

Biogas based polygeneration plant options utilizing dairy farms waste: A Bolivian case



J. Villarroel-Schneider^{a,b,*}, Brijesh Mainali^c, J. Martí-Herrero^{d,e}, Anders Malmquist^a, Andrew Martin^a, Lucio Alejo^b

^a Department of Energy Technology, School of Industrial Technology and Management (ITM), KTH Royal Institute of Technology, Stockholm SE 100 44, Sweden

^b Facultad de Ciencias y Tecnología (FCyT), Universidad Mayor de San Simón (UMSS), Cochabamba, Bolivia

^c Department of Built Environment and Energy Technology, Linnaeus University, 351 95 Växjö, Sweden

^d Biomass to Resources Group, Universidad Regional Amazónica Ikiam, Tena, Ecuador

^e Building Energy and Environment Group, Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE), Edifici GAIA (TR14), C/Rambla Sant Nebridi, 22, 08222 Terrassa, Barcelona, Spain

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ABSTRACT

This study presents a comparative techno-economic feasibility analysis for two polygeneration plant solutions, applied to low-income dairy farms in Bolivia. The first option considers an internally fired microturbine (IFMT) and, the second, an internal combustion engine (ICE). They are integrated with an absorption refrigeration system and a fertilizer dryer. Biogas, produced with farms waste, fuels these power generators. The levelized costs of biogas for cooking, electricity, cooling and fertilizers were determined. The cost of biogas, for both options, was found to be 0.020 USD/kWh, which is lower than the subsidized price of LPG. The most competitive cost of electricity was determined for the ICE plant option; it was found to be 0.082 USD/kWh and is lower than the subsidized cost of fossil fuel-based electricity. The cost of cooling was found to be around 0.082 USD/kWh, which is slightly higher than the cost of cooling supplied by using grid electricity. In a realistic scenario, the shorter payback period was found to be 4.4 years for the ICE plant option. From this, the ICE-based plant was found as the most feasible option. Additionally, if no subsidies are applied to the fossil fuel-based services, the proposed polygeneration systems are a highly competitive alternative.

Introduction

Background

Developmental challenges are of a complex in nature and most often tangled with social, technological, economic and environmental agendas. These multifaceted developmental challenges were agreed by world leaders in “The 2030 Agenda for Sustainable Development” with seventeen specific goals under UN initiation [1]. Regarding access to energy services, technological solutions should be evaluated with a holistic approach since they contribute not only providing energy services such as lighting, heating, refrigeration and electricity but also generating benefits in social, education and health aspects [2]. On the other hand, the use of alternative energy sources, to meet energy demands in residential as well as in productive sectors, can help to promote an integral and sustainable development of a country.

Bolivia, like many other developing countries, is in its early stage of implementing policies to promote sustainable use of energy resources. The new “Constitution of Bolivia” emphasizes on new forms of alternative energy production considering the environment conservation. Another aspect addressed in the constitution is the promotion of communitarian labor in economic activities through productive organizations [3]. These two aspects can be related, for example, to the possibility of having the active participation of productive sectors in the energy system while producing energy services for their own consumption and/or for the market.

In this context, a decentralized energy system where combined energy solutions are applied to productive sectors could be an interesting alternative. A combined energy solution, when arranged as a polygeneration plant (PP), can supply various services simultaneously (e.g., electricity, cooling, heating, clean water and other processes that require heat). However, the lack of knowledge and mistrust about the

* Corresponding author at: KTH Royal Institute of Technology, Department of Energy Technology, Division of Heat and Power, Brinellvägen 68, 100 44 Stockholm, Sweden.

E-mail address: jhonnyvs@kth.se (J. Villarroel-Schneider).

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integration of different technologies in a single system are still the main obstacles in its development [4]. On the other hand, the benefits of implementing this type of systems in productive activities while using locally available energy resources are in the line of the Sustainable Development Goals (SDG's) [1].

Undoubtedly, in a developing country, the incursion of different alternatives to conventional energy solutions requires a techno-economic feasibility study. In the case of the application of a polygeneration plant, this study can be considered as a fundamental part of an integrated assessment. This techno-economic evaluation should conclude by determining the levelized cost of the supplied services which is an important economic indicator. Although, this indicator is mostly used to determine the levelized cost of electricity (LCOE) when comparing different technological solutions, as proposed by Mainali and Silveira [5], it can also be applied to determine the levelized cost of additional energy services and other products.

A local energy source accessible to impoverished farmers, in the so-called developing countries, is the biogas generated by the anaerobic digestion of farm waste. Usually the use of this fuel is limited for cooking purposes; however, it has the potential to be used in energy solutions that can supply electricity and thermal services. Several initiatives around the world have been implemented to promote biogas technology, with very different results. In south Asia and Africa the national biogas programs were carried out successfully [6] while in Latin America the initiatives never have reached the scale of a national biogas program [7,8], except for Nicaragua where a national biogas program was carried out. The results from Nicaragua were limited in the number of systems implemented (around 1,200 digesters in five years) but it allowed expanding the range of biogas uses in small farms towards productive usage (pumps, electricity production and mechanical milking machines) [9].

Regarding techno-economic studies of biogas-based polygeneration applications, it was found that Khan et al. [10] have presented the levelized cost of biogas, electricity and safe drinking water proposed for a small rural village in Bangladesh. The prime mover of the plant is an internal combustion engine. The results show that the costs of the proposed services are more competitive compared to other available technologies. In the case of combined heat and power (CHP) applications, it was found that Trendewicz and Braun [11] presented a techno-economic analysis of biogas-fueled solid oxide fuel cell systems. It was done for wastewater treatment facilities in the USA. They have determined the levelized costs of electricity and heat to compare to the cost of services supplied by other technologies including the cost of the grid electricity. Additionally, the efficiency of the CHP system (for different operating states) was analyzed. It was concluded that biogas quality, price of grid electricity and incentives are the factors that influence the economic viability of the proposed solution. Coimbra-Araújo et al. [12] carried out a study for the agricultural sector in Brazil. This study is related to the use of biogas in CHP applications for the production of electricity, fertilizers, and heating services. However, a precise focus on determining the levelized costs of the services was not considered.

