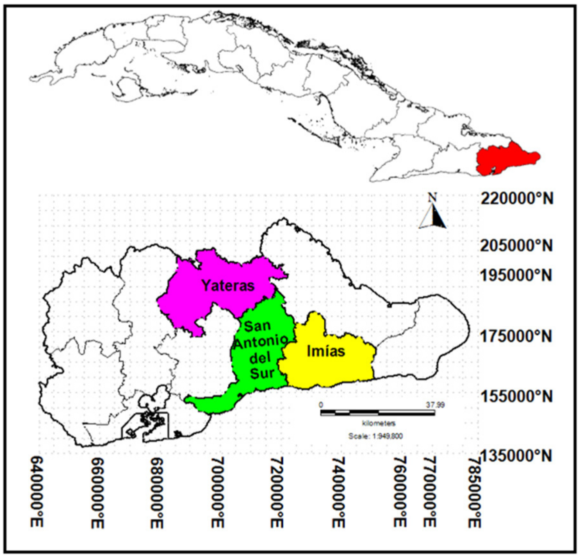

Fig. 3. Location of the three municipalities (Yateras, San Antonio del Sur, and Imias) where the nine isolated rural communities to be electrified are located.

2.2. The method of calculating CO_2 emissions for families cooking with firewood

As in the present study no rigorous accounting was made of the daily consumption of firewood by families cooking with traditional or open fires, a bibliographic search was conducted in order to estimate this reduction in emissions.

The consumption kg/day of firewood in a household is directly related to the number of people in the family nucleus who use it as energy to prepare food. In other words, families with more members consume more firewood. However, when consuming firewood, it is the number of members of each family that results in an inverse relationship between consumption and number of members, consumption per individual-day (per capita). That is, the expenditure of an individual at the time of preparing food in a small family is greater than that consumed by a single individual in a large family. This relationship suggests greater efficiency in the use of firewood per capita among large families. The consumption of firewood is 50%–55% lower compared to the consumption of families with fewer members (Ramírez and Taborda, 2014).

The following formula is used to determine the total annual CO_2 emissions from the use of firewood ($TACO_2EF$)

$$TACO_2EF = NFCF^{*}VFF6Y^{*}CO_2CEF \quad (1)$$

where NFCF is a number of families cooking with firewood; VFF6Y the average amount of firewood consumed by a family of six members per year (kg/yr); and CO_2CEF, the CO_2 emission coefficient (1 kg of firewood produces 1.83 kg of CO_2)

2.3. The method of calculating CO_2 emissions for families cooking with kerosene

In order to calculate the CO_2 emissions for kerosene stoves, we estimated that each family consumes 20 liters of kerosene per month.

The following formula is used to determine the total annual CO_2 emissions from the use of firewood ($TACO_2EK$):

$$TACO_2EK = NFCK^{*}VKF6Y^{*}CO_2CEK \quad (2)$$

where NFCK is a number of families cooking with kerosene; VKF6Y, the average amount of liters of kerosene consumed by a family of six members per year (240 L/yr); and, CO_2CEK the CO_2 emission coefficient (1 L of kerosene produces 2.5 kg of CO_2).

Fig. 4. View of one of the homes with its three solar panel module installed.

3. Results and discussion

The main results are presented below, as a consequence of the installation of PV systems in 216 homes (Fig. 4), as part of the second phase of electrification of isolated communities in the province of Guantánamo, eastern Cuba.

3.1. Results of calculating the CO_2 emissions for families cooking with firewood

The results of firewood consumption rates for various regions of LAC are shown in Table 3.

In the present study the rate of 3.58 kg/person/day (arithmetic mean of the values collected in the five sources of information consulted; (Hernández, 2014; Valderrama and Linares, 2008; Muro et al., 2011; Masera et al., 1997; Bustos and Ferrada, 2017)) will be used as the representative consumption value of the families living in the area of project development.

Table 4 shows the results of calculating the annual volumes of firewood consumption for cooking and the respective CO_2 emissions for families cooking with firewood. One can appreciate how by eliminating the use of firewood for household activities in the 148 homes of the seven communities to be electrified, in addition to all the impacts produced in the improvement of the quality of life of these inhabitants, 1160.32 metric tons of firewood will no longer be consumed annually and 2123.39 metric tons of CO_2 will no longer be emitted into the atmosphere as a result of burning firewood, which in itself speaks to the sustainability of this project.

