A new integral management model and evaluation method to enhance sustainability of renewable energy projects for energy and sanitation services.

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Abstract

Autonomous systems based on the use of renewable energy (RE) have proven suitable for providing energy and sanitation services to isolated communities. However, most of these projects fail due to managerial weaknesses. In these systems, designing an appropriate management model is a key issue for sustainability and it is especially complex if it has to include different RE technologies. This paper is aimed developing a novel management model for RE projects to provide energy and sanitation services able to deal with any kind of technology. Moreover, a new method to evaluate the sustainability is proposed regarding the technical, the economic, the social/ethical, the environmental and the institutional/organizational dimension. In particular, the case study of Pucara (Peru) is presented, in which a RE project with six different technologies was implemented and the integral community management model was designed in 2011. The project sustainability was evaluated in 2013 and results showed the management model has succeeded to strengthen the sustainability of the project, especially in the institutional/organizational aspects.

Keywords

Renewable energy projects
Basic energy and sanitation services
Rural areas
Management model
Sustainability

1. Introduction

Energy services are crucial for eradicating poverty, improving human welfare and raising living standards (Vera, 2007). However, providing access to these services remains a major challenge (Bhattacharyya, 2012a; Mainali and Silveira, 2013; Mainali et al., 2014; Spalding-Fecher et al., 2005) as the vast majority of the world's population, especially in rural areas, still lacks access to these services. Indeed, one in four people on the planet lacks access to basic energy services, this being a huge barrier to improving living conditions and a serious hindrance to economic and social development (IEA, 2010). Moreover, there is a generalized lack of sanitation services. UNDP (2006) concludes that water and sanitation crisis is a direct and immediate threat for poor people in development countries. Thus, providing appropriate and reliable modern energy and sanitation services using secure and environmentally sound technologies, in conformity with socioeconomic needs and cultural values, is essential in the race for sustainable development.

Autonomous systems based on the use of renewable energies (RE) have proven suitable for providing affordable, reliable, safe, and high-quality energy and sanitation services to isolated communities. Moreover, RE projects might potentially strengthen people's self-reliance and empowerment and improve the quality of their environment, including the immediate environment in their households (Johansson et al., 2002).

In Andean rural communities RE based development projects have been implemented, both by public or private initiatives (Midilli et al., 2006). However, most of these projects have failed due to deficient managerial skills (ESMAP, 2010), as these have a big influence on systems' sustainability (Gomez and Silveira, 2012; Palit, 2013; Shyu, 2013; Yadoo and Cruickshank, 2010; Zhang, 2011).

Thus, establishing an adequate management model is a key process when implementing any kind of technology project in rural areas. Sanchez (2006) identified that the management model is the most important factor in achieving sustainability for rural stand-alone electrification projects. Defining an adequate management model may promote technology adoption, reduction of social inequalities, production increase, and redefinition of power structures and strengthening of individual and collective empowerment. Although there are numerous management models for rural technology projects, most of them are generally focus on one single technology or service. Among them, the most common are those privately managed, cooperatively, or by state or local municipalities or communities. These models have different characteristics in terms of ownership of the systems, level of user participation, responsibility for operation and maintenance (O&M) of systems, users' involvement in infrastructure construction and installation of equipment, management of tariff payments, etc. (ESMAP, 2001).

Furthermore, establishing a robust method to evaluate the sustainability of technology projects must be addressed as a key element within the project management cycle. Appropriate evaluations can support decision making procedures, enhance learning processes, improve management, develop capacities and strengthen coordination between stakeholders. However, the vast majority of the evaluation methods for RE projects in rural areas are focused on energy or sanitation services separately, and do not emphasise the assessment of the key elements of the management model, for instance users participation, accountability, organization and coordination skills, etc.

In the Andean community of Pucara, in the region of Cajamarca (Peru), the local NGO Soluciones Prácticas (Practical Action) implemented a RE project to give access to basic energy and sanitation services. A stand-alone microhydro power plant, individual solar photovoltaic systems, solar water heaters, improved cookstoves, biodigesters and Trombe walls were installed to provide electricity, domestic hot water, upgraded cooking conditions and enhanced household heating. Since the complexity of managing several different types of technologies at a time in one single community is a big challenge, an innovative management model was needed to deal with all the energy and sanitation services at once. Moreover, the model included the drinking water system and latrines that existed already before the RE project's implementation.

This paper is aimed at contributing to the sustainability enhancement of RE projects to provide energy and sanitation services in remote rural areas by developing a novel management model able to deal with any kind of technology. Moreover, a new method to evaluate the sustainability of a wide range of technologies is proposed regarding the technical, the economic, the social/ethical, the environmental and the institutional/organizational dimension. In particular, we will present the project of Pucara, where this integral community management model was designed in August 2011 and the project's sustainability was analysed in September 2013.

The rest of this paper is organized as follows. Section 2 presents the community of Pucara and technologies of the project. The management model design is developed in section 3. In Section 4, the methodology used to evaluate the project sustainability is presented. Section 5 shows the results of the aforementioned evaluation. The results are discussed in Section 6 and finally Section 7 summarizes the conclusions.

2. Description of the case study

This section describes the main socioeconomic characteristics in Pucara to provide the reader a better understanding of the context of the community where the project was implemented.

2.1 Description of the community

The project is located in the community of Pucara, in the northern Peruvian Andes, 3320 metres above sea level and two hours journey from the city of Cajamarca, the capital of the region. In this community there are 224 inhabitants and 29 households. There is a primary school with 30 students and two churches, but there is no health care centre, so villagers must go to another community to receive medical assistance.

The majority of the population is under the age of 25 (around 62%). The average education level is quite low, 30% of the population has not finished primary school and 6.1% are illiterate. Each family owns an average of 12 hectares of land for agriculture and livestock. Whereas agricultural production is intended for family consumption, they sell the milk produced by beef cattle and receive an average monthly income of S/. 790 Nuevos Soles[a] per family.

In terms of energy expenses prior to the implementation of the project, families used to spend a monthly average of S/. 16.75 Nuevos Soles, predominantly on candles and batteries. They can collect their own firewood at no monetary cost.

[a] Exchange rate US Dollar/Nuevo Sol is approximately 2.60

Before the project's implementation, Pucara had already a community drinking water system and family latrines for all villagers. To manage these systems, a Management Board for Sanitation Services (MBSS) composed by local villagers (see Section 3.1) was established, as it is mandatory according to Peruvian law requirements[b]. Each user had to pay a monthly tariff of S/. 1 Nuevo Sol to cover operation costs. However, this tariff was just enough to cover the operator's salary, who performed basic O&M actions when needed. When any disruption appeared the MBSS had to ask the local Municipality for economical to support, which generally provided it with significant delays, thus leaving the community without access to these services for excessive time.

2.2 Renewable energy technologies implemented in the project

The design of the technologies that would be implemented in the project was defined according to the result of the previous energy demand and socioeconomic analyses. However, the limited budget the NGO had for this project restricted the decision-making process regarding the kind and number of systems to be implemented in Pucara.