In the case of studies focused in the dairy sector, it was found that Gebrezgabher et al. [13] have presented different business models for biogas production applied to dairy farms in The Netherlands. They have proposed the use of biogas-based CHP systems and have calculated the cost of electricity. The recovered heat of the combined systems was proposed for using in drying processes in the biogas plants without considering the production of additional services for sale. The economic success of the proposed solutions was found to be dependent on various factors as investment costs, biogas yield of the feedstock, production costs, fertilizers prices and level of subsidies. White et al. [14] has proposed small-scale biogas production by employing the concept of modular biogas plants that can produce electricity. This study was proposed to be applied to small dairy/beef farms in the USA, and the results shows that this proposal is economically attractive since

electricity produced by biogas receives incentives in the site of application. In Bolivia Romero [15] has presented an economic-environmental and competitiveness analysis for the dairy industry chain (i.e. from the production of milk in dairy farms to the consumption of dairy products and final disposal of the generated residues). The study provides a general overview of the existing policies, economic aspects and the environmental impact of the milk industry chain. However, a special emphasis on energy issues has not been part of its scope.

Some studies have focused on analyzing the use of renewable energy sources in dairy farms in order to determine the economic viability and to estimate the reduction of greenhouse gas emissions. Among the energy resources considered in these studies we have biogas (that can be produced with farms waste [16]), solar photovoltaic (PV) [17], wind [18], solar PV/biomass hybrid energy system [19] and the integration of algae bioenergy for dairy manure digestion [20]. On the other hand, the use and management of energy in dairy farms is an important issue since the efficient management of energy resources would help improving the profitability of the dairy activity. It has been found that apart from electricity, refrigeration (for milk preservation), is an indispensable thermal service regardless of the size of the farms [21–23].

This literature review has been focused on: (i) techno-economic studies of biogas-based polygeneration/CHP applications, (ii) studies of energy solutions that are specifically applied to the dairy sector, (iii) studies that address the inclusion of renewable energy sources in the dairy sector, and (iv) studies about the use and management of energy in dairy farms. From this review, it is concluded that a specific techno-economic feasibility study for a small-scale polygeneration plant applied to the impoverished dairy sector has not been done before. The need to conduct this work is reinforced by the fact of the inexistence of this type of research in a developing country like Bolivia, especially when it comes to solutions for low-income farmers.

This study proposes polygeneration system solutions for dairy farmers in central Bolivia. These solutions consider the use of dairy farms waste for providing biogas, electricity, cooling (for milk refrigeration) and fertilizers (for the community). Therefore, a feasibility evaluation is necessary for determining the costs of such services and their market competitiveness. This evaluation considers the current energy situation of the dairy sector, the energy market conditions and the related economic variables. The final results of the techno-economic analysis will help to determine if the production costs of the mentioned services are more competitive than the costs of fossil fuel-based services that are available in the market. Addressing this economic aspect when proposing an alternative to replace fossil fuels usage is important in the Bolivian context since most of the grid electricity produced comes from thermoelectric plants based on natural gas [24], which is subsidized by public funds [25,26] like LPG tanks used for cooking purposes. On the other hand, a biogas-based polygeneration plant contributes to reduce or avoid the grid dependence while reducing fossil fuel consumption and, consequently, greenhouse gas emissions (GHG).

Objective and scope

The purpose of this paper is to present a techno-economic feasibility study of polygeneration solutions applied to the dairy sector in central Bolivia. The study focuses on determining the costs of the services supplied by the polygeneration plant. The polygeneration plant enhances the utilization of cow dung from farms for biogas production; most of the biogas is used for the production of electricity and heat (recovered from the exhaust gas) in an Internally Fired Microturbine (IFMT) or an Internal Combustion Engine (ICE). The heat is used to (i) drive an Absorption Refrigeration System (ARS) for milk refrigeration and, (ii) dry bio-slurry for fertilizer production. Then the final services are biogas, electricity, refrigeration and fertilizers. The levelized cost of each service is analyzed to see its competitiveness under the Bolivian market situation. Dairy farmers require these services, including the fertilizer, which is dried to facilitate its handling and transport when it

is sold to farmers from distant regions.

Methodology

For the purpose of our analysis, the following steps were followed:

- (i) data collection about energy situation and energy demands of the dairy farmers (fieldwork, interviews with related institutions and literature review),
- (ii) estimation of biogas production potential and energy demands,
- (iii) proposal of polygeneration plant solutions and their production capacity, and
- (iv) techno-economic evaluation of the proposed solutions on which this work is focused.

The techno-economic study considered: data collected from fieldwork, referential equipment prices in the Bolivian market, investment capital, operation and maintenance costs and, the production capacity of the proposed plants for determining the levelized costs of the services. Then, these costs were compared to the current subsidized and non-subsidized prices of similar competitive services (i.e. electricity from the grid, conventional refrigeration and LPG) of the local market. A sensitivity analysis for the cost of the services was done, considering the variation of: (i) the feedstock cost (for biogas production), and (ii) the percentage of subsidies applied to the investment capital that allows reducing the final cost of electricity and refrigeration. Finally, sales prices of the services were defined allowing determining a discounted payback period of the investment capital for each of the proposed solutions.