3.2. Results of calculating CO_2 emissions for families cooking with kerosene

Table 4 shows the calculation of the annual volumes of kerosene consumption for cooking and the respective CO_2 emissions. One can appreciate how by eliminating the use of kerosene for household activities in the 68 homes of the four communities to be electrified, in addition to all the impacts produced in the improvement of the quality of life of these inhabitants, the annual consumption of 16,320 L of kerosene will be reduced and 40.8 metric tons of CO_2 will no longer be annually emitted into the atmosphere as a result of burning kerosene, which in itself speaks of the sustainability of this project. The positive impact of the project on the environment is evidenced by the amount of CO_2 no longer emitted into the atmosphere. The results are listed below in Table 5.

Table 3
Firewood consumption rates for various LAC regions.

Consumption Rates (kg/person/day)	Place, Country	Source of Information
5.0	Department of Santander, Colombia.	Hernández (2014)
4.8	Community of San José de Suaita, Santander, Colombia.	Valderrama and Linares (2008)
3.0	Vilacota-Maure Regional Conservation Area of the Tacna region, Peru.	Muro et al. (2011)
2–3	Various Mexican territories.	Masera et al. (1997)
3.7[a]	Osorno,Chile	Bustos and Ferrada (2017)

[a]Six inhabitants per home are assumed here.

Table 4
Approximate volumes of firewood consumed and CO_2 emissions resulting from the burning of firewood in the communities to be electrified.

Communities to be Electrified	Number of Homes	Firewood Burned (t/yr)	CO_2 Emission (t/yr)
Najesial	18	141.12	258.25
Arroyo de Carlos	14	109.76	200.86
Los Asientos	15	117.60	215.21
La Carolina	45	352.80	645.62
Felicidad	19	148.96	272.60
Maya	10	78.40	143.47
Jobo Arriba	27	211.68	387.37
Total	**148**	**1,160.32**	**2,123.39**

Note: Average Firewood Burned for one home per year: 7.84 t/yr.

Table 5
Approximate kerosene volumes consumed and CO_2 emissions, resulting for burning kerosene in the communities to be electrified.

Communities to be Electrified	Number of Homes	Kerosene Burned (L/yr)	CO_2 Emission (L/yr)
Jobo Arriba	27	6,480.00	16,200.00
Arroyo de Carlos	13	3,120.00	7,800.00
El Baga	10	2,400.00	6,000.00
Los Asientos	18	4,320.00	10,800.00
Total	68	16,320.00	40,800.00

Note: Average Kerosene Burned for one home per year: 240 L/yr.

In general, CO_2 emission reductions from electrifying 216 houses in the nine communities reach an annual amount of 2,164.19 t/yr, reducing firewood consumption by 2,123.39 t/yr and kerosene consumption by 40.80 t/yr.

These results are highly encouraging, considering that the costs of single-family PV modules have remained low in recent years, while their adaptability to various power and energy storage requirements is evolving very satisfactorily. Adopting circular economy principles will help offset environmental factors such as emissions associated with manufacturing stages and increase recycling and recovery rates (Farrell et al., 2019, 2020), where there is the potential for technological innovation throughout the product life cycle of PV modules and inverters that significantly reduces the environmental impact of these systems, based on the use of less polluting materials and greater availability for their reuse (Polverini et al., 2021).

There are several works that report the advantages for the health and well-being of the inhabitants, where the use of wood or kerosene and derivatives of fossil fuels is replaced by PV. Such is the case in Nigeria, where a large part of the poorest and most rural population uses diesel generators of electric current, which are being replaced by solar PV energy right now (Babajide and Centeno, 2021).

In the case of Cuba, both the improvements in terms of the standard of living of the inhabitants of these isolated communities (now with greater access to clean and safe cooking, better lighting, better connectivity to the media), as well as the notable reduction in CO_2 emissions is evident.

Authors such as (Lund, 2014) highlight how these transformations can contribute to strengthening and improving other social issues, including democracy and living conditions in local communities.