Concerning access to electricity, off-grid RE systems were used, as they have proven suitable for rural contexts (for example, Pasternak, 2000; Chaurey et al., 2004; Nguyen, 2007; Borges et al., 2007; Benecke, 2008; Lhendup, 2008; Breyer et al., 2009; Love and Garwood, 2011; Terrapon-Pfaff et al., 2014a, 2014b). A combination of a microhydro power minigrid and individual photovoltaic systems were selected.

A **microhydro power plant** produces electrical power (alternating current) through the use of the gravitational force of falling water, driving a water turbine and generator. This technology was chosen because microhydro systems are usually the lowest cost option for off-grid rural electrification (Coello et al., 2006; REN21, 2008; Williams and Simpson, 2009; ; Kaygusuz, 2011), the energy is continuously available (Drinkwaard et al., 2010), they have flexible power production for electrical equipment (Guitonga and Clemens, 2006), are reliable for off-grid systems (van Els et al., 2012) and the technology requires little maintenance and is long-lasting (Paish, 2002).

Individual photovoltaic systems generate electricity from solar radiation and are suitable for providing decentralized electrical services to individual homes or businesses (Jacobson, 2007) in remote areas (Chaurey and Kandpal, 2010a), have low running costs (Gullberg et al., 2005), are frequently cheaper than photovoltaic minigrids (Millinger, 2012), the comprehensibility of the source tends to lead to a larger acceptability of the technology (García and Bartolomé, 2010), and are typically used for providing basic electricity services to rural households (Chaurey and Kandpal, 2010b; Valer et al., 2014).

After an economic analysis, the microhydro power plant was installed to electrify only the closest 22 households, the school and both churches. As extending this minigrid to reach the farthest users would be very expensive, in this project individual photovoltaic systems were considered a good alternative for electrifying 7 households located far from the microhydro power plant.

Regarding access to improved cooking facilities, low cost tubular household biodigesters and improved cookstoves were considered in the project.

[b] Article No. 173 of the Regulations of the General Law of Sanitation Services; Law No. 26338

Biodigesters produce biogas and organic fertilizer through the anaerobic digestion of dung and water. This process takes place in a tubular PVC (geomembrane) reactor, which is buried in a trench and covered with a greenhouse, in order to increase process temperature and minimise overnight temperature fluctuations (Ferrer et al., 2011; Garfí et al., 2012). Biogas is stored in a reservoir in the kitchen, to be used directly for cooking, and organic fertilizer is deposited in a basin located under the biodigester outlet. This technology has the potential to contribute to the reduction of wood consumption (Katuwal and Bohara, 2009); biogas is produced mainly from raw materials that are locally available and can be harnessed in controllable, containable and useable quantities (Walekhwa et al., 2009); the indoor environment is improved and crop productivity is increased (Garfí et al., 2011; 2012). However, this technology is only appropriate for families who own enough cattle, thus ensuring a sufficient quantity of dung available to feed the system. In terms of workload reduction for women and children, biodigesters do not commonly have a strong impact in Andean communities because although the firewood collection workload can be reduced, it is necessary to collect 20 kg of dung and 60 litres of water per family daily, which can be a heavy task depending on the characteristics of each household. Moreover, biodigesters installed in Andean communities only provide enough biogas to cook for 2 hours a day (Garfí et al., 2012), so the demand for cooking is not fully covered and firewood collection is still necessary.

Improved cookstoves are aimed at reducing indoor air pollution, firewood consumption and greenhouse gas emissions (Troncoso et al., 2013; Venkataraman et al., 2010). The system installed in Pucara has a combustion chamber where efficient firewood combustion takes place, with three cookers and a chimney to channel the smoke outdoors. This technology is widely spread in rural Peruvian areas, but since in the region of Cajamarca many people are still not aware of its benefits, the majority of households still use traditional stoves.

Due to budget constraints, only five biodigesters could be installed, but improved cookstoves certified by SENCICO[c] were built in every household, complementing the biodigesters in households where both technologies were installed and contributing to the scaling-up process of this technology.

Concerning access to improved heating technologies, **Trombe walls** were installed. This technology can reduce buildings' energy consumption to a great extent (Göksal and Kartal, 2010; Hordeski, 2011) and finely adjust the indoor humidity (Chen et al., 2006). The wall absorbs diffused and direct solar radiation during the day and transfers the heat to the interior of the thick storage mass wall by convection or conduction at night (Agrawal and Tiwari, 2011; Torcellini and Pless, 2004). In this case, classic Trombe walls, in which plastic and an air space separate the wall from the outdoor environment (Saadatian et al., 2012), were selected due to their low cost, easy installation and simplicity in repairing them when needed. For optimal performance, these walls were positioned facing north; materials with high heat-storage capacity, such as stone and adobe, were used; and the external surface of the wall was coloured black to increase the absorption rate (Thumann and Mehta, 2008). Trombe walls not only provide thermal comfort in the spaces connected to the system, but also in adjacent spaces (Boukhris et al., 2009).

[c] National Training Service for the Construction Industry (SENCICO) is a public institution that, among other activities, analyses the performance of different kinds of improved cookstoves and certifies their appropriateness for rural households in Peru.

In Pucara, families normally meet in the kitchen in the evenings and, as it is a heated space, Trombe walls would have caused insignificant temperature variation (Thumann and Mehta, 2008). Hence, it was decided to install these systems in bedrooms with any of their walls facing north and free of shading obstacles. Taking these considerations into account, 7 Trombe walls were installed, as this was the amount of houses that met the requirements for this technology.

Finally, sanitation services were improved by installing **solar water heaters**, which heat up water from the existent community network pipeline using solar radiation. While this technology is being increasingly promoted in different countries (Chang et al., 2008; Li et al., 2011; Grieve et al., 2012), it has often been overlooked in most developing countries in spite of the fact that many regions have high annual levels of solar radiation (Langniss and Ince, 2004). To prove the suitability and promote the dissemination of this technology in rural Andean communities, solar water heaters were installed in Pucara to provide hot water for bathing for 19 users and the school. It was not possible to provide this service to all families because the budget for the project was insufficient.

3. Management model

This section presents the management model of Pucara. First the processes of designing and implementing the model are explained. Next, the stakeholders of the management model and the technology classification are detailed.

3.1 Management model design

Designing the management model for a technology project in rural areas is always a difficult task. Indeed, the bigger the amount of technologies to be managed, the more complex the management model. That is the reason why the majority of management models are focused on one single technology or service. Indeed, prior to the implementation of this project, there were no management models in Peru that involved so many technologies as in Pucara, especially considering the mixture between energy and sanitation services. In fact, in Peru there only existed management models for rural electrification or for drinking water systems and latrines. Hence, there was no model for Trombe walls, biodigesters, solar water heaters or improved cookstoves, and there were no models to deal with energy and sanitation services at once. For these reasons, a new ad hoc management model had to be designed for Pucara.

A participatory process was carried out during the first 6 months of the project with different stakeholders such as the Housing, Building and Sanitation Regional Management; Energy and Mines Regional Management; OSINERGMIN[d]; local NGOs, engineers and sociologists; Practical Action's (PA) technical team; and villagers from Pucara to define an appropriate management model.