Fieldwork for data collection and current energy situation

Fieldwork was carried out in dairy farms and in milk storage centers (MSC) in the area of “Alba Rancho”, Cochabamba (central Bolivia), which is a traditional area of milk production. The dairy farmers in this region are organized in associations, cooperatives and most of them are part of a federation. Depending on the milk capacity production, they are classified in small, medium or big producers. The majority are small farmers. They usually have around 10 cows (per farmer) and do not own individual refrigeration systems because of the high costs. In this case, they are forced to be grouped in small associations for sharing milk storage centers (for milk refrigeration) where they store their daily milk production. From these centers, the only big milk company collects the milk every day. There are about such 70 milk storage centers (or milk cooling centers) in this region [15,27–29].

Farmers have the milk as the final product and the cow manure as the main waste. Although the farms are close to each other that can facilitate the waste collection, there is no biogas production, in spite of a big potential. The cow dung is just accumulated in open spaces without considering a proper waste management. Sometimes it is sold to other farmers and/or used in agriculture as fertilizer for the production of various crops [15]. However, if this manure would be used as a substrate for biogas production, it would allow obtaining a high quality fertilizer which results from the anaerobic digestion process [30].

The selected milk storage center for this study is “Modulo-A # 2900” where 30 families store the milk daily. Almost all the villagers that live along the route shown in Fig. 1 are dairy farmers, so there is the necessity of many milk storage centers with refrigeration systems.

Milk storage centers (MSC) have a relatively high demand for refrigeration. They use to have from one to four independent electric compressor-driven refrigeration systems, each with its own milk tank. The total storage capacity can be higher than 5,000 L of milk. The centers use electricity from the local electric company and all the associated farmers share the monthly cost of this service. Other services required by farmers are gas for cooking, which is currently supplied by

LPG tanks, and fertilizers for agricultural purposes.

Estimation of potential biogas production and energy demands

The number of cows owned by the 30 associated families was, at the time of the fieldwork, 364 of which 255 were producing milk. From fieldwork a daily production of 35 kg of fresh manure per cow is estimated (as they are improved breed cows [15]) but, only 28 kg is used for biogas production (assuming 20% losses in the collection). The potential of biogas production was determined considering data from previous studies that report performances of biodigesters in that region [32]. They are: a specific biogas production yield of 0.28 m³ per kilogram of volatile solids (organic matter), a total solid factor of 16% and, a volatile-solid/total-solid fraction of 80%. The energy potential of the biogas with 60% methane content is assumed to be 6 kWh/m³ or 21.6 MJ/m³ [10]. With these data, the current biogas production was estimated to be 371 m³ (at local ambient conditions) per day or 2,228 kWh/day in terms of its energetic content. This amount of biogas should meet the daily demand of the power generator (prime mover) plus the biogas for cooking required by the associated small dairy farmers. The demand of biogas for cooking has been estimated considering the current use of LPG for cooking in the village (a family requires two LPG tanks per month, of 10 kg each, data collected from fieldwork). The energy content of this LPG and the energy factor conversion for biogas (6 kWh/m³) were used to determine the equivalent demand of biogas per family. It was found to be 1.4 m³/day per family and 42 m³/day for the 30 families associated. The delivery point of biogas is proposed to be in the plant; therefore, this work does not consider the distribution pipes.

The refrigeration demand of the milk storage center was estimated for 5,100 L of milk per day, which is the current storage capacity of the center. Half of the produced milk is stored in the refrigeration tanks during the morning and the rest in the afternoon (according to the milking schedule). The cooling capacity was determined considering: the initial temperature of the milk that was assumed to be the ambient temperature while the final was set at 4 °C and; the period of time in which the milk should be cooled down, which is 4 h. As the ambient temperature varies during the year, the cooling capacity required was found to be 8 kW_{th} in June and 12.3 kW_{th} in November, which are for the coldest and the hottest month, respectively [33].

The monthly average temperatures in the area were considered for the estimation of thermal energy demands. This refers to the cooling (for milk refrigeration) and heating (for drying semi-solid fertilizer) demands. It is assumed that the ambient temperature is the initial temperature of the products to be cooled (milk) or dried (semi-solid fertilizer). The most relevant average temperatures are 16 °C and 22 °C for the coldest (June) and hottest (November) month, respectively [33]. On the other hand, the optimal temperature for milk preservation and the temperature for the drying process are considered as final temperatures. However, the negative effects on the equipment performance due to the environmental conditions (humidity and temperatures) of the installation site were neglected.

Although the area is already electrified, this study considers important to know if the electricity produced by the proposed solutions could have a more attractive cost and if so, it could be sold to the electric company and/or villagers in the area.

A proposed polygeneration plant

A systematic description for setting up a biogas-based polygeneration plant (PP) is presented in Fig. 2. The existing demand of cooling for the milk storage center (MSC) and the demand of cooking fuel (for the associated farmers) are the basis for setting the PP. The cooling demand is proposed to be supplied by an absorption refrigeration (thermally driven) system (ARS); this is the first step in Fig. 2. An ARS that can supply the exact demand for refrigeration was not found. For this



Fig. 1. Alba Rancho route in central Bolivia, “Module A #2900” milk storage center [31].

reason, the ARS selected is the Pink Chiller PC19 that allows covering the cooling demand of the MSC and producing a surplus of cooling. This ARS requires a heat source that is provided by the combustion gas of an internally fired microturbine (IFMT) Capstone C30, which is easily available in the Bolivian market [34] or; an internal combustion engine (ICE) which, according to consultations, can be imported from China [35]. These prime movers supply electricity and heat (required by the ARS and for drying fertilizer); this is illustrated in the second step of Fig. 2. Finally, in the third step, the size of the biodigester is calculated in order to supply the biogas demand of the prime mover (IFMT/ICE) and the biogas for cooking required by the farmers. In this final step it is determined whether the biogas production capacity of the associated farmers (presented in Section “Estimation of potential biogas production and energy demands”) is enough to cover the total biogas demand or if it is necessary to increase the number of farmers (not associated), so they can also contribute with additional cow manure from their farms.