It must be recognized that introducing these solar PV systems in isolated communities is part of a natural and gradual transformation process of the energy matrix towards clean energy, an aspect pointed out by Cabrera et al. (2018), when they state that in a general sense, but particularly in the case of islands, there is a general consensus that energy systems will have to change in the near future.

However, according to (Yépez-García et al., 2019), while energy and investment needs in LAC will experience steady growth in the coming years, they will not be free from development challenges and technology disruptions. As an example, in the residential sector, rural electrification and electric cook stoves are going to challenge the last 3% of the population still lacking access to electricity (p. 42).

Other authors such as (Rahut et al., 2017), point out that access to electricity is a crucial determinant for the use of electricity for lighting as well as for both lighting and cooking. Households in villages with access to electricity are likely to increase the use of electricity for lighting by 190 times and by 239 times for both lighting and cooking. The results also show that with the passage of time, the likelihood of using electricity increases for lighting and cooking. (p. 15).

Table 6
Proposal of general time distribution of the use of the equipment and accessories to be connected to the PV System.

	hours of the day																							
	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Refrigerator	x	x	x	x	x	x			x	x	x	x			x	x	x	x			x	x	x	x
Electric pot													x	x					x	x				
Domestic fan	x	x	x	x	x	x	x															x	x	x
Luminaires							x	x												x	x	x	x	x
Audio–video system																					x	x		
TV								x							x						x	x	x	x
Mobile phone charger	x	x																						

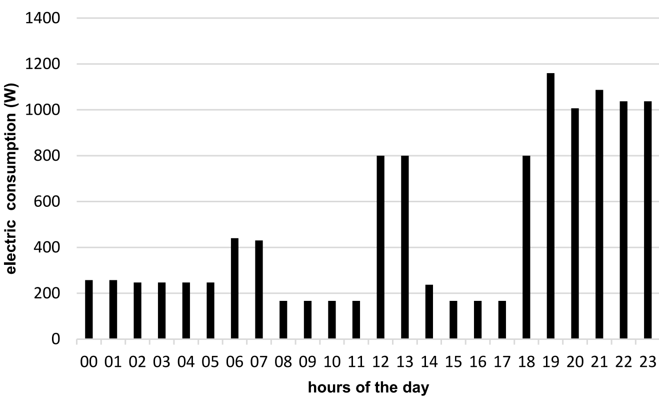

Fig. 5. Schematic distribution of the daily levels of electricity consumption.

Another interesting aspect is related to the need to create technical capacities among the inhabitants of isolated communities, aiming to achieving independence and immediacy of systematic maintenance and replacement of PV systems components, without having to depend on external agents, which could jeopardize the sustainability of this community electrification effort.

3.3. Hourly proposal for the use of the energy provided by the PV system and additional alternatives for cooking food

Since the past decade, authors such as (Fumo et al., 2012; Khatib et al., 2012), highlight the importance of optimizing the size of the photovoltaic field and the battery bank, for which it is essential to know the levels of solar radiation and the needs energy of the home and its distribution throughout the day.

Taking into account these interesting aspects, within the framework of this study, an hourly distribution schedule is proposed throughout 24 h a day, which allows the correct operation of the equipment and accessories module that includes the electrification program and ensures the useful life of the installed PV system (Table 6).

The hourly electricity consumption corresponding to this proposal for the use of equipment and accessories during the day is illustrated in Fig. 5.

As can be seen, in Fig. 4 there are two times of the day, where electricity consumption increases considerably due to the input depending on the electric pop, with the aim of preparing food at lunch (from 12:00 pm at 2:00 pm) and dinner (from 6:00 pm to 8:00 pm), which makes it necessary to maintain adequate control over the operation of the remaining equipment, mainly the refrigerator due to its consumption levels.

However, as a complement to photovoltaic systems, it could be to incorporate solar thermal energy from the use of stoves and ovens that take advantage of sunlight, concentrate radiation, and achieve high temperatures during the day.

Fig. 6. Portable Solar Oven with Glossy and Reflective Surfaces.
Source: https://pannellisolarifv.com/cocinar-con-hornos-solares/

Currently, there are different models of solar cookers and ovens that have a high degree of energy efficiency and relatively affordable costs. A first group, where the solar oven or cooker captures the heat energy of the sun through mirrors or aluminum plates placed so that the sunlight is reflected on the mirrored surface or aluminum foil, directly in its center (Fig. 6).