The first outcome of this process was that a community management was the best option in this area, as community managed projects are considered to be successful (UNDP, 2002). In rural Peru two community management models have proven successful for energy and sanitation technologies. On the one hand, the microenterprise management model for off-grid electrification projects designed by PA, whose main stakeholder is the Rural Electricity Service Unit (RESU), has proven suitable in Andean rural communities (Sanchez, 2006; Ferrer-Martí et

[d] Peruvian supervisory body for investment in energy and mining

al., 2010; Ferrer-Martí et al., 2012; Yadoo and Cruickshank, 2012). On the other hand, the legally established Peruvian model for rural water and sanitation services, whose main stakeholder is the Management Board of Sanitation Services (MBSS), is widespread among rural communities in Peru (Castillo and Vera, 1998).

The MBSS, which already existed in Pucara before the RE project implementation, has rigid regulations, is completely focused on drinking water and sanitation and, according to the law, it is not possible to include technologies which are not strictly related to sanitation services. Hence, this model was not feasible for all the technologies considered in the project.

Moreover, the PA's microenterprise model was only focused on standalone renewable energy technologies for rural electrification, as microhydro power plants, wind turbines or solar photovoltaic systems. This model is too standardised to deal with different technologies which require completely diverse operation and management tasks as solar water heaters, improved cookstoves, biodigesters or Trombe walls. Thus, this model was not appropriate for the technologies implemented in Pucara.

Considering this and taking into account that establishing an independent model for each technology in the same community would have been extremely complex to manage, a new integral model was designed to deal with all the RE technologies at once. This novel management model was based on the experiences of the MBSS and RESU but new roles, regulations, tariff systems and organizational procedures were defined. Moreover, the model was extended to include not only the systems of the RE project but also the drinking water system and the latrines already existing in Pucara. Moreover, it is important to highlight that this management model was conceived in a way that any new technology installed in the community in the future could be included in it. Hence, it has the advantage that it can be very easily disseminated among rural communities and might even promote the addition of new systems to the existing ones.

Figure 1 shows a general scheme of the new integral management model.

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Figure 1. General scheme of the management model

The management model was designed considering the internal social relations within the community, its forms of organization, values, and group and individual capacities, which were especially strengthened to ensure the correct functioning of the systems. It is based on the combination and flexibility increase of the RESU and the MBSS, who coexist and share stakeholders, to provide a unique integral management model. They are responsible for the technical operation and maintenance of the systems, which are under the control of the RESU or the MBSS depending on the technology and its O&M requirements. The RESU and the MBSS are redefined with relationship to their original standards, so that they can work together to keep the population informed and trained about the systems, and to promote improvement and expansion of the systems if needed. The financial sustainability is guaranteed by defining a special tariff system that covers the running and maintenance costs and by involving the Municipality when greater funds are needed. The users are the main stakeholders in this scheme, as they have the power to democratically define the norms and regulations in community assemblies; have the obligation to attend monthly financial review meetings; and are able to choose and control their representatives, as there is a Control Unit aimed at supervising each stakeholder and through which complaints about the service can be made. In order to promote synergy development with a wide range of stakeholders, the closest Health

Care Centre also contributes to the correct use of the systems, as its workers carry out periodic campaigns to train the population in healthy habits.

3.2 Management model implementation process

Strong emphasis was given to the process of implementation of the management model in order to promote sustainability. The implementation strategy was based on the idea that any strategy for promoting access to energy and sanitation services has to consider various dimensions such as the techno-economic, socio-political, environmental, financial, governance, etc. (Bhattacharya, 2012a) and project beneficiaries must be the key actors in shaping their own social and economic development, not only the passive recipients of external assistance (Ortiz et al., 2012). Indeed, the sustainability of technology projects is threatened by many factors. In addition to technical aspects, economic, social, environmental and organizational issues need to be considered and strengthened.

During the implementation process the implication and motivation of the population was very much promoted in all phases of the project. For instance, their participation in decision-making was encouraged by promoting horizontal processes where everybody's voice is taken into account. In fact, organizational skills to control the systems were improved by establishing periodic meetings and defining adequate roles and procedures, according to local context.

The management model implementation process especially focused on strengthening local capacities and field training programmes were developed. In these programmes especial emphasis was put on strengthening practical capacities, thus ensuring local villagers could really apply theoretical knowledge achieved on real O&M activities. For instance, the users actively participated when installing the RE technologies and these processes were also used to strengthen practical capacities. As part of the training process, it was crucial to ensure that the operators had enough information about where to buy spare parts or components for all technologies to cope with corrective maintenance autonomously.

The development of productive initiatives was promoted as even little the economic incomes increase population quality of life. Moreover, economic incomes have proven to be very effective to strengthen the implication and user's motivation to maintain the projects. Villagers were encouraged to invest in microbusinesses taking advantage of the new technologies, especially for electricity. To do that, showing successful experiences carried out in similar areas was very illustrative.

Finally, environmental consciousness was raised through special trainings, especially focusing on efficient use of natural resources. Several workshops were developed to discuss how the forest could be maintained through a sustainable use of firewood, how the dung can be reused as energy resource and why fuel consumption should be reduced to prevent environmental damage.

3.3 Management model stakeholders

Management Board of Sanitation Services (MBSS)

The MBSS is responsible for the operation and maintenance tasks of sanitation systems; the preparation of the annual work plan and budget, calculation and collection of the monthly tariff, which provides a reserve fund to pay for operation and the preventive and corrective maintenance of the systems; the imposition of penalties on users; the promotion of healthy habits in households; the organization of community clean-up campaigns and other minor functions. In the proposed model MBSS functions are widened with respect to its original definition, as the amount of technologies under its responsability increased (see Section 3.4).

Rural Energy Service Unit (RESU)

While this name normally refers to "Electric Services", in Pucara it refers to "Energy Services", as the systems are related to cooking and heating as well. The RESU is a microenterprise formed by two local villagers, who are responsible for operation, preventive and corrective maintenance; the collection of monthly tariffs, which provide a reserve fund to pay for operation and preventive and corrective maintenance of the systems; service cut-off and/or replacement; promotion of the extension of services to new users and other minor functions. It must be noted that new organizational procedures have defined to allow the RESU and the MBSS sharing representatives. These stakeholders should be deeply involved and coordinated one with the other to perform their activities in the most efficient way. In fact, if there were no legal restrictions, there could only be one single institution performing all these tasks.

Users

Each user is responsible for using and maintaining their systems appropriately, as well as paying the specific tariffs defined for each technology, which can be flat rate tariffs, variable depending on the consumption, or variable depending on the extent of the repairs (see Section 3.4). Moreover, the users make up a General Assembly, which is the highest authority in the management model, and is responsible for the election of the MBSS and RESU personnel; the approval of plans and budgets; the monitoring and evaluation of the MBSS and RESU activities; and other functions that may be required. The General Assembly meets monthly and the attendance of users is mandatory. In case any user does not attend, and has no important justification, a S/. 10 Nuevos Soles fine is imposed.

Control Unit (CU)

The CU is elected by the General Assembly and is composed of local people, mainly authorities. Specific regulations have been defined to give the CU the responsibility to monitor the administration of both the RESU and the MBSS (use of tariffs, non-paying clients, quality of service, etc.), and ensure compliance of users' obligations; auditing water, sanitation and energy services; and addressing complaints, suggestions or conflicts. It should operate impartially and its controlling tasks should be completely separated from political affairs.

