Chapter 54
Techno-Economic Study of a Biogas-Based Polygeneration Plant for Small Dairy Farms in Central Bolivia

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54.1 Introduction

The use of alternative sources of energy in productive activities is an aspect that should be considered when promoting a sustainable development of a country. In the case of rural and semi-urban areas, the provision of energy services also generates benefits in social, education and health aspects [1]. Bolivia, as many other developing countries, is in its early steps to implement energy policies to promote a sustainable use of its energy resources. The new "Constitution of the Plurinational State of Bolivia" supports "new forms of alternative energy production" considering the conservation of the environment. It also emphasized the communitarian labour in rural economic activities through productive organizations [2].

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Decentralized and combined energy systems can be applied in productive activities when arranged as a multiservice (polygeneration) plant (MP) providing services simultaneously (electricity, cooling, heating, clean water, dry processes, etc.). However, the application of these systems is seen as a complex technology by policy makers and investors. On the other hand, the lack of knowledge and mistrust about the technology is still the main obstacle in its development [3]. The benefits of implementing this type of systems in productive activities while using the local available energy sources are in the line of the Sustainable Development Goals (SDG's). We can mention the 7th goal (Affordable and clean energy), 9th goal (Industry, innovation and infrastructure), 13th goal (Climate action) and 15th goal (Life and land) among others [4]. Using these systems generates a positive impact on the technological, economic, social and environmental aspects when targeted at low-income populations. It is even better if waste resources are used to meet the energy demands while reducing fossil fuel consumption and, consequently, greenhouse gas emissions (GHG).

The application of these concepts can be applied when, for example, farmers' associations are involved. These community associations may also be able to manage small industries by making use of their own resources, generating direct and indirect benefits. The associations of dairy farmers in central Bolivia (Cochabamba) are examples of community work. They have the milk as final product and the cow dung as the main waste. Although the farms are close to each other, which can facilitate the collection of the manure, there is no biogas (BG) production, in spite of the big potential. The manure is just accumulated in an open space, sometimes it is sold to other farmers and/or used in agriculture as fertilizer when growing maize, alfalfa and some vegetable crops [5]. Apart from the bad smell that affects the nearby residents, there is a high risk of diseases for humans and animals [6]. Also the accumulation of animal waste in open space generates more GHG than those resulting from anaerobic digestion while producing biogas [7, 8]. On the other hand, the waste from the anaerobic digestion process allows obtaining a high quality fertilizer [9].

Biogas can be used for cooking but also for producing electricity, refrigeration, heating and fertilizers. It can contribute to reduce or avoid the grid dependence and to reduce GHG using waste resources. That is important considering that most of the electricity produced in Bolivia comes from thermoelectric plants based on natural gas [10], which is subsidized by the government [11, 12] like LPG tanks (used for cooking).

Romero Padilla [5] has presented an economic-environmental and competitiveness analysis of the dairy industry chain in Bolivia. That study describes the existing policies, economic aspects and the environmental impacts of the milk industry chain. It is a general overview of the state of the Bolivian dairy sector. The purpose of that study is to inform that there is no proposed solutions for the problems that the sector is currently facing. One of these problems can be identified as the lack of attention in the exploitation of a waste resource that, if used in a multiservice plant, can provide diverse services while providing additional benefits.

54.1.1 *Objective and Scope*

This paper presents a techno-economic feasibility study of a multiservice plant (MP) aimed to be implemented in a milk storage (refrigeration) centre for dairy farms located in “Alba Rancho” central Bolivia, a traditional area of dairy farmers. Cow dung from farms will be the source for the production of biogas, electricity, cooling and fertilizer using Anaerobic Digesters (AD), an Internal Combustion Engine (ICE), an Absorption Refrigeration System (ARS) and a bio-slurry dryer (BSD). These services are a necessity for the farmers including the fertilizer which is dried to facilitate its handling and transport when it is sold to farmers from remote regions.

The results of the present study will be the levelized costs of the proposed services under the particular conditions of the Bolivian market. These results can be considered as referential for the specific application in the dairy sector where the main energy resource utilized is the farm waste (cow dung). However, the same methodology can be followed when considering the application of polygeneration systems in other productive (or not) sectors.

