A comprehensive solution approach to the sustainability problem of photovoltaic systems: The Bolivian case

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Abstract: Assess the sustainability of electricity provision for rural families through off-grid Photovoltaic Systems (PVS) in Bolivia during the last 10 years, is the essential core of this research. The sustainability analysis is considered under a multidimensional approach: documental analysis complemented by a field research and semi-structured interviews with local experts. In the Bolivian case more than 36 thousand PVS have been installed in the last 10 years under different schemes, but more than 90% of these, are out of operation, shown the absence of sustainability approach in these interventions. For this and considering the international experience, is sketched a proposal under an integrality approach. The proposal contemplates substantial modifications in the way of granting the SFV to the families, their faculties as well as the institutional roles; a tariffed service has been suggested as it happens throughout an off-network system.

Subjects: Universalization of Access Policies; Rural Electrification

Keywords: electricity; off-grid photovoltaic systems; non-renewable energy; sustainability; environmental

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PUBLIC INTEREST STATEMENT

Organizations such as United Nations and World Bank point out that energy is crucial for welfare today. Universal access to reliable, modern energy services is fundamental for sustainable development. Energy, especially electricity, is a condition to improving the standard of living of people in low- and middle-income countries. Therefore, achieving 100% coverage with the service is nowadays one of the major challenges imposed by government agendas. The high costs and the technical infeasibility of accessing remote populations by grid power, lead to off-grid photovoltaic systems to be a real alternative to achieve the service universalization. But sustainability is the core of the problem. This paper delves into the exploration of main causes that would lead to failure of efforts to provide electricity through SFV to remote populations and a reasoned and feasible proposal is drawn up to build a sustainability scheme under an integral approach to face the problem solution.
1. Introduction

According to the World Bank, 11.15% of the world population didn't have access to electricity in 2017. The percentages reached 21.35% for the rural population. In Bolivia, about 25.18% of the country's population was without access to electric power in 2017, per the same source (World Bank, 2019). In contrast, most of the urban centers in the country were served by the electric distribution system in 2018, according to the Bolivian Authority for Electricity (AE, 2018).

International organizations, such as the World Bank or the United Nations, have not expressly recognized access to energy as one of the goals of the millennium; yet, this seems to be a key factor in achieving the stated goals (OECD, 2015; International Energy Agency [IEA], 2015). In this regard, clean and sustainable energy has been explicitly recognized as one of the 17 goals of sustainable development (goal # 7) by the United Nations; a goal that should be achieved by 2030 (United Nations [UN], 2015).

In recent years, governments of developing countries have put forward efforts towards addressing such condition, which affects significantly the inhabitants of rural areas, particularly in remote regions, by taking advantage of alternative energy sources, enabled by technological innovation.

Some studies (e.g., Acker & Kammen, 1996; Chakrabarti & Chakrabarti, 2002; Huacuz, 2005) analyze the problem of access to electricity for distant rural areas. They have one coincident position. When inclined to maintaining the efforts towards providing electricity to families located in remote regions, these efforts should be geared to favor the generation of electric energy without the development of a distribution system. This solution is known as generation systems “off grid”, i.e. not connected to conventional systems via the distribution network. In this context, electric energy generated from photovoltaic solar energy turns out to be notably advantageous. Decentralized energy generation with fossil or renewable fuels may be more accessible to remotely located population, than extending the existing electric grid over long distances or difficult terrains, with its consequent costs, which cannot be recovered via the fees charged to its users.

It is worth noting the work of Barnes, Samad, and Rivas (2018), which concludes that the financial barriers to obtaining electricity service are often significant, due to initial connection costs, charged by the energy distribution companies to the householders. In their research, Barnes et al. (2018, p. 46) point out that “In Bolivia, for example, a small local distribution system, despite charging circa 25 to 30 cents per kilowatt-hour, immediately doubled the number of consumers when they offered the option of paying the connection costs in five years”.

On the other hand, new technologies that take advantage of renewable sources—which have their best allies in international organizations and multilateral entities—, are the options that States promote within their own policy frameworks today. Therefore, the possibility of solving the problems of access to energy in remote areas through the adoption of clean technologies turns out to be a very attractive scenario to countries and so it seems to be understood by international organizations.

In recent years, countries such as Bolivia, Argentina, Ecuador, and Peru, in South America, or Guatemala and El Salvador, in Central America have started programs and projects to reach the rural population without access to the electric distribution system. Essentially, these projects have been developed through the installation of solar photovoltaic systems (PVS) under various schemes of sustainability (OLADE, 2013, 2015), using both resources of the State and those resulting from international cooperation.

Even when the literature suggests certain criteria about the elements or the aspects that lead to qualifying some projects of this sort as successful or not, in practice, there is no definition that can be applied uniformly. In this way, each Entity defines its criteria for judging its own projects as successful or not. Indeed, as shown by Naudet and Delarue (2008), little attention has been paid to
assessing the success of a project based on its results and its impact, although there is an increasing trend. Corsair (2013) shows that, according to almost all methods to measuring the success of a project, projects to install photovoltaic systems “off grid” in rural areas, in general, have not been qualified as successful.

Specifically, in the Bolivian case, a very important portion of the population living in rural areas does not have access to energy, even when, paradoxically, the country has a great potential to produce energy from renewable sources that currently is only marginally exploited, as indicated by Zegada (2016). According to this research, in the country, slightly less than 40 thousand rural homes have been electrified using photovoltaic systems “off grid”. However, the programs and projects that have been executed so far are not supported by sustainability schemes that guarantee their permanent and continuous operation.