District Municipality

The legal owner of the systems is the District Municipality, which signs a concession contract assigning the service management to the MBSS and the RESU; thus, it cannot interfere with day-to-day operations. However, as the legal owner, the municipality shares responsibility for replacing equipment when needed, so it must add to the reserve funds when they are insufficient, reinforcing the sustainability of the systems.

3.4 Technology classification

Considering the MBSS rigidity to include new technologies, two criteria were employed to decide whether each technology should be operated and maintained by the RESU or the MBSS:

1.-Monitoring simplicity for the RESU or the MBSS, regarding the kind of maintenance of the technology.

2.-Possibility for the MBSS to do it, according to regulations, as it can only include sanitation services

According to the aforementioned criteria, O&M responsibility for solar water heaters and improved cookstoves was assigned to the MBSS, in addition to the drinking water systems and latrines that were already managed by this organisation. In the first case, hot water for bathing is clearly related to sanitation services, which fits the aim of the MBSS, and the members of this organisation already had the skills needed to operate and maintain water systems, thus simplifying the training programme for operators. In the second case, as one of the tasks of the MBSS involves monitoring and promoting healthy habits within households in coordination with the closest health care centre, and in some other communities in Cajamarca the MBSS was already responsible for this technology, it was decided to assign the O&M responsibilities for the improved cookstoves to this stakeholder. Management responsibility for the microhydro power plant, individual photovoltaic systems, biodigesters and Trombe walls was assigned to the RESU. While the first two cases were assigned to the RESU because it was originally created to manage and operate off-grid electrification systems, Trombe walls and biodigesters could have been assigned to either the RESU or the MBSS. However, they are more related to energy services than to sanitation services so, in accordance with the PA technical team, it was decided to assign this technology management to the RESU.

The MBSS' O&M tasks related to each technology are summarized as follows:

- **Drinking water system:** The MBSS is responsible for the water disinfection by chlorination process. This disinfection should be performed quarterly, as well as maintaining the infrastructure (pipeline, reservoir, valves, etc.). Users pay a monthly tariff whose amount is S/. 1 Nuevo Sol. This payment is intended for the purchase of inputs for water disinfection, operation expenses as well as spare parts and tools.
- **Latrines:** The MBSS periodically checks the condition of the latrines, and verifies that all users maintain them correctly. If the system needs repairing, the MBSS could provide the service, but the cost of this task must be covered by the user.
- **Solar Water Heaters:** The MBSS periodically verifies that all pipe connections and operation habits are correct. If the system needs basic repairing, or the user needs plumbing services, these tasks can be carried out by the MBSS. In case the break is severe, the MBSS will contact local suppliers, located in the city of Cajamarca, to solve complex problems. The cost of the repair will vary depending on the extent of the repair and will be covered by the user.
- **Improved cookstoves:** The MBSS periodically checks the condition of the cookstoves and provides repair services if needed. The latter have a variable cost, depending on the extent of the repair, which will be covered by the user.

The RESU's operation and maintenance tasks related to each technology are summarized as follows:

- **Microhydro power plant:** The RESU performs preventive and corrective maintenance of all system's components (civil works, electromechanical equipment and power grids). Users pay a monthly tariff that depends on consumption and was designed to promote the creation of new businesses. Up to 10 kWh/month families pay a baseline of S/. 10 Nuevos Soles; if consumption varies between 11 and 15 kWh/month, the cost per kWh exceeding 10 kWh/month is S/. 0.50 Nuevos Soles; and when consumption is greater than 15 kW, the cost per kWh exceeding 15 kWh/month is S/.0.30 (decreasing block tariff). In this case, micro-credits are available for new users' connections to the microhydro power plant, as it is the only centralized system and expanding it is generally cheap if the new house is built close to the minigrid.

- **Photovoltaic systems:** The RESU is responsible for performing monthly preventive maintenance tasks, and supervising whether users care for and use the equipment properly. The users of these systems pay a flat rate tariff of S/. 10.00 soles.
- **Trombe walls:** The RESU supervises whether users maintain and use the equipment properly, and provides repair services if needed. The latter have a variable cost, depending on the extent of the repair, which will be covered by the user. Due to the simplicity of the technology, the wall can be repaired with local materials.
- **Biodigesters:** As for the Trombe walls, the RESU supervises whether users maintain and use the equipment properly, and provides repair services if needed. The latter have a variable cost, depending on the extent of the repair, which will be covered by the user. Due to the simplicity of the technology, the biodigester can be repaired with local materials except for the geomembrane, which can be found in Lima.

4. Assessment of the sustainability of the project

Several studies have assessed sustainability of energy projects, using different sets of indicators and different approaches, either at macro and micro levels.

Regarding country level sustainability evaluations, the UN-CSD (1996) developed more than 130 indicators divided into four primary dimensions of sustainable development—social, economic, environmental, and institutional. Vera et al. (2007) proposed an analytical tool based on indicators for sustainable energy, considering social, economic and environmental dimensions, for assessing current energy production and use patterns at a national level. Mainali et al. (2014) defined a composite energy sustainability index regarding social, economic, technical and environmental dimensions of sustainable development, focusing on rural energy sustainability. Other energy indexes have been defined at an aggregated national level, such as the Energy Development Index (WEO, 2012) and the Energy Sustainability Index (WET, 2012), and comprehensive lists of energy indicators for sustainable development have been published (IAEA, 2005; UN, 2001; UNDESA, 2007). However some of the indicators defined in these studies are broad in nature and hard to quantify (Ugwu and Haupt, 2007), country level indicators may hide urban/rural inequities (Doukas et al., 2012) and are not suitable for evaluating local projects.

To overcome these barriers, Ilskog (2008) proposed, and Ilskog and Kjellström (2008) tested, a method to evaluate the sustainability of electrification projects by means of 39 indicators, in which five dimensions of sustainability were considered: technical, economic, social/ethical, environmental and organizational/institutional sustainability. Moreover, indicators were defined to facilitate data collection and reduce the risk of subjective assessments. On the basis of this methodology, several adaptations have been made. For instance, Yadoo and Cruickshank(2012) defined 43 sustainability indicators, considering the five sustainability dimensions proposed by Ilskog (2008), to evaluate rural electrification projects in Nepal, Peru and Kenia. Furthermore, other methodologies have been used to assess rural electrification projects. Brent and Rogers (2010) applied a methodology considering 20 indicators to assess the sustainability of renewable energy technologies for off-grid applications, focusing on a rural village in the Eastern Cape Province of South Africa; and Ferrer-Martí et al. (2012) defined and tested a methodology to evaluate and compare three community small-scale wind electrification projects.

However, since these methodologies are defined to analyse electrification projects, a wide range of technologies for providing access to basic energy and sanitation services are beyond their scope. Regarding this weakness, Bhattacharya (2012b) defined a methodology, based on Ilskog (2008), with 26 indicators to analyse six generic energy access programs, namely grid extension, off-grid solar home systems, off-grid electrification through local mini grids, petroleum fuel promotion for cooking, biogas programmes and improved cookstove programmes, thus broadening the scope of this methodology.