54.2 Methodology

The methodology follows these steps: data collection about energy situation (fieldwork, interviews with related institutions and literature review); quantification of biogas production potential using cow dung from farms; quantification of energy demands and proposal of a multiservice polygeneration plant; and finally techno-economic evaluation of the proposed system.

The techno-economic study to determine the levelized costs of the proposed services will be done considering data collected from fieldwork, referential equipment prices in the Bolivian market, investment capital, operation and maintenance costs. A sensitivity analysis for the services prices will be presented considering the variation of: the cost of feedstock handling cost (for biogas) and subsidies in the investment capital. These prices are then compared to the current subsidized and non-subsidized prices of similar competitive services in the Bolivian market. The techno-economic study ends by defining sale prices of the services which allow to determine a payback period of the initial investment capital cost for the proposed system.

54.2.1 *Potential of Biogas Production, Cooling and Biogas (for Cooking) Demand*

For this study the electrical and thermal energy demands have been previously determined to propose a polygeneration plant. The thermal demands consider the average of the monthly temperatures of the last 20 years in the zone [13].

The input demands for sizing the plant are the cooling capacity for milk refrigeration and the biogas for cooking required by the 30 families that are part of the association.

The refrigeration capacity was determined for the 5100 L of milk per day (current storage capacity of the centre). The initial temperature of the milk is assumed to be the ambient temperature while the final is set at 4 °C. The number of cows owned by the 30 associated families is 364 heads (255 producing milk). It is assumed a daily production of 35 kg of manure per cow but only 28 kg are used for the production of biogas (assuming losses in the collection). The biogas potential produced was determined using parameters from previous studies in the area whit a yield of 0.335 m^3 of biogas per kilogram of volatile solids (VS) [14] while the energy potential of the biogas is assumed to be 6 kWh/m^3 for a biogas with 60% methane content [15].

It is proposed to meet the refrigeration demand using an absorption refrigeration system (ARS), which uses the recovered heat (from the combustion gases) of a biogas power generator, in this case an internal combustion engine (ICE). The biogas demand for the power generator plus the biogas for cooking demand is the total biogas that should be produced in the plant. From the calculations the production of biogas cannot meet the demand (when considering the number of cows of the association), then it is proposed to increase the number of farmers (not associated) for the contribution with additional manure. The total number of cows is 471.

54.2.2 A Proposed Polygeneration System and Technical Characteristics

The proposed system considers an internal combustion engine (ICE) which can be imported from China [16] to Bolivia. This prime movers is proposed to be configured with an absorption refrigeration system (ARS), Pink Chiller PC19 [17], and heat exchangers in such a way that the plant can provide electricity, cooling and heat services. The polygeneration plant shown in Fig. 54.1 requires a cow dung/water mixture, which produces biogas (BG) and bio-slurry. Biogas is used as gas for cooking and for producing electricity and heat (in the flue gas) using the prime mover (ICE) after being cleaned and pumped. The heat is recovered in water heat exchangers and used for driving the refrigeration system (ARS), for drying the bio-slurry (BSD), and, optionally, to regulate the temperature inside the biodigesters. The final products of the plant are biogas, electricity, refrigeration and dry/liquid fertilizers.

Internal Combustion Engine (ICE): The engine does not need a compressor but a biogas pump and a cleaning stage (to remove solid particles, sulphur and water remains). The nominal power output is 40 kW_{el} while its electrical efficiency is 37%. It is assumed that the nominal data is determined for ISO conditions. The electrical efficiency is diminished by the ambient conditions of the installation site and due to the use of a part of the power produced in the biogas pump. Although some manufacturers of large gas engines say that the altitude does not