Considering these findings, it can be said that there is a reasonable doubt about the effectiveness of the efforts deployed so far in Bolivia, to solve the problem of long term and sustainable access to electricity. That is an evident result of the field research carried out is that the rural inhabitants that benefited from the projects executed so far were in worse conditions a few years after the installation of the service than in the beginning. This is because, after experiencing the benefits of this technological change in their lives, they were forced to return to an unwanted situation, without possibilities of obtaining further help from the State or from the entities in charge of developing these projects. This resulted in a sense of frustration, now added to the condition of not having electricity.

In view of this, our research work has analyzed the sustainability mechanisms applied to projects for the provision of micro-photovoltaic systems (PVS) “off grid” in Bolivia. Likewise, as a reference, we have studied the experiences with similar programs in other countries of the region, to establish findings that allow us to propose improvements under an integral sustainability approach for future efforts in the Bolivian case. Our integral sustainability scheme takes into account institutional, legal, techno-economic, social, and environmental aspects.

2. Research work objective
The general research objective has been to develop a comprehensive sustainability scheme for projects for provisioning electric energy via Off-grid Photovoltaic Systems.

To this purpose, the following specific objectives have been set:

• To Study, the sustainability mechanisms tested in projects for provisioning photovoltaic micro-systems “off grid” (PVS), in the programs and projects carried out in Bolivia.
• To Study the compared experience and within countries of the region with photovoltaic programs.
• To specify findings and to propose improvements to give integral sustainability to the programs and projects of energy endowment through SFV, in the case of Bolivia.
• To Estimate the tentative costs of supplying energy to households through off-grid photovoltaic microsystems, in the case of Bolivia.
• To propose adjustments in the institutional and regulatory approach to provide sustainability to state intervention in the provisioning of electricity through SFV solutions.

3. Methodology
For the fulfillment of the described objectives, the investigation has begun with the compilation of documentary information and with the analysis of the different projects/programs executed by the government and other organizations to provide electricity through PVS for benefiting inhabitants of remote rural areas of Bolivia. Once these Programs/Projects have been identified, the beneficiary rural communities were identified and through the geo-referencing of the same, it has been
possible to know the spatial distribution of these projects and to plan a representative field research work to obtain conclusions that may be then generalizable.

Taking this into account, the extension and characteristics of the ecological floors that make up the Bolivian territory, for the collection of information from primary sources, it has been reached a stratification, considering three ecological levels. The Llano (communities in territories ranging from 400 to 1000 m above sea level), Valleys (communities in territories ranging from 1000 to 3000 m above sea level) and Altiplano (high and plane lands) (communities located at 3000 m or more above sea level). Likewise, the communities that would be visited for interviews and inspection of the installed PVS have been defined considering their accessibility. The field research work has sought: (i) to verify if the PVS is working; (ii) to establish the beneficiary’s satisfaction level and the suggestions regarding the quality of this service; and, (iii) to identify the reasons/problems in the case of out-of-service PVS’s.

The comparative experience analysis has been carried out by searching for information from secondary sources, particularly research studies, in government documents and reports from regulatory institutions in countries of the region. For this work, the specific cases of Argentina, Peru, Ecuador and Guatemala were selected, among other reasons, because: (i) their comparability with the Bolivian case; (ii) they have developed projects that have been internationally mentioned as studies and/or successful cases in the effort to solve the problem of access to electricity in remote areas; and (iii) by the availability/access to information about the projects and programs executed through state or private intervention. The investigation of the international experience was carried out to (i) establish if those projects are considered successful or failed, (ii) identify the success/failure indicators that have been used; and, (iii) identify findings that should be considered to generate a proposal for the Bolivian case.

The field research has also allowed to establish the needs of energy demand, the costs of parts, their duration, and maintenance or substitution needs, have allowed modeling the cost of supplying energy to households through PVS off grid, through the design of a standard PVS. The necessary adjustments that should be made in the institutional and regulatory framework of the state have been too identified, in order to propose a scheme for providing access to electricity to remote regions, using these standard PVS under a service provision approach, as in the case of service provision within the conventional distribution system.

4. Off-grid photovoltaic systems and sustainability options
Thanks to the technologic advances and due to the social demand for use of less polluting technologies, solar energy has become the technology with greater projections for the solution of access to energy in remote areas. The energy provided by a PVS is clean and inexpensive to produce on a small scale, since the main cost is related to the installation of the necessary infrastructure to use it. In fact, only the production of some parts, such as batteries, generates waste during its production process and at the end of its useful life, so that PVS is the best alternative as source of clean energy to replace fossil fuels.

For this one, among other reasons, more and more often, you can see solar panels located in buildings and houses as a source of energy for the direct use of the same building. Solar system plants are also being built in recent years using large areas of territory. For example, in the Bolivian highland (altiplano), in the round of the “Salar de Uyuni”, the largest salt desert in the highlands of the world, a power generation plant has been built using solar panels, with a capacity of 60MW; The area covered with solar panels is about 100 ha, forming a giant mirror of photovoltaic cells (ENDE, 2019).

Technically, solar panels are flat surfaces formed by units called photovoltaic cells that collect solar radiation and transform it into useful energy for human consumption. Each photovoltaic cell generates a small amount of energy that is conducted through integrated cables to the same
panel to be added to the energy produced by the other panels that make up the park, thus reaching important magnitudes as the Salar de Uyuni's Plant. The result is the generation of an electric current that can be used to meet the energy needs of human activity. So, renewable energy is obtained from a natural resource as abundant as sunlight. Specific references about solar energy systems can be found in the work of Fthenakis and Kim (2010).

Despite the great advances of recent years, the solar panels technology still has its limits. Nowadays, the main problem is that they need large areas of land for their installation in order to generate electricity to meet an increasingly growing demand, as shown, for example, by ENDESA on its website (ENDESA, 2018).