Nevertheless, the range of technologies and basic energy and sanitation services needed in this project not only consider electricity and cooking, but a wider range of services. Therefore, considering the previously described methodologies, and based on the successful methodology proposed by Ilskog (2008), a series of 34 Sustainability Indicators were developed to analyse the aforementioned five dimensions of sustainability for energy and sanitation technologies in rural communities, as the majority of rural populations living in developing countries do not have access to sanitation services and are energy poor, and there is a need for rural energy to be analysed separately (Mainali et al., 2014). This set of indicators, which is shown in Table 1, was defined by the authors and some villagers from Pucara, bearing in mind the importance of stakeholders' participation (Bhattacharya, 2012a).

Since ranking methods may reduce large absolute differences or exaggerate smaller discrepancies between cases (Ilskog and Kjellström, 2008) and limit the chances of evaluating one single project, this methodology to evaluate energy projects by means of indicators has been defined in such a way that absolute measurements can be carried out. It must be noted that some indicators' scores have to be normalised to a common 0-100 scale. Moreover, to prevent biases from evaluators' subjectivity, many indicators are not based on evaluators' judgments but on users' opinions, as they are the important subjects of development and their opinions and values must inevitably be taken into account.

PLEASE INSERT TABLE 1

Table 1. Sustainability Indicators

The technical dimension focuses on ensuring the correct operation of the systems during their lifespan. This dimension deals with the fulfilment of the local energy and sanitation needs, the reliability of the systems, the operation and maintenance tasks, and technical support availability. This dimension aims to address the need to ensure safe technical solutions in energy and sanitation provision and it is considered one of the keys to achieving the MDGs (Modi et al., 2005).

The economic dimension deals with the ability of the project to promote increases in household incomes, the capacity to pay the tariff and the level of tariff lag, and the appropriateness of the tariff definition to cover operation and maintenance costs, thus avoiding major disruptions and collapses (Villavicencio, 2002).

The social/ethical dimension is the most complex of the five dimensions. As these kinds of projects are aimed at alleviating poverty in rural contexts, their impact in terms of development as a whole must be evaluated. Therefore, issues like equity, gender, health and education must be addressed. It should be noted that gender equity carries a lot of weight, as there are 3 indicators related to this issue, since technology projects might have negative impacts on women's lives if a gender strategy is not defined and implemented during the course of the project (Fernández-Baldor et al., 2014).

The environmental dimension focuses on how the project affects the environment in terms of use of natural resources, emissions and wastes. Environmental sustainability not only deals with outdoor air pollution, deforestation or soil contamination, but also with the indoor environment, reducing the use of fossil fuels for lighting or biofuels for cooking.

The organisational/institutional dimension is the one that mostly evaluates the appropriateness of the management model designed. This dimension focuses on how the organisation capacities are reinforced within the community, on how the human capacities are strengthened, on the level of accountability, and finally on the users' participation in decision-making processes, which is a key factor for the development process to succeed (Sharachchandra, 1991).

5. Results

To evaluate the sustainability of the RE project, a wide range of information had to be collected, regarding systems' technical assessment, socioeconomic development, environmental impacts, organisational strength, etc. To obtain this information and give a score to every indicator, methods included transect walks; semi-structured interviews with all users, MBSS, RESU and control unit members; specific surveys for each technology; observation and photographic evidence; and semi-structured interviews held with the PA's technical team. Fieldwork was conducted between August and December 2013. It should be noted that we obtained information from 45 participants, 27 men and 18 women, using various techniques to properly triangulate our findings and ensure their validity. Table 2 shows the total households with each of the technologies total users of each technology, the number and the percentage of the households visited for each technology.

PLEASE INSERT TABLE 1

Table 2. Households visited for each technology.

Spider web diagrams and a bar chart are used to show the results in a reader-friendly way, so that the extent to which every sustainability dimension is reached by each technology can be easily analysed and compared. Moreover, as stated by Yadoo and Cruickshank (2012), and learning from Ilskog and Kjellström's (2008) experience, we decided not to aggregate the scores of the different dimensions in order not to hide interesting differences between dimensions. The scores of the different technologies after applying the sustainability indicators are shown in Figures 2 and 3.

PLEASE INSERT FIGURE 2

Figure 2. Spatial representation of the technologies' sustainability scores.

PLEASE INSERT FIGURE 3

Figure 3. Bar chart representation of the sustainability dimension scores

6. Discussion

Next, the results are analysed and discussed on the basis of the five dimensions of sustainability, namely technical (TD), economic (EcD), social/ethical (SED), environmental (ED) and organisational/institutional (OID), described in Section 4.

In the first section, we carry out an overall assessment of the performance and the sustainability of the project, and we globally analyse the five dimensions defined to identify how the project has succeeded in each of them. In the following sections we analyse the results for each dimension with more details.

6.1 Overall analysis of the management model and sustainability of the project

Overall, the rural energy and sanitation project as a whole is performing well, with low level of disruptions, repairs do not take excessive time, population actively participates in decision making assemblies, financial status of the organization is safe and users are highly satisfied in general. We can affirm the proposed management model has been effective to maximise the sustainability of the project, especially considering the high level of complexity of this project, the high amount of different technologies, and the challenges and barriers that had to be overcome all along the process, such as the lack of technical knowledge and experience of the population, weak organizational capacities and lack of successful projects like this one to learn from.

Moreover, the new management model has contributed to enhance the sustainability of the drinking water system and latrines. The financial sustainability of these systems was weak, as the tariff was too low. Now, the economical sustainability of the system is not in danger because the energy fund can contribute to cover maintenance costs, thus enhancing the autonomy of the community to carry over repair actions.

According to the obtained results, the best valued dimension is organizative/institutional, the second one is technical, the third and fourth are environmental and economic, with similar results, and finally the social/ethical. These dimensions have an average score of 0.97, 0.88, 0.71, 0.68 and 0.47, respectively. Organizative/institutional, technical and environmental obtained good scores for all technologies, especially the first two. economic shows bigger variability among the different technologies, with very high scores for biodigesters but lower ones for Trombe walls or improved cookstoves. Finally, social/ethical shows the lowest scores, especially for biodigesters and Trombe walls. The statistical significance of evaluation results was analysed by the Paired t-test, which tests the mean difference between paired observations; with a significance level (a) of 5%, using the Minitab Statistical Software (Garfí et al., 2011). Statistical analysis confirms the results the results are statistically significant, and remarks that organizative/institutional and technical dimensions, which obtain good results for all technologies, are the best valued ones.

6.2 The technical dimension

This is one of the best valued dimensions for all the technologies. As there are local operators, maintenance services are available permanently. Thus, whereas there are slight differences between technologies, the systems are well maintained and the level of disruptions is minimal. In all cases the support infrastructure is available in case it is needed. However, for the microhydro power plant, photovoltaic systems and biodigesters, operators might need to contact supply distributors located in Lima in case of major repairs. That is the reason why these technologies are less valued regarding this indicator. All the technologies are considered safe to use and operate, and they generally meet demand requirements. However, in this latter case, biodigesters are less valued than the rest because they cannot completely meet the demand for cooking and fertilizing, as stated by users. Regarding villagers' level of satisfaction with respect to the technologies and the operation and maintenance services, the scores obtained are generally high. In the first case all the technologies are very well valued. However, the level of satisfaction with biodigesters seems to be lower because they do not completely meet the demand for cooking and fertilizing. In the second case the level of satisfaction is higher in the case of the microhydro power plant because, as it is a centralised system, it is easier for the operator to perform maintenance tasks frequently. In the case of the individual technologies, the level of satisfaction with operation and maintenance services is lower because the maintenance tasks are less frequent as households are far from each other and more time is needed for operators to visit each house in comparison with the centralised systems. This problem could be solved by hiring new operators, but this would increase the costs for operation and maintenance and thus increase the monthly tariff, which in Pucara was not possible due to the high level of poverty in the area.