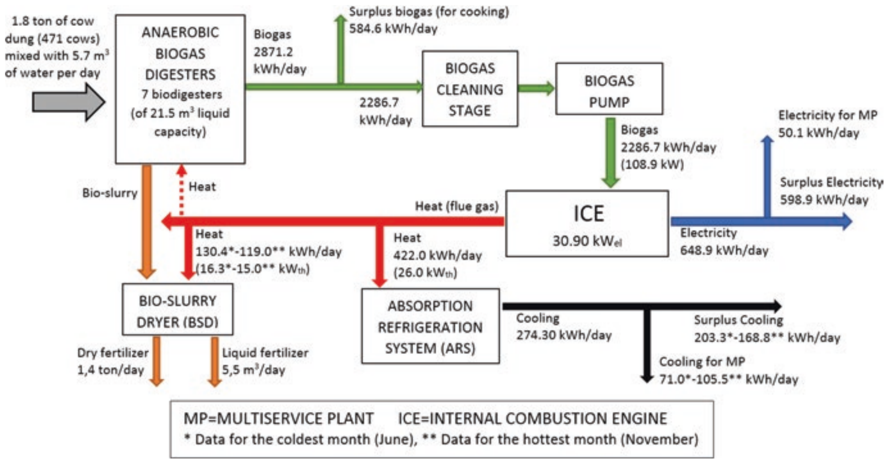

Fig. 54.1 Diagram of the proposed polygeneration plant

affect the power of the engine [18], for this work we will assume a referential derating factor [19]. The actual resulting electrical power is 30.9 kW_{el}, with an electric efficiency of 34%.

Biogas Production System: The incursion of biogas technology in Bolivia has been scarce. Most of the few implementation projects have focused on the production of biogas for cooking in rural areas where the lack of basic services is evident. The technology used for these small systems has been called "low cost tubular digester" because the materials used are relatively cheap when compared to other technologies [20, 21]. Being the only technology that has worked in the region, this study proposes its utilization while considering improvements in the quality of materials [22]. The hydraulic retention time for biogas production is set at 20 days. The calorific energy of the biogas is 21.6 MJ/m^3 [15].

Absorption Refrigeration System: This system (ARS) is marketed in Europe as Pink Chiller PC19 [17]. It requires heat for its operation that is given by a flow of hot water gained in a water heat exchanger. According with data sheet of PC19 the cooling capacity depends of the inlet/outlet temperature of the hot water circuit, they are set at 95/88 °C (flow rate of 3.2 m^3/h). Then the cooling capacity is 17 kW_{th}, the heat required by the ARS's generator (hot water circuit) is 26 kW_{th} and the COP is 0.65. The cooling is given in a cold-water circuit which is proposed to be used in the evaporators of the milk tanks.

Bio-slurry drying system (BSD): In a first stage, the bio-slurry drying system drains the liquid from the bio-slurry keeping a semi-dry product inside a rotating drum. This drum consists of a mixing system while a permanent flow of warm flue gas produces the drying of the product. The final product is a consistent organic fertilizer for use in agriculture. The initial temperature of the bio-slurry is the ambient temperature while the final is set at 95 °C.

54.2.3 Capacity of Production of the MP, Costs of the Production Units (Subsystems) and Investment Cost of the MP

Table 54.1 shows the annual capacity production of the services supplied for the MP when considering the ICE as prime mover. It also shows how much of the production is destined for the functioning of the MP and for sale. The annual rate considers 355 days, which are the operation days fixed for the MP. The rest of the days are assumed for maintenance and equipment revision, also unexpected failures.

Table 54.2 presents the cost data of the MP used to determine the levelized costs of the services, which also includes a raw estimation of the costs of other items involved and the total investment capital cost. The costs of the energy sources considered for the subsystems are cow dung for the production of biogas; biogas for

Table 54.1 Annual capacity production of the multiservice plant when using an ICE

		MP-ICE		
Service	Unit	For MP	For sale	Total
Biogas	kWh	811,763.77	207,527.28	1,019,291.04
Electricity	kWh	17,767.75	212,591.75	230,359.50
Cooling	kWh	31,236.47	65,760.69	96,997.15
Dry fertilizer	ton	–	507.11	507.11
Liquid fertilizer	m^3	–	1954.97	1954.97

Table 54.2 Costs/investment for the polygeneration plant and its production units

Description	Unit	MP-ICE
Biogas production—investment cost	**USD**	**69,638.00**
Cost of the land	**USD**	**50,500.00**
Tubular biodigesters of 7 × 22.3 m^3 (liquid volume)	USD	14,000.00
Pipes, accessories & minor components	USD	5138.00
Feedstock handling cost	USD/ton	10.00
Electricity and heat production—investment cost	**USD**	**29,770.83**
Internal combustion engine	USD	20,167,66
Treatment biogas system (cleaning and pumping)	USD	9603.17
Cooling production—investment cost	**USD**	**65,139.00**
Absorption refrigeration system	USD	38,025.00
Milk tanks, including evaporators	USD	25,500.00
Pipes, accessories and minor components	USD	1614.00
Fertilizer production—investment cost	**USD**	**6360.00**
Bio-slurry drier	USD	5000.00
Pipes, accessories and minor components	USD	1360.00
Total investment cost of the MP	**USD**	**170,907.83**

the production of electricity and heat; and electricity and heat for the production of refrigeration and fertilizer. Therefore, first the price of biogas has to be determined, then the price of electricity and, finally, the price of cooling and fertilizers.