4.1. Sustainability of off-grid photovoltaic systems

The development of photovoltaic energy micro-systems has become the capture of solar energy to generate electricity, a very interesting alternative to increase the electric coverage, particularly to give access to populations of remote rural populations. Renewable electric microsystems are mechanisms for the generation, storage, and supply of electricity that operate on the basis of renewable energies and that are characterized by being isolated from any electric distribution system. These micro-systems can be used to supply electricity to different types of buildings such as homes, health posts, schools, etc., typically, home photovoltaic systems (PVS) are the ones that have received the most attention.

Jelle, Breivik, and Røkenes (2012) found that these photovoltaic solar energy microsystems integrated into the structure of buildings have a great advantage compared to non-integrated systems, because in this case there is no need to use other spaces or to develop independent photovoltaic systems.

According to the evidence found, the off-grid PVS's installation projects executed so far, have not contemplated an integral vision of sustainability, which refers, by definition, to the satisfaction of current needs without compromising the capacity of the future generations to satisfy theirs, guaranteeing the balance between economic growth, the environment care and social welfare (Wieczorek, Raven, & Berkhout, 2015; Feron, 2016).

From the perspective of the previous conceptual definition, sustainability should have as a condition, the capacity of PVS to provide electric power service to their beneficiaries in an enduring manner, in harmony with the environment. The durability depends on technical, economic and social factors, among them: i) the equipment durability, properly said, ii) their correct installation, iii) the existence and accessibility of spare parts and replacement parts, iv) the technical ability to make the replacements, v) the beneficiaries economic conditions to make the economic expenditures required for the replacement/repair of parts and equipment, vi) the training and knowledge levels of the beneficiary families, and, the institutional configuration and regulations that allow the generation of a comprehensive sustainability system. An approximation of this is shown in Figure 1.

5. Projects of PVS in Latin America

Some elements associated with the sustainability of PVS projects in Latin America are analyzed from the perspective of sustainability (Feron, 2016) (Barnes et al. (2018)). Next, some reflections on such experiences.

5.1. Sustainability

The investigation of experiences of selected Latin American countries shows that the applied sustainability concept is based on three basic pillars: i) technical sustainability, ii) economic sustainability, and iii) social and organizational sustainability (PERMER, 2012) (OLADE, 2013, 2015):

- Technical sustainability: The technical sustainability is related to the configuration, selection and adequate sizing of the equipment, the quality and guarantee of operation and maintenance
offered by the suppliers, as well as the possibility of having service centers (including the spare parts provision), remote monitoring and management of impacts and risks and cadaster of installed equipment.

- **Economic sustainability**: The economic sustainability goes through the appropriate evaluation of the community’s needs, the pricing of the service and the adoption of innovative ways of collection and continuity in collection.

- **Social and organizational sustainability**: Social sustainability has to do with the appropriation by the community and users of the benefits and commitments of the project. For their part, local and national institutions must be able to establish effective mechanisms for communication, knowledge transfer, and long-term monitoring.

### 5.2. Organizational aspects

In the case of Argentina, under a political organization of the federal type, the PERMER (2012) guarantees the financing and national coordination of the PVS projects executed by the provincial governments, which in order to benefit from the PERMER, must be subscribed by signing agreements with that program and constitute their own executing units. The responsibility on PVS operation and maintenance (O&M) corresponds to the local electricity distribution operator, which operates the PVS under supervision of the regulatory provincial entity.

In the Ecuador case, the FERUM (CENEL, 2013) oversees financing the installation projects of PVS that are presented by the companies that provide the electricity distribution service. The National Electricity Council (CONELEC) reviews these projects and approves them for funding, establishing an order of priorities, due to the limited availability of resources. Subsequently, the Installation, and the O&M as well as the replacement of defective parts are responsibility of the same distributor. There are also Local Electrification Committees that are formed by members of the community and the distributor, mainly for the preparation phase of the projects (Feron, Heinrichs, & Cordero, 2016; OLADE, 2015).

In Guatemala, isolated photovoltaic systems which have been installed lack a regulatory framework to which they must be subjected. Usually, there are rules for financing, operation, and O&M for the program that promotes the facilities. The Projects developed by the Directorate General of Electricity (DGE, 2018), have the support of local boards for the management of the facilities. In
these projects, the beneficiaries commit to pay monthly a certain amount that is administered by local boards to hire companies or specialized technicians to perform the tasks of O&M (Corsair, 2013; OLADE, 2013, 2015).

5.3. Economic aspects: collection and payment

In Argentina, due to the federal nature of the country, the billing scheme is defined by each province. In the specific case of Mendoza and Catamarca, payments are made twice a year, under post-payment modality of fixed amounts. The fee is charged by the distribution operator (FERUM-CNEL EP, 2018).

In Ecuador, according to the information shown, the billing is monthly. PVS users must make the payment to the “Community Administrative Operator” who is a member of the Local Electrification Committee which is defined and constituted by the community. The payment is of a fixed amount (Feron et al., 2016; OLADE, 2015).

In Guatemala, it has not been possible to obtain data for the projects and facilities developed by NGOs. In the case of projects in which the community has assumed responsibility for maintenance, payments of a fixed amount previously agreed, are made through community leaders, appointed by the community itself (Corsair, 2013; OLADE, 2013, 2015).

In the Peruvian case, the collection of payments is responsibility of the distribution company to which the service was awarded in a competitive bidding for each region. The payments are made ex—post, monthly, although some of the companies for reasons of collection costs, have extended this period to bi-monthly payments or more (Dirección General de Electrificación Rural [DGER], 2015; Johannes, 2008).