Description of the polygeneration plant operation

The main component of the polygeneration plant (PP) is the prime mover, which provides electricity and heat. As mentioned, the poly-generation system considers two options as prime movers: an internally fired microturbine (IFMT) and an internal combustion engine (ICE).

Fig. 3 shows a scheme of the plant processes. The anaerobic biogas digesters are fed with a mixture of fresh cow dung and water. The anaerobic digestion process produces biogas. A part of this biogas is proposed to be distributed among the farmers for cooking purposes and the rest is cleaned and compressed/pumped to fuel the prime mover (IFMT or ICE) for the generation of electricity and heat (recovered from the exhaust gas). The electricity is used in some equipment of the plant while the excess is available for sale. The heat is recovered in a flow of

water using a heat exchanger (WHE), which is used for driving the absorption refrigeration system (ARS). The remaining thermal energy from the exhaust gas is then used for drying the bio-slurry (Bio-slurry dryer-BSD), which is the residue coming from the biogas digester. The cooling supplied by the ARS (required for milk preservation) is sufficient to cover not only the demand of the small farmers’ association but also for the storage of additional milk, which is proposed to be sold as cooling/refrigeration service. The bio-slurry dryer allows obtaining liquid and solid fertilizers. The final products of the plant are biogas, electricity, refrigeration and fertilizers.

Table 1 summarizes the technical information of the main components of the polygeneration plant (PP). It is also shown the daily production capacities and the share of the services/products that are required for the PP and proposed for sale.

Absorption refrigeration system (ARS)

The selected Absorption Refrigeration System is marketed in Europe as Pink Chiller PC19 [36]. It requires three circuits of water as it can be seen in Fig. 3. The first circuit provides the thermal energy required for its operation, which is given by a flow of hot water that is heated in a water heat exchanger (WHE). The second circuit is for heat dissipation in the condenser, which is inside the ARS. Here the flow of water leaves the absorption system with an increased temperature. This flow of warm water is sent to a radiator where the heat is dissipated. Finally, the cooling is supplied by a cold water circuit which is proposed to be connected to the evaporators of the milk tanks for cooling down the milk. Each circuit requires a small pump for the recirculation of the fluid.

According to the datasheet of PC19, the cooling capacity depends on the heat dissipation capacity of the condenser (heat dissipation circuit) and mainly on the inlet/outlet temperature of the hot water circuit;

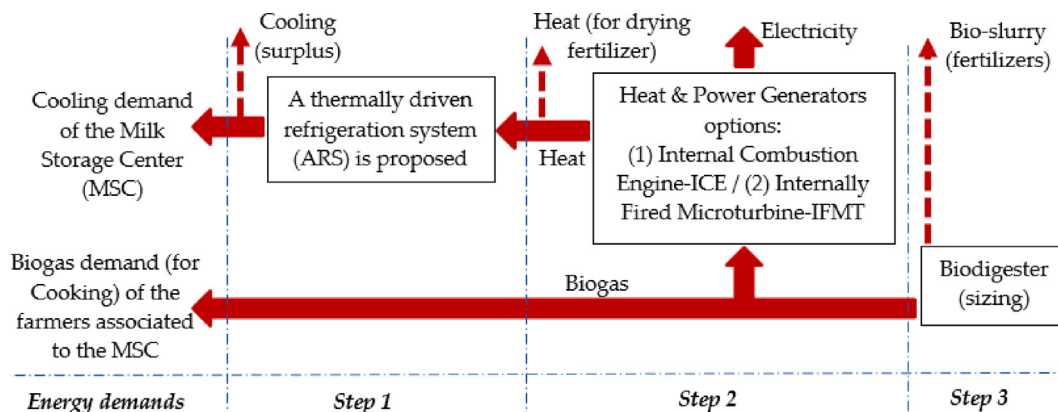


Fig. 2. Illustration for setting up a polygeneration plant step-by-step.