54.2.4 Economic Analysis, Levelized Cost of the Services and Payback Period

The method of Levelized Cost of Electricity (LCOE) proposed by Mainali and Silveira [23] will be used (excluding the environmental factor of the equation). That will be done considering the capacity production of the services and the costs presented in the previous section. The result of LCOE calculation is a price that serves to evaluate the proposed technology when compared to alternative technologies, which also generate electricity. Such technologies can be of smaller or larger scale, have different investment costs and/or periods of operation. The LCOE considers the total life cycle cost of the project instead of the simple comparison of the capital costs [15, 23]. The LCOE is defined by Eq. (54.1).

$$\mathrm{LCOE} = \frac{\text{Total life time cost of the project}}{\text{Total life time useful electricity produced}} \tag{54.1}$$

To calculate the annual costs, a project time period, a discount rate and a scaling factor of the prices were defined to be 20 years, 10% and 5% [15, 23], respectively.

This method is also applied to determine the Levelized cost of biogas (LCOB) [15], cooling (LCOC) and fertilizer (LCOF). The units of the services costs are USD/kWh for biogas and refrigeration, and USD/ton and USD/m^3 for dry and liquid fertilizer, respectively.

The payback period is also calculated. That is, the time (in years) in which the sum of the net cash flows (revenues) of the MP equals the initial investment capital.

54.3 Results and Discussion

54.3.1 Levelized Costs of the Services Supplied by the MP and Costs of the Current Services in the Bolivian Market

Table 54.3 shows the levelized costs of the services determined for the proposed system, they are shown together with the prices of similar competitive services in the Bolivian market. They correspond to the current subsidized (S) and non-subsidized (NS) prices for electricity [10], refrigeration and LPG [24, 25]. The non-subsidized prices are approximations based on studies conducted in Bolivia that try to predict

Table 54.3 Services costs of the MP and subsidized (S)/non-subsidized (NS) prices in Bolivia

Service			MP-ICE	S-Prices		NS-Prices	
Biogas/LPG	USD/kWh	**LCOB**	**0.018**	S-LPG	0.025	NS-LPG	0.038
Electricity	USD/kWh	**LCOE**	**0.088**	S-EL	0.100	NS-EL	0.160
Cooling	USD/kWh	**LCOC**	**0.102**	S-CO	0.091	NS-CO	0.128
Fertilizer	USD/ton	**LCOF**	**3.13**	–	–	–	–

what the real price of electricity would be [26, 27]. The non-subsidized price of LPG corresponds to the exportation price [28, 29] while the cooling prices were determined using the cost of electricity used in conventional systems, the cost of the refrigeration equipment and the refrigeration demand.

In Bolivia the price of natural gas used in thermoelectric plants is subsidized. Therefore, the price of electricity for the final users, indirectly, has a reduced cost [26, 27]. The refrigeration, considered as a final service, which is obtained with subsidized electricity is consequently subsidized. In the case of LPG used for cooking, the price has been fixed for several years [11, 12], while the exportation price from Bolivia is much higher [28]. There is no evidence of commercialization of dry fertilizers from bio-digestion processes, so prices were not found.

From results shown in Table 54.3 it can be seen that the price of biogas of the proposed system is much lower when compared to the equivalent LPG price subsidized or not. The electricity produced in a MP-ICE is even lower than the S-price. The price of the cooling service produced is slightly higher than the S-price of the cooling service in the market. The only reference with which the price of the dry fertilizer can be compared is with the cow dung price in its natural state, where the selling price was found to be 10 USD/ton for the MP (for biogas production) and for other customers as well (according to consultations). In the present study, the prices determined for the dry fertilizer are much lower, which allows having a greater margin of profit when selling it. This considering that the fertilizer produced in the MP has better quality than the cow dung in its natural state [9], which increases its economic value.

From Table 54.3 it can be seen that the levelized costs of the services of the MP-ICE are attractive and competitive especially when considering a scenario without subsidies.