As a comparative reference, Table 1 shows the rates charged in the countries analyzed by the PVS use.

| Country  | SFV capacity | Subsidy (USD/ Month) | Paid by the User (USD/ Month) | Monthly Service Cost (USD/ Month) | Observations                  |
|----------|-------------|----------------------|------------------------------|----------------------------------|------------------------------|
| Argentina| 10 kWh/ Month | 6.40 | 2.75 | 9.15 | Amount Paid to System Operator |
|          | 15 kWh/ Month | 9.38 | 4.02 | 13.40 | Amount Paid to System Operator |
|          | 20 kWh/ Month | 10.86 | 4.65 | 15.51 | Amount Paid to System Operator |
| Ecuador  | 19 kWh/ Month | 1.49 | 1.46 | 2.95 | Amount Paid to System Operator |
|          | 10 kWh/ Month | 2.50 | 2.50 | 2.50 | Paid to Community board        |
|          | Prepayment per 15 kWh/ Month | 15.00 | 15.00 | 15.00 | Amount Paid to System Operator |
| Peru     | 10 kWh/ Month | 10.39 | 2.59 | 12.98 | According to Model Results     |
|          | 15 kWh/ Month | 6.64 | 3.43 | 10.07 | According to Model Results     |

Source: Own elaboration with information from various cited sources.
6. Programs/projects of SFVs in the Bolivian case

Fifteen programs/projects have been identified which include the provision of PVS to families in the Bolivian rural areas, executed during the last 10 years. With these programs/projects, off-grid photovoltaic systems have been provided to approximately 36 thousand families, as shown in Table 2.

The financing of the PVS provided in the different programs/projects developed has had the following characteristics:

(i) **PVS delivered free of charge.** These programs/projects were supported through international cooperation and charged to the budgets of the Central Government and the Regional and Municipal Governments.

(ii) **PVS delivered with counterpart contribution.** The percentage of contribution that has been required from the beneficiaries has varied between 10% and 60% of the equipment value, depending on the financing source of the program/project.

(iii) **PVS purchased by the beneficiary himself.** The least of the cases have been those in which the beneficiary has committed to cover 100% of financing. It has generally occurred in cases in which a family has not been included in the program/project of their region and took advantage of the presence of the provider to acquire their PVS.

In all these programs, after the guarantee period that has varied between 1 and 4 years in which the supplier has been responsible for the maintenance of the PVS and the replacement of the damaged parts, the operation of the equipment has overseen the own users. The assumption on which these programs/projects have supported, according to the interviews conducted in this research, has been that by becoming accustomed to the use of energy and appropriating the benefits of technology, the rural inhabitant would appreciate the improvement in their quality of life and, consequently, he would seek, with its own resources, that his installed PVS continue working. However, in the fieldwork interviews conducted it has been shown that even though, in general, all families have appreciated the improvement in their living conditions, different factors mean that they are not able to give sustainability to their PVS.

6.1. Findings in the Bolivian case

The main findings, which are summarized below are:

- In most cases, the electric power generated by the PVS is used for (i) lighting, either for homes with fixed bulbs or for charging lanterns, (ii) for recharging mobile phone batteries, and (iii) for the operation of radios. Only in very few cases has been found a family which uses energy for the operation of a television set and other devices such as low energy consumption DVD player.

- Absence of technical maintenance to the PVS. As a result, 38% of the inspected PVS are not in operation due to the components deterioration. In the case of PVS installed more than 5 years ago, this percentage is higher than 90%, mainly due to the end of the battery life.

- The beneficiaries themselves perform preventive and corrective maintenance. In this context, during the fieldwork, it has been verified that with a proper prior training process, families can

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**Table 2. SFV installed by executor (last 10 years)**

| Type of Project | Home Category | Grand Total |
|-----------------|---------------|-------------|
|                 | SFV           | PSFV        |             |
| State           | 1,961         | 15,768      | 17,729      |
| Cooperation     | 1,000         |             | 1,000       |
| Totals          | 2,961         | 15,768      | 18,729      |

Source: Own elaboration with information from various cited sources.
perform some basic maintenance tasks, mainly the periodic increase of distilled water to the battery.

- PVS with panels fixed to a base such as a metal pole are those that are best preserved and in operation. Conversely, in the cases of installation by the beneficiary himself, mainly the peak PVSs, they had greater difficulties in their operation, either due to inadequate panel orientation or due to family neglect. This finding demonstrates the need for a specialized company to be in charge of the installation and the O&M.

- Diversity of brands, capacities, and origins of parts such as throttles and control equipment were found. This situation hinders the development of a market for standard spare parts, as well as the centralization of O&M activities in a specialized organization. In most of these installations, the modules require maintenance and/or replacement.

- Despite the notorious difference in altitudes of the different geographical areas of Bolivia, it has been evidenced in the inspections that the technical design and the characteristics of the equipment have not influenced the system functioning, in any of the ecological floors.

- The size of the PVS kit with panels of 50–55Wp and acidic batteries of 100Ah, does not maintain balance or proportion with the required energy, since for the full charge of this type of batteries it takes more than 2 days of total solar light. However, this circumstance has made it possible that batteries with more than 7 years old to continue functioning.

6.2. Environmental aspects

Although as Tsoutsos, Frantzeskaki, and Gekas (2005) point out that photovoltaic energy does not produce significant impacts on the environment, under a comprehensive sustainability approach, it is necessary to implement an environmental plan for waste handling of parts and components, mainly the batteries. In interviews with the companies that provide solar energy equipment in Bolivia and in the fieldwork developed in the research, it has been possible to demonstrate that the batteries and equipment in disuse remain in beneficiary households, generating a potential focus for contamination.