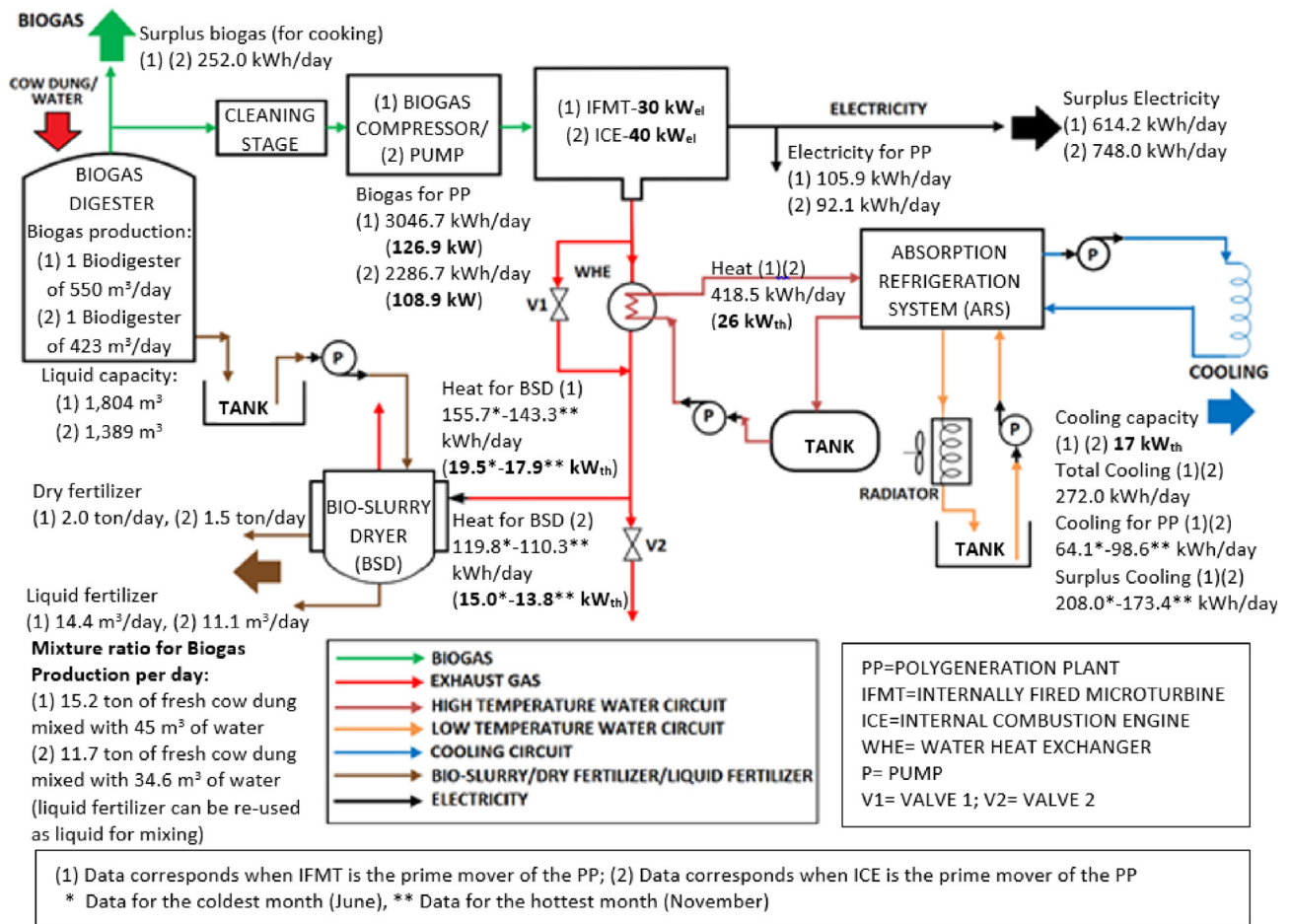


Fig. 3. Diagram of the proposed Polygeneration plant options.

they are set at 95/88 °C (flow rate of 3.2 m³/h) with a thermal power demand of 26 kW_{th}. Under this condition, the cooling water circuit has inlet/outlet temperatures of 0/−3 °C (flow rate of 3.5 m³/h) which allows a cooling capacity of 17 kW_{th}. Considering these parameters (thermal power input/output), the coefficient of performance (COP) is 0.65 [36,37].

The heat recovered from the combustion gas of the power generators (IFMT or ICE) supplies the thermal power demanded by the ARS (given in the hot water circuit). The power generators have electrical efficiencies lower than 40%. In this case, it is assumed that a large portion of the energy (contained in the biogas), that is not converted into electricity, is present in the form of thermal energy in the combustion gas. Therefore, there is thermal energy available that is sufficient to meet not only the thermal demand of the ARS but also for using in the bio-slurry drying unit (BSD). The refrigeration system (ARS) is proposed to work 16 h per day considering that the cold water flow will alternate between the milk tanks according to their cooling requirement (Table 1). The cooling capacity of the equipment meets the current demand for refrigeration of the storage center (which has been estimated in Section “Estimation of potential biogas production and energy demands”) and allows the storage of additional milk (deposited by non-associated farmers).

Internally fired microturbine (IFMT) – Capstone C30

The biogas required by the microturbine needs to be cleaned (to remove solid particles, sulphur and water remains) and compressed. Therefore, a scrubber and a biogas compressor is needed. The nominal power output of the microturbine is 30 kW_{el} while its electrical efficiency is 26% [38]. It is assumed that the microturbine works ideally

under its nominal conditions (Table 1). According to the manufacturers, this microturbine does not require rigorous maintenance and can operate continuously because of the free oil lubrication system and the only rotating element (the turbocharger) [39,40]. For that reason, we assume that the microturbine operates continuously at full load 355 days per year. The daily amount of biogas required by the microturbine is around 508 m³ (or around 21 m³/hour), so the potential of biogas production calculated in Section “Estimation of potential biogas production and energy demands” is not enough. In this case, the manure of 542 cows will be required for the production of biogas (for the IFMT and for cooking). The total production of biogas in this case has to be around 550 m³/day. As previously mentioned, this is achieved with an additional contribution of manure from other farms (for which the farmers will be paid).

Internal combustion engine (ICE)

An Internal Combustion Engine does not need a compressor but a biogas pump and a cleaning stage. The nominal power output of the selected ICE-genset is 40 kW_{el} while its electrical efficiency is 37% [41,42]. It is also assumed that the engine works according to its nominal capacity. Unlike the microturbine operation of this engine cannot be continuous, it can operate only 21 h per day (data about features of this engine provided by manufacturer [35]). Additionally, it requires more frequent maintenance, compared to the microturbine because of the many moving elements and the use of lube oil that needs to be replaced at specific service intervals. However, this prime mover has better electric efficiency than the microturbine [41]. It is assumed that the engine runs at full load. The daily amount of biogas required by the internal combustion engine is around 381 m³ (around 18 m³/hour

Table 1
Description of the components of the polygeneration plant (PP) and daily capacity production.