6.3 The economic dimension

Two main issues are addressed by this dimension: the coverage of costs to maintain the technologies during their lifespan and the promotion of villagers' economic development.

The first aspect mainly depends on the management model. The tariff was determined according to the users' choice and decided in an assembly where everybody can participate in the decision-making process. Hence, the tariff appears to be appropriate and the level of tariff lag is low in all cases. Operation and maintenance costs are also met, except for electrification systems. As these are considerably more expensive than the rest of the technologies installed, the Municipality will have to support the organization economically when major replacements are needed (batteries, turbine, solar panels, etc.). However, as the Municipality is considered an important stakeholder in the management model, its support is guaranteed from the beginning of the project.

The second aspect mainly depends on the characteristics of each technology. In this case the results are more variable than in the previous one. Access to electricity has only allowed small pre-existing groceries to open at night, which is not a significant increase in terms of income generation considering the overall impact on each family. Only biodigesters have proven effective in increasing productivity, as the fertilizer produced allows a considerable increase in crop and pasture production. No productive uses were observed in the rest of the technologies. Furthermore, income increases could be achieved by saving money from previously used fuels. In this case, electricity systems reduced these expenses considerably as the tariff is lower than the cost of candles, batteries or kerosene. The rest of the technologies reduce the amount of firewood used, but as in Pucara this resource is abundant and villagers' do not have to pay for it, no economic improvements have been observed.

For future projects, in order to get a significant improvement in this dimension, productive development needs to be promoted to increase family incomes. Nevertheless, lack of access to credit and organizational skills to develop collective entrepreneurship are the main roadblocks to achieve these goals.

6.4 The social/ethical dimension

This dimension has the lowest score for the majority of technologies. As this dimension is crucial for development projects these results are discussed in detail.

Not all villagers had access to all the technologies due to some of their characteristics and budget limitations. Whereas all users had access to electricity and improved cookstoves, not all families could be provided with solar water heaters, biodigesters and Trombe walls. Furthermore, as micro-credits are only available for new users' connections to the microhydro power plant, and in the case of individual systems new users must pay for the whole system at once, equity is affected and the scores of some technologies is lowered. Hence, whereas the decision about the micro-credit offer was taken by the General Assembly, it seems not to be the best solution and micro-credits should be available for all users and technologies.

Another important issue that has diminished the scores is related to gender equity. In Andean communities power structures are biased towards masculine domination, and the role of women is generally limited to household affairs. These structures are so rigid that it is very difficult to reach ambitious objectives in terms of gender equity during the period of implementation of these projects. For that reason, despite promoting the involvement of women in the O&M training process and the inclusion of women in the staff, these objectives could not be reached. Women and children benefitted especially from different services to have more time for themselves, as they can stay awake longer at night thanks to improved lighting conditions at home and the workload is reduced. However, women often use this extra time to extend their workload in household tasks (Fernández-Baldor et al., 2014), and that can be a reason why this indicator's score is low in some cases. Since reaching gender equity goals has proven to be a very difficult task in Andean communities, special measures should be included in future models to promote it. Of course, the strategies to address these issues need to be defined in accordance to the socioeconomic characteristics of the community where the project is implemented.

The process of technology adoption was especially considered as well, as it is a determinant factor in promoting sustainability (Ruiz-Mercado et al., 2011; Troncoso, 2013). Therefore people were involved during the whole process of the project, even as labour. With an actively involved and motivated population in the project, users adopt technology more completely, thereby minimising the risk of system neglect or deterioration, which will have a positive effect in terms of sustainability. Moreover, the appearance of local innovations was promoted to strengthen the technology adoption process, but only few ideas related to improved cookstoves, biodigesters and Trombe walls appeared.

Finally, a major issue regarding sustainable development is health improvement, and in this case all the technologies are highly valued as they reduce indoor air pollution, reduce fire risks and lower the probability of diseases.

6.5 The environmental dimension

The indicators used for this dimension were based on highly ambitious environmental criteria, as Nature is a key issue in Andean villagers' world vision. That is the reason why, although all the technologies use renewable resources and no adverse environmental impacts have occurred, the scores have not been as high as if softer criteria had been used.

Only electricity substitutes "dirty" fuels like batteries, candles or kerosene, while the rest of them reduce firewood needs, which is considered by the authors as a renewable resource as its use in Pucara is responsible and equilibrated with the forest production. Local materials were used in general, except for the solar panels, the turbine, the biodigesters's geomembrane and the solar water heaters' pipes. Finally, many of the technologies are not easily re-used or recycled after reaching their lifespan. Solar panels, batteries and electronic devices, greenhouse plastics, geomembrane, PVC pipes and debris cannot be reused or recycled in the area. Only the microhydro power plant water channel can be reused for irrigation, the solar water heaters' water tank can be reused for liquid storage and wood from Trombe walls structures can be used as firewood.

6.6 The institutional/organisational dimension

This dimension is the most dependent on the management model and it is the best valued in Pucara, which means that the design of the management model was effective, efficient and appropriate for rural Andean contexts.

In all cases there was strong emphasis on strengthening users' and staff's capacities, developing an efficient training process to ensure all stakeholders had the appropriate knowledge about the technologies and the management model.

All users were involved during the installation of the systems. This process involved a routine of frequent community meetings and collaboration, which increased the sense of community and strengthened the mechanisms for conflict resolution. In addition, open-access assembly decision making was established, which promoted horizontal power procedures, and high rates of user assistance were identified, thus enabling high quality democratic processes.

Furthermore, accountability and answerability are really emphasised, as transparent financial accounts are kept and effective channels are defined, through which complaints about the service can be made. Hence, all stakeholders feel confident with the management model.

Therefore, managerial and operational autonomy, which is recommended by Zomers (2003), is guaranteed as external dependence was not identified. This allows Pucara's villagers to strengthen organizational and institutional assets, encouraging collective empowerment processes and promoting the development of new projects aimed at improving their living conditions.

7. Conclusions

In this paper we develop an integral management model and we evaluate the sustainability of the RE project implemented in Pucara (Peru). An innovative management model was created to provide basic energy and sanitation services with six different technologies: a microhydro power plant, individual photovoltaic systems, biodigesters, improved cookstoves, Trombe walls and solar water heaters. The management model was based on the combination of the Rural Energy Service Unit and the Management Board of Sanitation Services, who coexist and share stakeholders, and are responsible for the technical operation and maintenance of the systems. It is focused on encouraging autonomous management of all technologies and is conceived in a way that any new technology installed in the community in the future could be included in it. Hence, it has the advantage that it can be very easily disseminated among rural communities and might even promote the addition of new systems to the existing ones. Since this model gives the community the opportunity to manage all systems at once, even mixing energy, water and sanitation services, it represents a step change compared to existing ones.