6.3. Factors to give sustainability to the PVS domiciliary

In Figure 2, the causality relationships of the identified problems are synthesized.

Below is a list of the factors that have been identified in the course of the investigation as necessary to consider the sustainability of home PVS:

(i) In general, after the guarantee period in which the supplier company had to perform the maintenance and replacement of the defective parts, the supplier has no longer presence in the communities, so the possibility of obtaining replacements has been practically null. These spare parts, except in the case of the battery, are not of great cost (for example, fuses,
switches or light bulbs) or technical complexity, so that a basic technical knowledge and the availability of replacements would have solved circumstantial operational problems.

(ii) The replacement of the battery at the end of its useful life has not occurred; families have not had the foresight (and/or possibility) to save to cover the replacement cost.

(iii) The impossibility of covering additional uses with the PVS, for example, a television set operation, has meant that, in general, families prefer the energy from distribution system, which is the reason several communities benefiting from PVS have continued with its demand for power supply from the grid system.

(iv) Due to in some projects, the PVS was delivered in an office with very short training for its installation and use, that is, without verifying the needs of the beneficiary family, households that have more than one PVS kit—voltaic peak and a PVS. This distorts the objective of reaching the maximum possible coverage in terms of the number of beneficiary families.

(v) The families interviewed expressed their willingness to pay a monthly fee for maintenance coverage and the scheduled replacement of the parts, in order to guarantee the regular operation of their PVS.

(vi) It has been found that to the extent that the beneficiary's counterpart contribution has been greater, the beneficiary's commitment to maintain and sustain its PVS has also been greater.

(vii) Local governments are the closest to the population in their jurisdiction, which has made them the main recipients of any complaint or claim related to the operation of their PVS. In this regard, their participation must be considered, both for the selection of beneficiaries and for the support of PVS provision programs, aspects of which have been absent in almost all the programs/projects analyzed.

7. Estimation of costs in the case of Bolivia
The PVS technical specifications have been established based on the electrical energy requirements of the users identified in the fieldwork. According to this, up to four possible categories have been configured, as shown in Table 3. The amount of energy (Wh/day) for each category has been determined considering the average power consumed.

For the technical configuration of the PVS, the technology was considered with the best performance and efficiency in the operation, and with the lowest associated operating costs.

- **PVS Basic characteristics:** Estimated useful life of 20 years or more. Low level of technical maintenance. Activation or deactivation of the service through the payment control module. Nominal service voltage 12VDC.

- **PVS Operation.** In the presence of solar radiation, during the day, the photovoltaic panel generates electricity from direct current that is stored in the battery. In the absence of solar rays, the battery is the one that supplies the electric energy. The PVS is designed for the operation of three electric lamps or luminaires, a flashlight with rechargeable battery, an AM—FM radio with rechargeable battery. The PVS includes the necessary protections against short circuits. The

| No. | Category | Wh/Day |
|-----|----------|--------|
| 1   | CD1      | 48     |
| 2   | CD2      | 143    |
| 3   | CD3      | 393    |
| 4   | CD4      | 1,130  |

Source: Own elaboration
control equipment regulates the charge of the battery protecting it from overloads. The PVS will have an autonomy of at least a day and a half.

- **PVS Installation.** PVS installation is in charge of specialized technical staff that depends on the supplier. The supplier must apply the performance tests and the users must be trained in the use of electric power and the PVS.

The estimate cost for four types of standard kits are shown in Table 4. These costs were established through quotations in the local market with five companies identified as suppliers of the different programs/projects in the past and the importation of spare parts, in which case all costs and import taxes have been included.

### 7.1. Activities for provision of the energy service through PVS off grid

It has been considered that the PVS energy distribution service must include the following activities:

- **PVS Installation.** The PVS provider must perform the correct installation of it in the place where it is intended to provide energy.
- **Administration.** The Administration includes, among others, administrative personnel, equipment and facilities (including offices, warehouses, and garages) and public communications and basic sanitation services for such facilities.
- **Operation and Maintenance (O&M).** Includes all actions to ensure the proper functioning of the PVS, inspections, predictive, preventive and corrective maintenance.
- **Investment.** Three types of investment have been identified:
  - **Initial Investment:** It is the expense for the purchase of the PVS, its storage and subsequent transfer and location is its final location.
  - **Modernization:** It is the expense for the replacement of components by more efficient ones, due to technological change.
  - **Replenishment:** The disbursement for the replacement of the PVS includes the partial or total change of an asset or the system as a whole.

### 7.2. Cost model

In the Bolivian case, the approach used to remunerate the electric distribution service providers, as well as the assets that make up the electric distribution system, corresponds to the requirement of estimated income, considering a reasonable return over investments, currently the rate set by the regulatory authority is 10.5%.

In this case, for the provision of the service, it is necessary to carry out the acquisition and installation of the PVS in the places of use, this is what in the modeling has been called INITIAL INVESTMENT.

The new replacement and the modernization of the components of a PVS are, due to their final objective, new investments, for that reason they can be grouped in a single activity that for the modeling has been called O&M INVESTMENT.

Meanwhile, the administration, operation, maintenance and partial replacement of components, have been grouped into an activity called Administration, Operation and Maintenance of the PVS (O&MA).