A second group are the parabolic solar panel cookers, the ones that use dish-shaped or reflectors to concentrate the sun's energy in a central focal point usually at the bottom of a black cooking pot. Depending on the diameter of the parabolic reflector, it is possible to generate very high temperatures quickly, since sunlight is focused on a very small area. The main advantage of these solar panel cookers is that almost any food can be cooked as quickly as it would in a conventional kitchen and its disadvantages is a greater complexity in its construction and that the reflectors must be rotated and focused following the trajectory of the sun during the course of the day (Fig. 7).

This is an example of an ALSOL 1.2 parabolic solar cooker model, available in the Spanish market at a retail price of 655 euros, with a 125 cm parabola and a 1.32 m^2 collection surface, it achieves 1500 W of captured power for insolation. average of 1000 W/m^2 and reaches temperatures of up to 200° C, according to its producers.

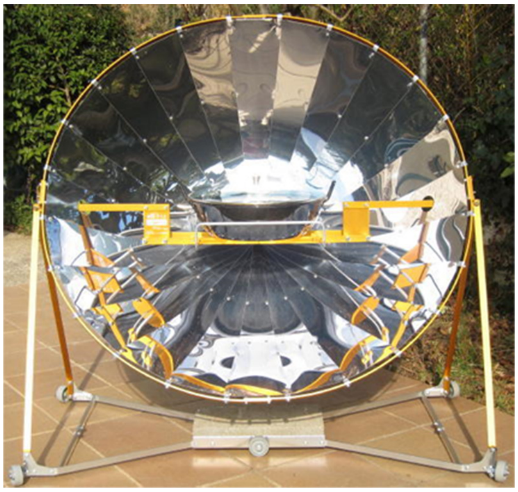

Fig. 7. ALSOL 1.2 1500Wp 125 cm parabolic solar cooker.
Source: https://www.tiendafotovoltaica.es/epages/61359426.sf/es_ES/?ObjectPath=/Shops/61359426/Products/%22ALSOL%201.2%20GS%22

On the other hand, solar heaters for sanitary water could also be incorporated, both of the type of flat solar panels or vacuum tube solar collectors. Its operation consists of capturing the thermal radiation of the sun and being able to store the resulting heat. Either of these two plates/ collectors are accompanied by a water tank either in the upper part or inside the houses.

These options that are presented could complement the PV systems that have been installed as part of the solar electrification program in remote rural areas of eastern Cuba, with a view to achieving total energy independence for these residents and a substantial improvement in their quality of life.

3.4. The environmental cost of PV energy and its energy payback periods

Although the environmental feasibility of PV energy is evident in comparison with the energy obtained from burning wood, kerosene or other fossil fuels, it should not be forgotten that the process of generating PV energy, in all its life cycle (from the initial phase of obtaining the raw materials to make the panels, inverters, batteries and other accessories, going through their operation and maintenance phase, until the final phase of dismantling the system) there are various environmental impacts and some of consideration. Authors' works such as (Fthenakis and Kim, 2012; Rahman et al., 2017; Fthenakis and Raugei, 2017; Fthenakis, 2018), agree that the Life Cycle Analysis Methodology (LCA) is a comprehensive framework to quantify the environmental impacts caused by the flows of materials and energy in each and every one of the stages of the PV energy life cycle.

In Fthenakis (2018) have developed a very complete diagram of the life cycle of this type of energy (Fig. 8).

As can be seen in each stage that makes up the life cycle, there is an input of materials, energy and output of some type of effluent. In general, the cycle begins with the obtaining of the materials (F1), their processing, and their purification (F2), it continues with the manufacture of the various components and their assembly (F3), their transport, installation, operation, and maintenance (F4), and at the end of its useful life, it is dismantling (F5), it is eliminated and what cannot be recycled (F7) is disposed of and the highest possible percentage is recycled (F6), the result of which is reintegrated into the process in F2.