Description	Unit	PP-IFMT			PP-ICE		
		Total	For PP	For sale	Total	For PP	For sale
<i>Cooling production unit</i>							
Cooling capacity	kW _{th}	17	8/12.3 ^(*)	11/4.7 ^(*)	17	8/12.3 ^(*)	11/4.7 ^(*)
Total cooling production	kWh _{th} /day	272	64.1/98.6 ^(*)	208.0/173.4 ^(*)	272	64.1/98.6 ^(*)	208.0/173.4 ^(*)
Thermal power demand of the ARS	kW _{th}	26			26		
Total thermal energy required	kWh _{th} /day	418.5			418.5		
Operating hours	hours/day	16			16		
<i>Electricity and Heat production unit</i>							
Power capacity	kW	30			40		
Electrical efficiency	%	26			37		
Electricity production	kWh/day	720.1	105.9	614.2	840.1	92.1	748.0
Operating hours	hours/day	24			21		
Biogas required for operation	m ³ /hour	21			18		
Biogas required for operation	m ³ /day	508			381		
Biogas required for operation	kWh/day	3046.7			2286.7		
Biogas energy input rate	kW	126.9			108.9		
<i>Biogas production unit</i>							
Biogas production capacity	m ³ /day	550	508	42	423	381	42
Biogas production capacity	kWh/day	3298.7	3046.7	252	2538.7	2286.7	252.0
Liquid capacity of the biodigesters	m ³	1804			1389		
Biogas energy conversion factor	kWh/m ³	6			6		
Operating hours	hours/day	24			24		
<i>Bio-slurry drying unit</i>							
Thermal power demand	kW _{th}	19.5/17.9 ^(*)			15/13.8 ^(*)		
Total thermal energy required	kWh _{th} /day	155.7/143.3 ^(*)			119.8/110.3 ^(*)		
Operating hours	hours/day	8			8		
Capacity for dry fertilizer production	ton/day	2.0		2.0	1.5		1.5
Capacity for liquid fertilizer production	m ³ /day	14.4		14.4	11.1		11.1
Thermal energy required for drying	kWh _{th} /ton	78/72 ^(*)			78/72 ^(*)		

(*) values correspond to: coldest month (June)/hottest month (November).

for 21 h a day) while the additional biogas required for cooking purposes is 42 m³/day. Then the total demand is met when increasing the production of biogas, for which the manure of 417 cows is needed. The total production of biogas has to be around 423 m³ per day when considering this engine as the prime mover of the plant. This data is also shown in Table 1.

Biogas production unit – biodigesters

The appearance of biogas technology in Bolivia has been quite modest. Most of the 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-scale systems has been named “low cost tubular digester” because of the materials used are relatively cheaper compared to other technologies [43–45]. Biodigesters of large capacity are almost inexistent, or at least not reported. A covered lagoon biodigester of 1,000 m³ (liquid capacity of pig-waste/water mixture) was implemented for a pig farm in eastern Bolivia [46]. Cost data provided by the company that implemented the aforementioned biogas plant is used as a reference for the biodigesters proposed in this work. A mixture of fresh manure and water in a ratio of 1:3 [32] (i.e. 1 kg of fresh manure is mixed with 3 L of water) is considered to reach an influent with total solid content (% TS) of around 3%. This mixture ratio facilitates the flow of the product inside the reactor without the need of mechanical devices. The hydraulic retention time is set to 30 days (assuming that the mixing water will be heated up, so the inside temperature of the biodigester will be higher than the ambient temperature), these parameters allows determining the liquid capacity of the proposed lagoon covered biodigesters [32]. The liquid capacities of the biodigesters were estimated to produce the biogas required for cooking and for the electricity generator (i.e. 550 m³ and 423 m³ per day, for the case of the plant with the IFMT and ICE, respectively). The liquid capacities for the lagoon-covered biodigesters are 1,804 m³ and 1,389 m³ for the case where the IFMT and the

ICE are the prime mover of the plant, respectively (Table 1). After the anaerobic process, the bio-slurry is sent for separation and drying processes. A part of the liquid resulting from the separation of the bio-slurry is proposed to be re-used for mixing with fresh manure, so water will be saved. The semi-solid product is sent to the drying system (BSD). The biodigesters are proposed considering the availability of companies that can install them in South America [47,48].

Bio-slurry drying unit (BSD)

In a first stage, there is a separation process where the bio-slurry drying unit drains the liquid from the bio-slurry (which is the residue that comes from the biodigester after the anaerobic process with a solid content of about 3%) keeping a semi-solid product (with a solid content of around 15–18% [49]) inside a rotating drum. This drum consists of a mixing system while a permanent flow of warm exhaust gas (which flows through a chamber that surrounds the drum) produces the drying of the matter. The final product is a consistent organic fertilizer with a solid content of about 25–30% [49]. In this state, it can be handled as solid and easily transported to distant places (where it is required for agriculture). The initial temperature of the semi-solid manure is the ambient temperature while the drying temperature is set at 95 °C. The equipment is proposed to work 8 h per day and the thermal power required for the drying process varies between 13.8 kW_{th} and 19.5 kW_{th} depending on the ambient temperature and the mass of the product to be dried. The thermal power required for drying a ton of semi-solid fertilizer depends on the ambient temperature. It was found to be around 78 kWh_{th}/ton and 72 kWh_{th}/ton for the coldest and hottest month, respectively (Table 1). It is assumed that the 75% of the liquid slurry will be re-used for mixing with fresh manure (to feed the biodigester) and the rest will be sold as liquid fertilizer. Finally, this equipment is proposed to be manufactured locally.