The initial investment is shown in Table 5.
| No. | Modules                                    | CD1      | CD2      | CD3      | CD4      |
|-----|--------------------------------------------|----------|----------|----------|----------|
| 1   | Photovoltaic panel                         | 1 x 30 Wp| 1 x 60 Wp| 1 x 140 Wp| 400 Wp   |
|     | Support (2.8 m metal poles, frame and cement base) | 44.30    | 44.30    | Support for two solar panel | 65.66 |
|     |                                            |          |          |          | Support for four solar panel | 177.20 |
| 2   | Charge controller and USB port 5 VDC x 1500 mA | 53.60    | 53.60    | relay 12/24 VDC, 15 A | 99.50 |
|     | Payment controller                         | Equipment and credit transfer device | 150.86    | Equipment and credit transfer device | 150.86 |
|     |                                            |          |          |          | Equipment and credit transfer device | 150.86 |
|     | Battery                                    | 1 x 20 Ah x 12 V, DOD 90%, ION-Litio (LiFePO4) | 341.50    | 300 Ah 12 V, DOD 50%, AGM-GEL sealed | 321.00 |
|     |                                            |          |          |          | 300 Ah 12 V, DOD 50%, AGM-GEL sealed | 963.00 |
|     | Datalogger equipment                        | equipment | 38.00    | equipment | 38.00    |
|     | Inverter                                   | Inverter 12 VDC—220 VAC, 300 W | 207.00    | Inverter 12 VDC—220 VAC, 1500 W | 1,035.00 |
|     | Central box or cabinet                      | Box      | Box      | Box      | Box      |
|     | LED type lamps                              | 2 x 3 W y 1 x 5 W | 27.00    | 2 x 3 W, 1 x 5 W | 45.00 |
|     | Cables and accessories                      | Chained cable, Bipolar cables, Switches, Sockets | 36.00    | Chained cable, Bipolar cables, Switches, Sockets | 45.00 |
|     |                                            |          |          |          | Chained cable, Bipolar cables, Switches, Sockets | 45.00 |
|     |                                            | Category 1 | 782.26 | Category 2 | 1,044.90 |
|     |                                            |          |          |          | Category 3 | 1,194.02 |
|     |                                            |          |          |          | Category 4 | 2,139.22 |
Into the costs of O&M (Direct Costs), preventive maintenance and corrective maintenance have been differentiated; the results are shown in Table 5. The estimated indirect costs are shown in Table 6.

7.3. Results of the cost model
To determine the required rate, an annuity has been estimated, considering a useful life of the PVS of 20 years. The results are shown in Table 7.

7.4. Dignity tariff
The Dignity Tariff has been established by Supreme Decree No. 0465 of 31 March 2010 and consists of a discount of twenty-five percent (25%) with respect to the total amount invoiced for monthly electricity consumption to home users of public electricity service with equal or less of 70 kWh.

### Table 5. Direct costs

| DIRECT COST               | Preventive Maintenance (USD per Year) | Corrective Maintenance (USD per Year) |
|---------------------------|---------------------------------------|---------------------------------------|
| Workforce                 |                                       |                                       |
| Electrical Technician     | 2.56                                  | 6.40                                  |
| Electrical Assistant      | 1.83                                  | 4.57                                  |
| Engineer                  | 0.09                                  | 0.09                                  |
| Expenses                  | 3.16                                  | 7.90                                  |
| Sub-total                 | **7.64**                              | **18.96**                             |
| Transport                 | 0.00                                  | 0.00                                  |
| Car Rental                | 5.03                                  | 12.57                                 |
| Fuel                      | 0.57                                  | 1.44                                  |
| Sub-total                 | **5.60**                              | **14.01**                             |
| Tools (6% of workforce)   | 0.46                                  | 1.14                                  |
| Sub-total                 | **0.46**                              | **1.14**                              |
| Materials                 | 0.00                                  | 0.00                                  |
| Cleaning                  | 0.20                                  | 0.50                                  |
| Work clothes              | 0.11                                  | 0.00                                  |
| Sub-total                 | **0.31**                              | **0.50**                              |
| Number of visits per year | 0.50                                  |                                       |
| failure rate              |                                       | 5%                                    |
| TOTAL PREVENTIVE MAINTENANCE | **7.00**                          | **1.73**                              |

### Table 6. Indirect costs

| INDIRECT COSTS | Annual Cost (USD/SFV) |
|----------------|-----------------------|
| — Administration | 2.59                  |
| — Communications | 2.07                  |
| — Collection costs | 1.72                  |
| — Consumer costs | 5.04                  |
| — Rentals         | 2.40                  |
| — Software        | 0.10                  |
| — Desktop Material | 0.30                  |
| TOTAL INDIRECT COSTS | 14.22               |
According to the present work, the Dignity Tariff, should be applied to Category 1 of Domiciliary use. The application of the Dignity Tariff should allow the PVS user to pay no more than the amount paid by a user of the conventional distribution system. That is, an amount not higher than Usd.3.89, so that the subsidy charged to the Dignity Tariff would be about Usd.3.44. According to the estimates in this research, the monthly amount to be covered by the subsidy amounts to approximately USD360 thousand per month.

Considering the information from the Ministry of Energy of Bolivia and data from the National Institute of Statistics (INE, 2012), about 278 thousand families may not have electricity by 2018, with this, it is expected that 73 thousand families are provided with energy through the PVS installation. The detail is shown in Table 8.

### 8. Towards a comprehensive sustainability scheme
Country experiences on energy sustainability schemes are summarized below.

#### 8.1. The international and national experience
Based on the review of international and national experience, it can be established that the applied sustainability schemes have only been related to some aspects identified in this work, none of them has considered sustainability into a comprehensive approach. The sustainability schemes applied in Bolivia and in the analyzed countries have had certain characteristics and results that are summarized below:

- **Bolivian case.** Delivery without cost or with a subsidized cost of the PVS to the beneficiary. The activities of O&M after the guarantee period oversaw the beneficiary himself. From the fieldwork carried out, it has been concluded that only in very few cases has the beneficiary been able to perform the operation and maintenance after the guarantee period, therefore, in most cases, the PVS whose battery has reached the limit of its useful life, it is out of service.