In the first three phases F1, F2 and F3, the greatest amount of energy and materials are consumed, including water, silicon, and toxic chemicals such as hydrochloric acid, sulfuric acid, nitric acid, hydrogen fluoride, 1,1,1-trichloroethane, and acetone and if the manufacturers do not strictly follow the laws and regulations of labor protection and environmental, can pose significant health hazards, particularly for manufacturing workers. It is also when more effluents are produced, both in the process of mining and processing of materials (F1 and F2), as well as in the production of the various equipment and devices that will make up the PV system. F4, unlike other conventional types of energy, is characterized by minimal use of materials, energy, and very low levels of greenhouse gases. Nor does decommissioning involve considerable material, energy consumption, and emission levels.

A good implementation of the recycling (F6), according to the most modern techniques, will allow, high re-use of the components of the system, minimizing the volumes of waste to be disposed of and contributing to the consume reduction of new volumes of materials in F1 and F2, thus guaranteeing a very satisfactory environmental performance of this type of energy.

Currently, at least in the European Union, the recycling of photovoltaic solar panels is regulated by a directive for the category of Consumer Electronics and Photovoltaic Panels, which by law obliges solar cell manufacturers to comply with legal requirements and standards specific recycling methods to ensure that solar panels do not become a burden on the environment (Parlamento y Consejo Europeo, 2012).

Recycling systems, both for silicon and thin-film panels, achieve an average utilization close to 95% and in the near future, recycling will allow the production of 2 billion new panels without the need to invest in raw materials. This means that there will be the capacity to produce around 630 GW of energy just by reusing previously used materials (Fotovoltaicos, 2020).

In the case of the electrification of these nine communities in eastern Cuba, the greatest impacts are referred to the first three phases (F1, F2 and F3), where the panels have been assembled in Cuba, from components produced in China. The current legislation on the development of renewable sources and the efficient use of energy in the country does not regulate the obligation, nor the way in which the recycling of the PV system should be carried out, a technical-legal gap that must be overcome (de Estado, 2019).

Regarding energy pay-back time (EPBT) it is defined as the period required for a renewable energy system to generate the same amount of energy (in terms of equivalent primary energy) that was used to produce (and manage at end-of-life) the system itself (Alsema et al., 2009).

Authors such as (Fthenakis and Raugei, 2017), presented an overview of a well-established life-cycle assessment methodology adopted by analysts in 14 countries which have been collaborating under the auspices of the International Energy Agency (IEA). Based on actual photovoltaic (PV) life-cycle materials and energy inventory data, estimates of energy payback times (EPBT), energy return on energy investment (EROI) and greenhouse gas (GHG) emissions were made; those are indicative of PV performance in early 2010; using more up-to-date PV efficiencies will result in lower EPBT and GHG emissions and higher EROI

In this sense (Fthenakis and Raugei, 2017), present a synthesis of values of the EPBT and GHG emission obtained from different studies in different regions or countries (Table 7). As can be seen, the average value of EPBT, depending on the type of PV module and the area of its location, varies between 2.3 and 6.1 years, with a general average value of 3.3 years, with the type of CIS module being the one with the best performance. The GHG average value varies between 25.5 and 50.5 g-CO2eq/ kWh, with a general average value of 40.6 g-CO2eq/ kWh. The type of module with the lowest emission is CdTe with a value of 25.4 g-CO2eq/ kWh.