54.3.2 Sensitivity Analysis for the Cost of Services Supplied by the Proposed MP

In this section the levelized cost of biogas will be identified as LCOB, in similar way for the rest of the services. S-LPG and NS-LPG are the reference prices for the subsidized and non-subsidized prices of LPG, respectively. In similar way for the electricity (EL) and cooling (CO) services.

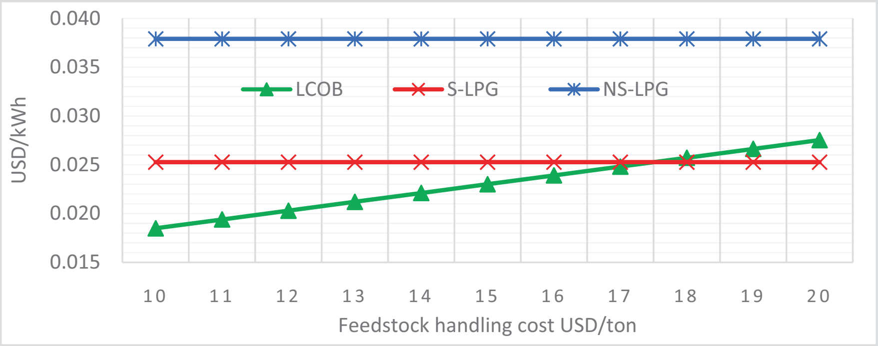

Fig. 54.2 Influence of feedstock handling cost on the LCOB

54.3.2.1 Influence of the Feedstock Handling Cost on the Price of Biogas

The collection and handling of cow dung can be seen as a dirty and unattractive task. This can be counteracted by offering higher payments for the product while improving the economy of the farmers. It is illustrated in Fig. 54.2 when the feedstock handling cost increases from 10 (the current price) to 20 USD/ton. The price of biogas (LCOB) equals the subsidized LPG price (S-LPG) at a feedstock handling cost of around 18 USD/ton. However, it never reaches the non-subsidized price (NS-LPG) even if the feedstock handling cost is 20 USD/ton.

54.3.2.2 Effect of Subsidizing the Initial Investment Capital of the MP on the Services Costs

The prices of most of the services were found lower than the referential prices of the market. However, the cost of cooling was found slightly higher than the subsidized price of cooling in the market, it can be seen in Table 54.3. Although the source of energy for the production of cooling in the MP is the heat whose price is zero, its final price results to be almost similar to the price of cooling produced in conventional systems that use electricity. This is due to the cost of the technology used for the production of cooling, the proposed system uses an absorption system whose cost is quite high compared to the compressor-driven system. Subsidizing the initial investment cost of the MP can be a way to reduce this cost while making the proposed MP more competitive. This subsidy can be also interpreted as a reduction in the technology cost that affects the final levelized costs of the services.

Cooling (refrigeration): When there is no subsidy the determined price (LCOC) is found between the calculated prices of conventional refrigeration system (S-CO and NS-CO). Figure 54.3 shows that this price decreases drastically when the investment capital subsidy increases, this is because it is almost fully dependent

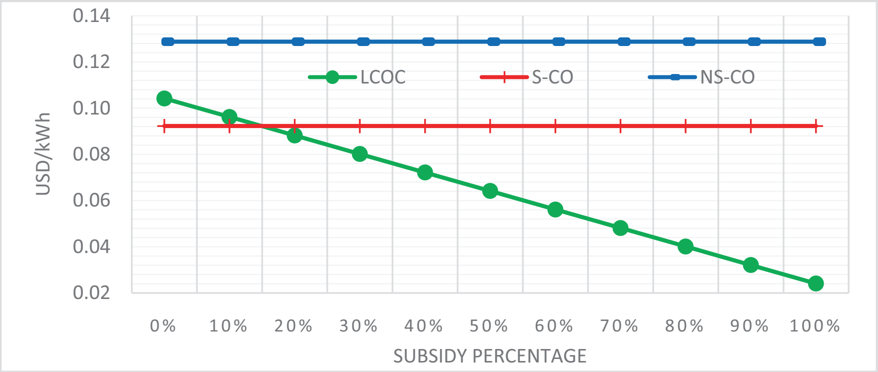

Fig. 54.3 Influence of subsidizing the investment capital cost on the LCOC

on the cost of the technology since the cost of the energy source (heat) is zero. At about 15% of subsidy for the MP, the cooling price (LCOC) equals the subsidized price (S-CO), reducing even more when the subsidy increases.