Table 2
Annual capacity production of the polygeneration plant when using IFMT and ICE.

Service	Unit	PP-IFMT			PP-ICE		
		for PP	for sale	Total	for PP	for sale	Total
Biogas	MWh	1,081.6	89.5	1,171.0	811.8	89.5	901.2
Electricity	MWh	37.6	218.0	255.6	32.7	265.5	298.2
Cooling	MWh	29.4	67.2	96.6	29.4	67.2	96.6
Dry fertilizer	ton	–	697.0	697.0	–	536.4	536.4
Liquid Fertilizer	m ³	–	5,104.8	5,104.8	–	3,928.6	3,928.6

Production capacity of the polygeneration plants and costs

The total daily production capacity of the polygeneration solutions was presented in Table 1. This has been prepared for the two options: for the polygeneration plant that uses a microturbine (PP-IFMT) and for the plant that uses an internal combustion engine (PP-ICE) as prime mover. In Table 2, it is shown the total annual production of biogas, electricity, cooling, and fertilizers. In addition, it is presented the services required by the operation of the plant (i.e. electricity for equipment and lighting; cooling to refrigerate the milk of the associated farmers; and biogas for the prime mover, described in Table 1) and the estimated surpluses of the services/fertilizers available for sale.

The annual production considers 355 days, which are the operation days fixed for both solutions. The rest of the days were assumed to be for maintenance (plant overhaul) and/or unexpected failures.

Fig. 4 illustrates the distribution (for use in the PP and for sale) and the magnitude of the services supplied by the two proposed solutions. It can be seen that cooling production in both cases, PP-IFMT and PP-ICE is identical which is due to the use of the same equipment for its production, same operation conditions and same amount of thermal energy utilized for its operation. The power capacity and the electric efficiency of the ICE, which is higher compared to the IFMT (as described in Section “A proposed polygeneration plant”), allows more electricity production but less biogas consumption. As a result, the PP-ICE offers more electricity for sale. More biogas is required for electricity production in the PP-IFMT than in the PP-ICE while the availability of biogas to be sold for cooking is the same amount in both cases.

Table 3 presents the cost and lifetime data of the components of the polygeneration solutions, they are used to determine the levelized costs of the supplied services. That includes approximate costs of some additional items required, the investment for each production unit (biogas, electricity & heat, cooling and fertilizers) and the total investment capital of the plant.

Economic analysis, levelized cost of the services and payback period

The economic analysis is focused on determining the prices of the services supplied by the PP solutions; electricity, biogas, refrigeration and dry fertilizer. It has been done considering the production capacity of the services and the costs presented in the previous section.

The paper adopt the method for estimating levelized cost of electricity (LCOE) as proposed by Mainali and Silveira [5]. The result of LCOE calculation is an indicator that serves to evaluate a proposed technology when compared to other alternatives which also produce electricity. Such alternatives can be of smaller or larger scale and 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 [5,10]. The LCOE is defined by Equation (1).

$$LCOE = \frac{\text{Total life time cost of the project}}{\text{Total life time useful electricity produced}} \tag{1}$$

To calculate the total lifetime costs within this study, a project time period, a discount rate and an escalation factor of the prices were defined. The lifetime of the project was set at 20 years. The discount rate was found to be 6%. It was calculated with the nominal interest rate of the Bolivian banks [50] and the inflation rate forecast (from the year 2020 forward) given by the International Monetary Fund (IMF) [51]. The escalation factor for the prices of the project was assumed to be 3% since the inflation rates of Bolivia during the years 2015–2018 were found to be lower than 3%, except for the year 2016 where the inflation was 4% [52].

The annual operation and maintenance (O&M) costs for the polygeneration plant were defined as a percentage of the initial investment cost of each production unit. For this, different literature sources were considered [10,42,56–58] since there are not specific data about the application of these technologies in Bolivia (or South America). The values were assumed considering the range of O&M costs found in these studies. They are 3% for biogas production unit; for heat and power

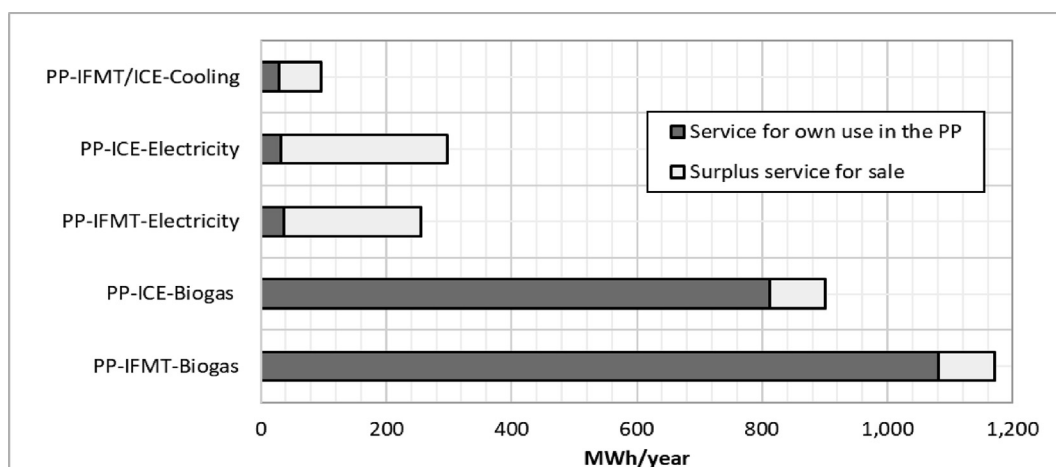


Fig. 4. Annual production and distribution of the services supplied.

Table 3
Costs/Investment for the polygeneration plant and its production units.