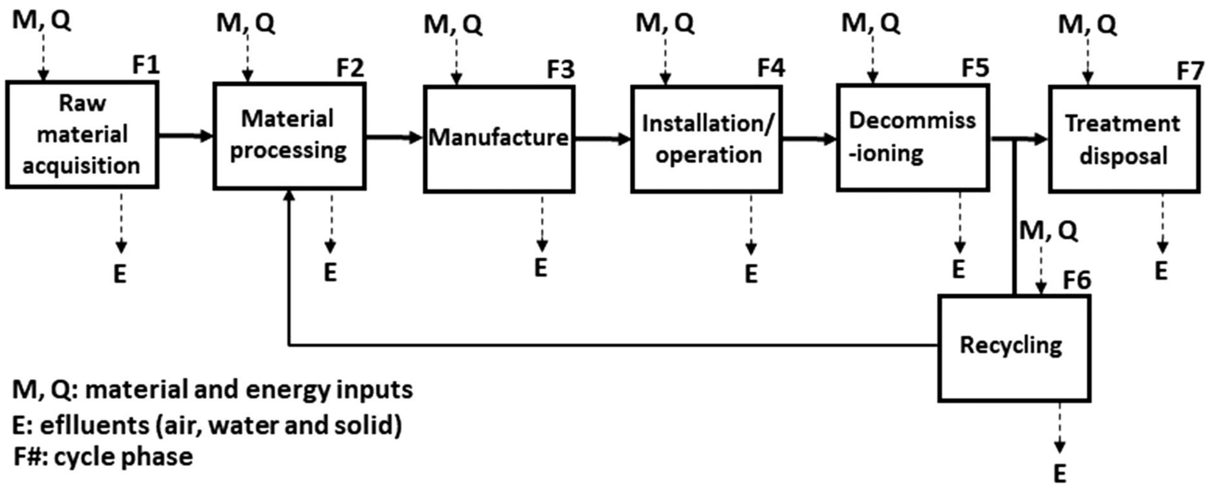

Fig. 8. The Life Cycle Stages of PVs.
Source: Modified from Fthenakis, 2018.

Table 7
Summary of the behavior of the EPBT and GHG for the different types of PV modules.
Source: Information taken from Fthenakis and Raugei (2017).

Module Type		EPBT (years)	Location	GHG Emissions ($g-CO_2eq/kWh$)	Location
Mono-Si (6)	Average	6.1		45.7	
	Minimum	2.1	South European	35.0	South European
	Maximun	12.1	UK	61.0	Japan
Multi-Si (8)	Average	2.5		39.3	
	Minimum	1.7	Gobi Desert of China	12.0	Gobi Desert of China
	Maximun	3.3	Italy	72.0	USA
a-Si (5)	Average	3.0		42.2	
	Minimum	2.7	South European	34.2	USA
	Maximun	3.2	Northwestern European & USA	50.0	South European
CdTe (8)	Average	2.6		25.4	
	Minimum	0.7	South European	14.0	Japan
	Maximun	11.0	Europe	48.0	South European
CIS (4)	Average	2.3		50.5	
	Minimum	1.6	China	10.5	China
	Maximun	2.9	Switzerland	95.0	South European
	Average	**3.3**		**40.6**	
General	**Minimum**	**1.6**		**10.5**	
	Maximun	**11.0**		**72.0**	

According to this same study, in the PV system, most of the emissions come from manufacturing of lead–acid batteries (45%), followed by PV modules (39%). Transportation, recycling, cables, and supporting structure together contribute about 10% CO_2 emission.

It should be noted that none of the data that have been taken into account in this study (Fthenakis and Raugei, 2017) refer to Latin America and the Caribbean, so this statistic should be taken with reserve if it is to be extrapolated to that area. This denotes the need to start collecting reliable and systematic data, in order to have information on the EPBT and GFG of the PV systems installed in this region in the near future.

4. Conclusions

In the LAC region, an important electrification process of the most remote rural communities with decentralized clean energy has been developing in recent years, where PV energy stands out for its characteristics of independence and progressive reduction of costs. Although in the region an important sector of the population still lives in remote and hard-to-reach areas, most of the time with very low purchasing power and a large number of neglected needs, the process of installing individual PV modules represents one of the best options in solving this pressing problem, which was evidenced in the different programs that were carried out in different countries.

The Rural Electrification Project with Photovoltaic Solar Technology (Phase II) in 216 houses in nine rural communities, located in isolated areas of the Guantánamo province of the Republic of Cuba, shows very positive changes are manifested in terms of improving the quality of life of the inhabitants, and especially their physical and mental health state. In addition, CO_2 emission reductions from electrifying reach an annual amount of 2,164.19 t/yr, reducing firewood consumption by 1160 t/yr and kerosene consumption by 16320 L/yr.

Considering that the food cooking process is the activity that requires the most energy at certain times of the day and that the PV system has a limited delivery capacity, it is recommended to assess the inclusion of solar thermal energy in the form of solar cookers and ovens, as a way to improve the supply of electricity to other household activities.

However, the undoubted advantages over its environmental performance compared to other types of energy, LAC countries must adopt laws and regulations that regulate the use of PV energy, with a view to minimizing its environmental impacts in its different phases of development, with an emphasis on recycling systems at the end of their life cycle.

Declaration of competing interest

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

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