Moreover, a novel evaluation methodology was proposed to assess five dimensions of sustainable development: technical, economic, social/ethical, environmental and institutional/organizational. The technical dimension is one of the best valued dimensions for all the technologies, as appropriate O&M services were defined, systems are generally in well condition and disruptions are rare. The economic dimension has shown disparate scores; biodigesters are the most valued in this case as they promote income-generating activities and reduce costs for energy. The social/ethical dimension is the worst valued dimension for almost all the technologies; not all villagers had access to all the technologies due to the characteristics of some of them and budget limitations. The environmental dimension is well valued in all cases. However, the scores are not as high as expected for RE technologies because high standard environmental indicators are used. The organisational/institutional dimension has obtained the highest scores for all the technologies, thus confirming that the management model has proven suitable for this kind of projects in rural areas. At the same time, the evaluation has identified some weaknesses in other dimensions that should be overcome in the race for sustainable development, and strategies to promote economic, social and environmental development are recommended.

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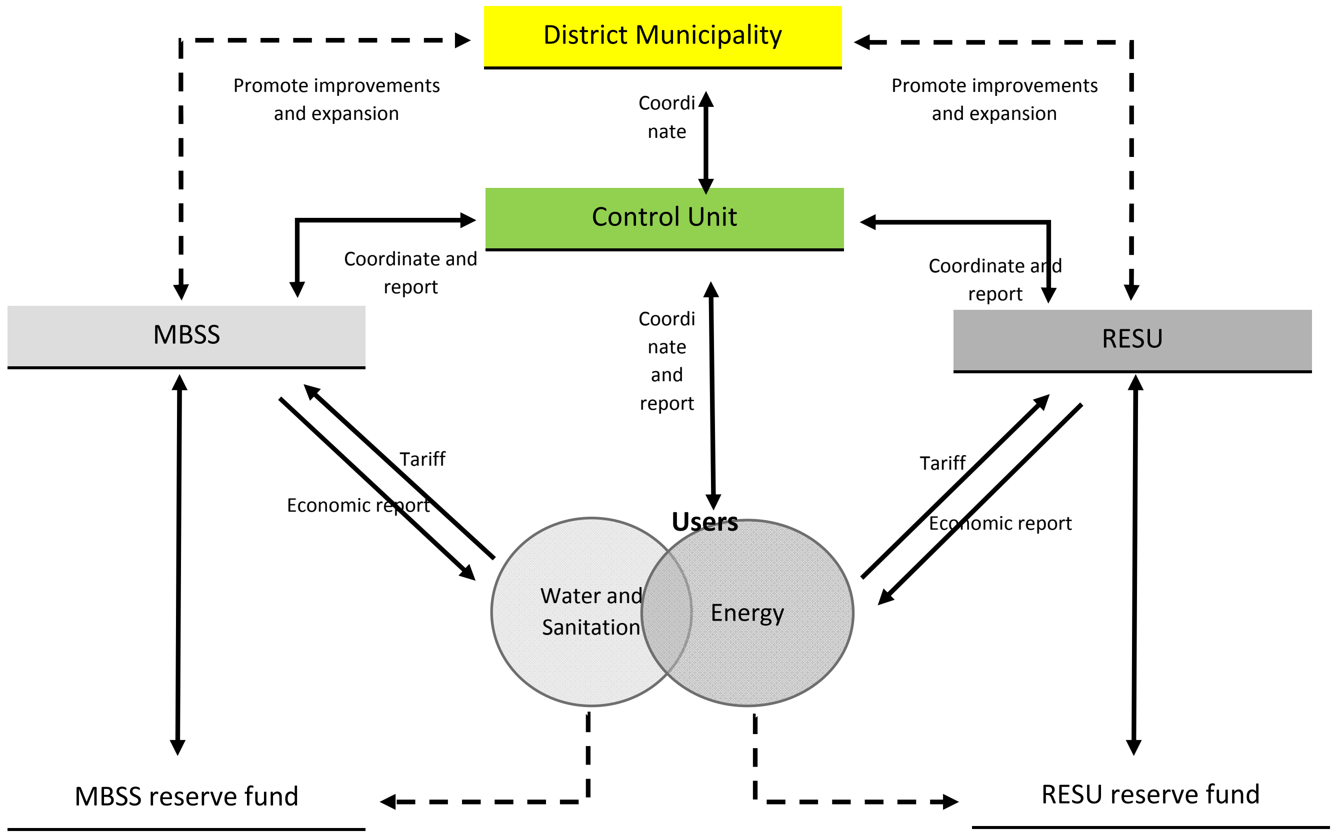


Figure 4. General scheme of the management model

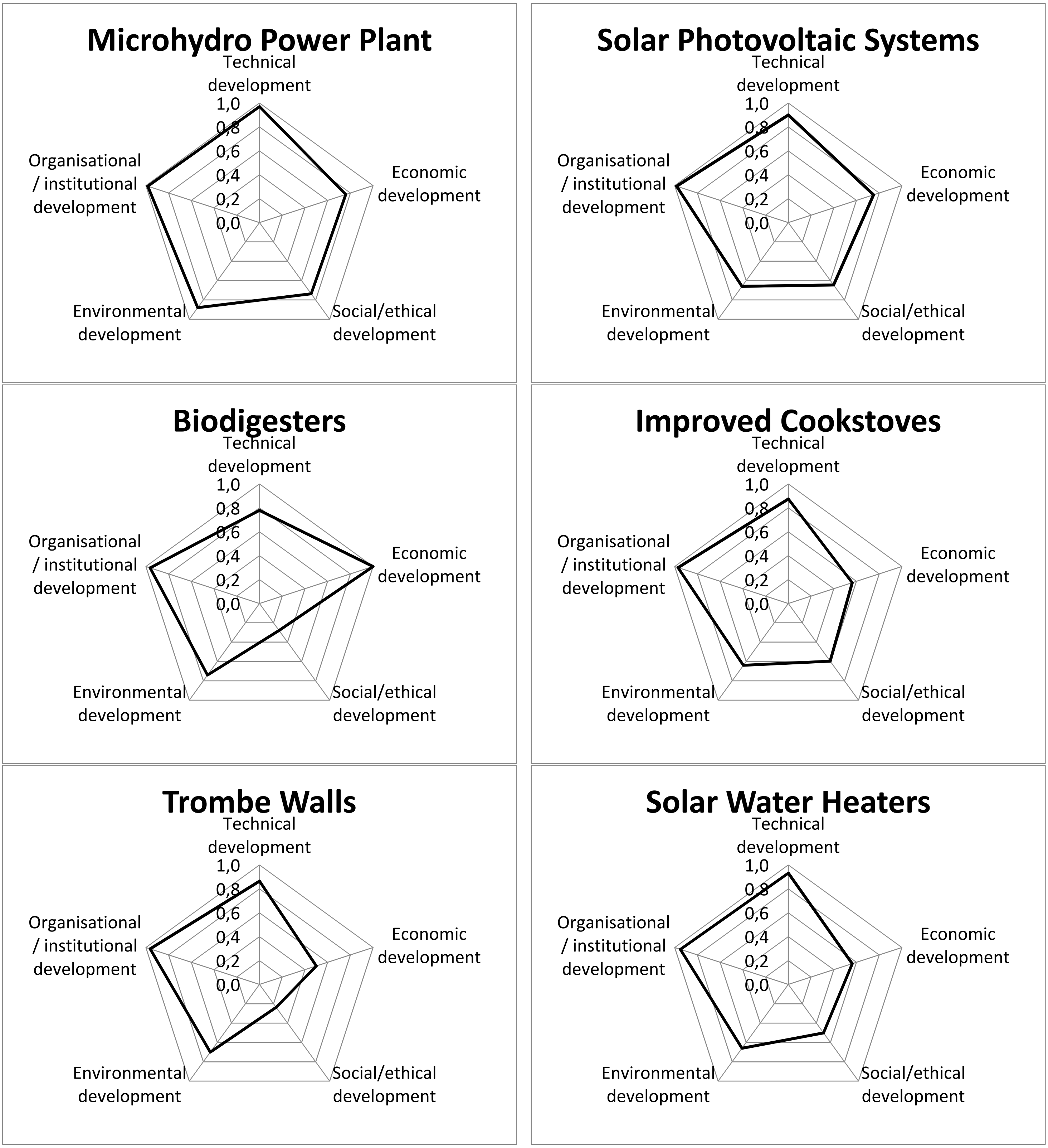
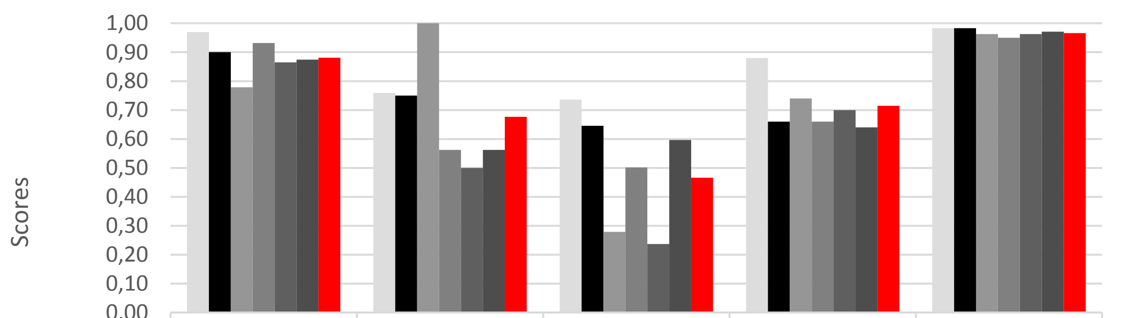