- **Guatemalan case.** The financing has been through isolated programs developed by NGOs, oriented to the provision of PVS equipment. The sustainability of the effective operation is a responsibility of a neighborhood committee, who is responsible for charging the beneficiaries a monthly maintenance fee. Of the studies carried out, for example, Corsair (2013, p. 14), citing Nieuwenhout (2001), states that 45% of the solar home systems did not work 5 years after their implementation. This question the effectiveness of sustainability in this scheme.
Ecuadorian case. The most recent programs are being developed through the FERUM Program, in which the equipment is 100% financed by the State and the O&M oversees the electric distribution companies in that region. The financing is made by the user through the payment of a fee. Although there is no general evaluation of these programs, the partial evaluations show that the model has been more successful than the previous schemes, in this regard Feron (2016, p. 13) states that in the case of “CentroSur”, this strategy has proved to be appropriate, and quoting Urdiales (2015) shows that more than 95% of the off-grid PVS installed by this distribution company are operating.

Argentine case. The PERMER Program grants the equipment financed by the State (National and Provincial) in about 100%. The maintenance in the most recent projects, has a scheme like the Ecuadorian one, supervises the distribution operators and is paid by users through a fee. Access to the PERMER requires preparing a preliminary draft of technical, economic, social and environmental pre-feasibility, where mechanisms for the sustainability of the project are proposed. At this respect, the Final Evaluation Report of the Project of Renewable Energies in Rural Markets (PERMER), points out that in the provinces with adequate management models very positive results were presented regarding the user’s perception of the quality of the product and service. The sustainability of the system is achieved through the payment of the service that, in addition, gives the right to submit claims, an aspect that is guaranteed by the regulator (PERMER, 2015a).

8.2. Regulations and institutions involved in the renewable energy policy

In the Bolivian case, as shown by Zegada (2016), the renewable energy policy is based on the Political Constitution of the State (CPE), the National Development Plan, the Autonomy Law, the Integrated Planning System—Law 2048, the “Electricity for Living with dignity “, the Plan for the Development of Renewable Energy in Bolivia by 2025, the Plan for Universal and Equitable Access to Electricity,” Bolivia with Energy “, the Law on Electricity, and finally the Framework Law for Mother Land and Integral Development for a Better Life—Law No. 300, which aims to gradually increase the share of renewable energy in electricity generation.

Also, at the national level, several institutions have relevant responsibilities with respect to the electricity sector. The most important actors are: The Ministry of Hydrocarbons, the Ministry of Energy, the Vice Ministry of Electricity and Alternative Energies, the Vice Ministry of Energy.
Development, the Authority for the Control of Electricity and Nuclear Technology (AETN), the National Electricity Company (ENDE) and the National Load Dispatch Committee (CNDC). In recent years, several of them have been taking actions to increase the use of renewable energy sources, in compliance with national development plans and the mandates of the CPE.

Zegada (2016), points out that the supply of energy is crucial for rural development. It could be an opportunity to develop renewable energies, through the introduction of appropriate legislation and energy policies.

9. Proposed integral sustainability scheme
Next, a sustainability scheme is synthesized for the specific case of Bolivia.

9.1. Guidelines for integral sustainability
Based on international experience and the review of national experience, it is established that, in the Bolivian case, sustainability is not viable under the schemes applied until now. Against this, the following guidelines are proposed to achieve integral sustainability:

(i) It would be convenient to carry out a standardization of the PVS equipment that will be installed for a domiciliary category that in the present work is called basic. In this way, the proliferation of brands and types of PVS kits would be avoided.

(ii) The provision of the PVS must be made under a service provision by a specialized operator. It is proposed that the specialized operator be the authorized operator of electric distribution in each region.

(iii) Technologic neutrality. The beneficiary of PVS must be as any user of the electricity service to obtain rights and duties such as the Dignity Tariff and other.

(iv) The definition of whether a rural inhabitant can be a user of the electricity grid or a beneficiary of the provision through a PVS off grid, should be given by the current and future technical feasibility of receiving energy from the distribution system through the plans of rural electrification. For this, an adequate coordination of the investment plans between the different levels of government is required. The central government should participate in the formulation and financing of the electrification plans through PVS, together with the departmental and municipal governments, and should preferably be the bidder for the purchase of PVS equipment at the national level;

(v) Given the high investment costs in PVS equipment, as shown by other experiences, this scheme can only be possible if the State is the one that provides the PVS equipment, preferably, free of charge or with a high percentage of subsidy.

(vi) Each beneficiary family must pay the operation costs, maintenance and replacement of parts and spare parts, paying a base rate. The results of the modeling cost show us that this rate must be with an important subsidy percentage that must be financed by the “Dignity Rate” Fund.

(vii) The regulator of the electricity sector must have tuition in the regulation of the activity developed by the electric power service provide via PVS off grid.

9.2. Normative and institutional adjustments
Under this scheme, from the user’s perspective, their rights and obligations should be similar to those of any user connected to the distribution system. Therefore, the only thing that will make the difference between both types of users, would be the technology with which the electric power is provided (technological neutrality).

In the case study, in order to operationalize and allow the sustainability of PVS projects, it is necessary to adjust the current regulatory framework, through the issuance of a Supreme Decree.
regulating the provision of photovoltaic systems, financing, institutional participation, and the corresponding attributions and functions.

The proposal for institutional and regulatory adjustments is summarized in Figure 3.

10. Discussion of results
Through the study of the objectives and characteristics of the different programs/projects applied in Bolivia to provide electric power with small PVS off grid and through field research in communities benefited from the three ecological levels of Bolivia (Highlands, Valleys and Llanos and
Chaco), it has been possible to identify findings that have made it possible to establish the existence of a causal relationship between the budgets of sustainability of the projects, the idiosyncrasy, and education of the beneficiary population, and the regular operation of the PVS off grid installed.