Applying this subsidy also means a reduction of the levelized costs of the rest of the services.

54.3.3 *Sale Prices of Services/Products and Payback Period for the Proposed Systems*

Three scenarios are presented for the sale prices of the services/products of the proposed system, they allow to determine a cash flow and the payback period for the investment capital.

In scenario 1 the sale prices are defined to be equal as the determined levelized costs (LCOB, LCOE and LCOC) for the proposed system (MP-IFMT). In scenario 2 and 3 the sale prices are defined to be the same as the subsidized prices (S) and non-subsidized prices (NS) of the conventional services, respectively. All these prices are shown in Table 54.3.

For these scenarios the cost of the dry fertilizer is set at 15 USD/ton. The resulting liquid from the bio-slurry dryer system (BSD) is also considered as (liquid) fertilizer which is proposed to be sold at a price of 10 USD/m^3 in all the cases. The payback period (in years) for the proposed system in the different scenarios is presented in Fig. 54.4.

Scenario 1 is only referential because of the slightly higher cost of the cooling when compared to the subsidized price. It is not feasible to sell this service at a higher cost than the service cost in the market. In scenario 2, the subsidy for the investment capital has to be only 15% which allows to sell the services at the same current subsidized prices of the market services. That is the most promising scenario which can be implemented under the actual conditions of the Bolivian market. In scenario 3,

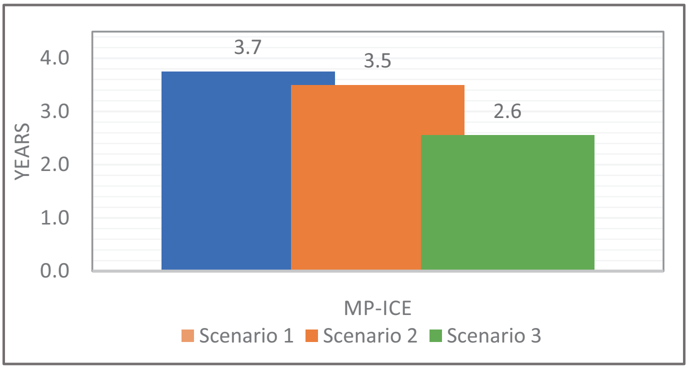

Fig. 54.4 Payback period for the proposed system (for different sale prices)

the supposed case of a non-subsidized market, the MP-ICE does not require any subsidy in the investment capital having a great advantage over the other presented scenarios. That is reflected in the shorter payback periods shown in Fig. 54.4.

54.4 Conclusions and Future Work

A multiservice plant has been proposed for the dairy sector in central Bolivia considering an internal combustion engine as prime mover, an absorption refrigeration system and a bio-slurry dryer. The final services from the plants are biogas, electricity, refrigeration and fertilizers.

The economic analysis has focused on determining the levelized cost of the services. The resulting prices were compared with the current subsidized and non-subsidized prices of similar competitive services existing on the market. The price determined for biogas was found lower when compared to the subsidized LPG price in terms of its energy value. The price of electricity was found lower than the subsidized price. The cost of cooling was found to be slightly higher than the subsidized price in the market. Sensitivity analyses were presented to see the effect on the levelized cost of biogas when increasing the feedstock handling cost and the cost of cooling when a subsidy is applied on the investment capital in order to reach the subsidized referential price. It was shown that the feedstock handling cost can be increased from 10 USD/ton up to 18 USD/ton while maintaining a biogas price lower than the non-subsidized price of LPG. That means better payments for the farmers while improving their economic status. As expected, the prices of the services tend to decrease when a subsidy is assumed in the cost of investment capital. Finally, different scenarios were presented to determine the payback period of capital recovery. From this analysis the plant with a subsidy in the investment capital of 15% and sale prices of the services equal as the subsidized prices of the market services has shown a payback period of 3.5 years being a promising option.

It is also shown that a market without (or with reduced) subsidies for the conventional services makes the proposed system more feasible and competitive. However, the high investment cost and the complexity of the technology can be seen as barriers for a real implementation.

As future work, it is necessary to study possible sources of financing and the compatibility with existing regulations in the Bolivian energy sector to determine the existing gaps.

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