Figure 5. Spatial representation of the technologies' sustainability scores.



	Technical development	Economic development	Social/ethical development	Environmental development	Organisational/ institutional development
MHP	0,97	0,76	0,74	0,88	0,98
PV	0,90	0,75	0,65	0,66	0,98
BD	0,78	1,00	0,28	0,74	0,96
SWH	0,93	0,56	0,50	0,66	0,95
TW	0,86	0,50	0,24	0,70	0,96
CS	0,87	0,56	0,60	0,64	0,97
AVERAGE	0,88	0,68	0,47	0,71	0,97

Figure 6. Bar chart representation of the sustainability dimension scores

Sustainability Dimension	Name of Indicator	Description
Technical development	Daily operation services	Ratio of days per week with available operation services (%)
	Service is reliable, disruptions are minimal	Users' valuation of the frequency of disruptions (1-5)
	Service meets demand capacity requirements	Users' valuation of the percentage of the demand met (1-5)
	Support infrastructure (expertise, supply parts) is readily available	Availability of support infrastructure (Low, Low-Medium, Medium, Medium-High, High)
	System is well maintained	Ratio of systems in perfect condition to the total systems (%)
	Service is safe to use and operate	Users' perception of systems' safety to use and operate (1-5)
	People are satisfied with the O&M service	Users' valuation of the O&M service (1-5)
	People are satisfied with technology	Users' valuation of the technology (1-5)
Economic development	System breaks even (O&M costs are met)	Percentage of the O&M costs met (%)
	Tariff/other payments are convenient	Users' valuation of the tariffs appropriateness (1-5)
	Tariff lag	Ratio of users who pay the tariff to the total users (R), considering a 20% tariff lag threshold (Indicator score=(R-80)*5; if R<80 -> indicator score=0)
	Energy is used for income-generating activities or for improved agricultural activities	Ratio of households using energy for income-generating activities or for improved agricultural activities to the total households (%)
	Reduction of energy costs (e.g. kerosene, candles, batteries, etc.)	Indicator score=100-100*((current costs for energy+tariff)/(previous costs for energy))
Social/ethical development	Share of population with access to energy services	Ratio of households with access to energy services to the total households (%)
	Energy is used in schools	Percentage of schools with access to energy services (%)
	Micro-credit (or alternative) possibilities are available for energy services connection and tariff payment if needed	Availability of micro-credits for energy services access and tariff payment if needed (Yes=100; No=0)
	All households who want it can have access to energy service	Ratio of households that can have access to energy service if desired to the total households (%)
	Women are trained for O&M	Indicator score=Number of women trained/Number of men trained
	Share of women in staff and management	Indicator score=Number of women in staff and management /Number of men in staff and management
	Women have more time for themselves	Women's valuation of the extra time available for themselves (1-5)
	Local innovations have been developed	Local innovations have been identified (Low, Low-Medium, Medium, Medium-High, High)
	Local human labour has been used during installation	Ratio of users who have been involved in installation processes to the total users (%)
	Health improvement	Users' valuation of health improvement after technology installation (1-5)
	Increased number of hours for children's education at home	Users' valuation of the children's extra time available for studying at home (1-5)
Environmental development	Share of renewable energy in production	Ratio of renewable energy to total energy generated (%)
	Share of households where "dirty" energy sources have been replaced	Ratio of households where "dirty" energy sources have been replaced to the total households (%)
	No adverse local environmental impacts have occurred	Appearance of local environmental impacts (No impacts, minor impacts, serious impacts)
	Materials can be re-used or recycled locally after reaching technology lifespan	Amount of systems' parts that can be re-used or recycled locally after reaching technology lifespan (Low, Low-Medium, Medium, Medium-High, High)
	Local materials have been used	Amount of systems' parts that are built with local materials (Low, Low-Medium, Medium, Medium-High, High)
Organisational/ institutional development	Appropriate training of staff	Staff valuation of the training process appropriateness (1-5)
	The management model promotes villagers' organisation and coordination skills	Users' valuation of the local organisation and coordination skills improvement (1-5)
	Transparent financial accounts are kept	Users valuation of financial accountability (1-5)
	There is an effective channel through which complaints about the service can be made	Availability of an effective channel through which complaints about the service can be made (Yes=100; No=0)
	Participation of users in General Assembly meetings	Average ratio of users attending General Assembly meetings to the total users (%)

Table 2. Sustainability Indicators

	Total households	Households visited	Percentage
Microhydro Power Plant	22	19	86,4%
Solar Photovoltaic Systems	7	5	71,4%
Biodigesters	5	2	40,0%
Improved Cookstoves	19	18	94,7%
Trombe Walls	7	4	57,1%
Solar Water Heaters	19	18	94,7%

Table 2. Households visited for each technology.