The office work and the field research in the beneficiary communities has made it possible to identify that the programs/projects in Bolivia and in the other countries have been conceived, mostly, to deliver the PVS free of charge or with small contributions from the counterpart, under the assumption that subsequently the beneficiary would perform the operation and maintenance tasks on their own and at their cost, to guarantee the operation of their PVS.

The research has established that, although the beneficiary families value the new comforts achieved with the PVS, they are not prepared, for economic and cultural reasons, to anticipate future expenses to replace the parts and spare parts of higher cost of their PVS, once they have exhausted their useful life.

Another aspect that has not been considered at the time of designing the adopted sustainability schemes has been the development and consolidation of a market where parts and spare parts can be obtained, as well as the provision of technical assistance services. In fact, in the Bolivian case, these aspects were the reason why the installed PVS stopped operating when the batteries exhausted their useful life or when some components, even the very low-cost ones, stopped working. Consequently, in future interventions, a sustainable scheme for this situation should be foreseen. This is also valid for the other countries analyzed.

Large-scale interventions, such as those developed by government programs and projects and international cooperation, should consider an integral sustainability approach. This necessarily implies considering the environmental aspect, since, even though each single PVS has a low polluting impact per se, the polluting impacts are cumulative and become increasingly significant when interventions are done at a larger scale. It has been identified, for example, that the PVS delivery schemes do not include a retirement system for the disused parts, leaving the family under the responsibility of carrying out the disposal of the waste that, like batteries, have a risk of pollution that should be considered. Similar situations have been identified in the other countries analyzed.

The solutions applied in the countries analyzed have been diverse. In the case of Guatemala, community intervention meetings were adopted to establish and administer the monthly contributions of beneficiary families in the O&M. In the cases of Argentina and Ecuador, the electricity distributors manage the installation activities of the PVS, but the regular O&M are handled with a periodic payment of the beneficiaries of the PVS. In Peru, companies were hired to install PVS and O&M in specific regions, charging a fee approved by the regulator.

The findings of the research work for the Bolivian case, in accordance with the trends identified in the countries studied, have allowed establishing comprehensive sustainability guidelines that cover regulatory—institutional, operational and financial aspects, which could be replicated in other countries with the corresponding personalization. Table 1 shows a calculation of monthly payments made by families for the use of their SFV in the analyzed countries.

11. Conclusions
Based on the results of the research and the found evidence, it has been possible to establish the following conclusions, grouped by objectives:

11.1. Findings associated with PVS
The main premise to assume the sustainability of the off-grid PVS installed in the last 10 years has been that families would be able to perform the O&M tasks themselves or through third parties, at
their own cost, as well as to replace the damaged parts and/or the parts that have reached their useful life. This premise has been proven not accurate.

There is no culture or custom for families to foresee future expenses and a market for spare parts and repairs has not developed. As a result, of the 36 thousand SFVs installed in the last 10 years, more than 90% of the units installed 4 years ago or more, are out of operation.

The provision of PVS has made it possible to improve the quality of life of the beneficiary rural families, which has generated a predisposition to pay a monthly fee to whomever guarantees that their teams will function regularly.

In Bolivia, the right to access to energy, as well as the development of renewable sources of energy, is a constitutional mandate; however, the regulatory development and the development of a regulatory and institutional framework are insufficient.

11.2. Regional comparison
The revised international experience shows findings similar to those found in Bolivia. Currently, the solution that is being imposed is the delivery of PVS under a way of services provision in which the user commits to the payment of a periodic fee. This solution, together with adjustments in environmental, institutional and regulatory matters, seems to be also the alternative of sustainability for the Bolivian case.

Research on the experiences of selected Latin American countries shows that the applied sustainability concept is based on three basic pillars: technical sustainability, economic sustainability, and social and organizational sustainability.

The payment for the use of PVS off grid under the electric service modality implies the existence of a subsidy higher than the amount paid by the user; this subsidy allows the O&M cost to be covered exclusively with the tariff.

11.3. Results of cost modeling
The determination of investment costs and O&M, in the Bolivian case, shows that a monthly payment of USD7.33 is necessary for the beneficiary families. Amount much higher than that paid for minimum consumption, by a user of conventional systems, whose consumption is benefited by a subsidy called Dignity Tariff.

The subsidy required to level the monthly payment to the amount paid by the beneficiaries of the Dignity Tariff is USD.3.44. According to the estimations of this investigation, the monthly amount to be covered by the subsidy is approximately of USD360 thousand each month, less than 3% of the total billing to the domiciliary category and significantly lower than the total amount required for the payment of the Dignity Tariff of the conventional system.

11.4. Proposal for the Bolivian case
It is proposed that the distribution operators of the conventional system take over the provision of the electric service through PVS off grid, against the payment of a monthly payment. The initial investment should be covered by the State and/or by concessional financing.

In consideration of the economic conditions of the beneficiary population of the PVS, it is necessary to apply subsidy mechanisms. In this regard, in the countries analyzed, subsidies have been considered for the initial investment and/or the use of PVS. Likewise, both in Bolivia and in the countries analyzed, a subsidy is applied to electric consumption, under the conventional modality, for low-income families. It is proposed to replicate this subsidy to avoid claims for discriminatory treatment.

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An integral sustainability approach must be considered, which implies necessarily contemplating the environmental component and a restructuring of the institutional roles.

Making policy adjustments and regulatory capacities is necessary to enable the intervention of the current electric distribution service operators and the Electricity Regulation Authority, as regulator of this service.

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Correction
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