Description	Unit	PP-IFMT	PP-ICE
Biogas Production – Investment cost	USD	81,386	62,679
Number of lagoon covered biodigesters	–	1	1
Daily biogas production capacity of biodigesters	Nm ³	550	423
Liquid capacity of biodigesters (cow-dung/water mixture)	m ³	1,804	1,389
Cost of biodigesters (including civil engineering work)	(**) USD	81,198	62,491
Annual land rent (for the plant)	(*) USD	1,000	800
Water pump (1 set)	[10] USD	188	188
Life span of water pump	[10] year	5	5
Feedstock (fresh cow dung) cost	(*) USD/ton	1.8	1.8
Life span of biogas production unit	year	20	20
Electricity and Heat Production – Investment cost	USD	90,000	29,898
Prime mover (IFMT or ICE)	(**) USD	60,000	20,168
Life span of the prime mover	[41,42,53–55] year	10	10
Biogas cleaning system (desulfurizer and dehydrator)	(**) USD	8,635	8,635
Life span of the cleaning system	year	10	10
Compressor (for IFMT)/Pump (for ICE)	(**) USD	21,365	1,095
Life span of compressor/pump	year	10	10
Life span of electricity and heat unit	year	20	20
Cooling Production – Investment cost	USD	65,139	65,139
Absorption Refrigeration System (as described in Section “A proposed polygeneration plant”)	(**) USD	38,025	38,025
Milk Tanks, including evaporators (and cooling circuits)	(*) USD	25,500	25,500
Water heat exchanger (1 set)	[10] USD	750	750
Life span water heat exchanger	[10] year	10	10
Water pumps (3 sets)	[10] USD	564	564
Life span water pumps	[10] year	5	5
Radiator and fan (1 set)	USD	300	300
Life span of radiator and fan	year	10	10
Life span of absorption refrigeration unit	year	20	20
Fertilizer Production – Investment cost	USD	6,191	6,191
Bio-slurry Dryer	(**) USD	4,762	4,762
Bio-slurry pump (1 set)	(**) USD	1,429	1,429
Life span of bio-slurry pump	year	5	5
Life span of fertilizer production unit	year	20	20
Total Investment cost of the polygeneration plant	USD	242,716	163,907

(*) Data from interviews conducted in Bolivia with staff of the dairy farmers' association and federation (APL & FEPROLEC).

(**) Data acquired from consultations to local specialist and equipment vendors (quotations) [34–36,48].

production unit, 5% when using the IFMT and 10% for the case of the ICE [58] (the O&M costs of the ICE is higher than that required by the IFMT since it involves more frequent maintenance as described in Section “A proposed polygeneration plant”, these costs also cover the O&M needed by the compressor/pump and biogas cleaning stages for both prime movers); finally, 2% and 5% for refrigeration and fertilizer production units, respectively. The annual increment of feedstock (fresh cow dung) cost was assumed to be 2%.

The initial investment capital for the implementation of the proposed polygeneration options (considering all the production units) includes labor and civil engineering work costs. It is also considered that the annual costs for operation and maintenance (O&M) include labor costs (payment to technicians required for operating the plant), as well as costs for the routine maintenance of the equipment (oil lube change, refilling of refrigerant, filters cleaning, replacement of filters and other consumables) that allows the normal operation of the plant.

Eq. (1) is also proposed to determine the Levelized cost of biogas (LCOB) [10], cooling (LCOC) and fertilizer (LCOF) replacing the useful electricity produced in the lifetime of the project by the corresponding service (i.e. biogas, cooling and fertilizer). The units of the services costs are USD/kWh for biogas and refrigeration, and USD/ton for dry fertilizer. The cost of the liquid fertilizer, which is an extra service supplied by the PP was not calculated but considered for sale, the cost unit for this is USD/m³.

The costs of the energy sources required by each production unit were considered to determine the levelized costs of the services. These energy sources are: feedstock (cow dung) for the production of biogas; biogas for the production of electricity and heat; electricity and heat for the production of refrigeration and fertilizer. Therefore, at first, the

price of biogas was determined, then the price of electricity, and finally, the price of cooling and fertilizers.

The discounted payback period was also calculated. For this calculation, it has been considered annual incomes from sales of the supplied services and expenditures for feedstock, operation and maintenance, and replacement costs (of equipment or components). In order to obtain more realistic and accurate results, all these cash flows were updated to net present value, applying the discount rate determined in this study.

Cooling (for milk refrigeration) as service

Normally, cooling is not sold as an individual service when demanded for domestic or industrial usage. Instead, the energy required for its production is purchased. This energy source is generally electricity, which is used for cooling production in conventional compressor driven refrigeration systems. For the case of the absorption refrigeration system (ARS) proposed in the polygeneration solutions, the main energy source is heat recovered from the exhaust gas of the power generators which in other cases is just released to the atmosphere.

The polygeneration solutions proposed in this study offer refrigeration service to dairy farmers; it means that farmers can deposit the milk (to be refrigerated) in the storage center when they require. They will be asked to pay only for the refrigeration service depending of the quantity of milk that is stored. This payment (calculated with the LCOC) already covers the investment and the operation/maintenance costs of the refrigeration equipment.

Cost of cooling when using electricity from the grid

For the current case in dairy farms, the cost of cooling provided by conventional systems was determined, applying the same parameters as

Table 4
Investment cost and cooling prices for the conventional production of cooling.

Conventional Cooling Production – Investment cost		USD	43,500
Condensing units, including compressors	(*)	USD	18,000
Milk Tanks, including evaporators	(*)	USD	25,500
Annual land rent (for the storage center)	(*)	USD	200
Life span of conventional refrigeration system		Year	20
Subsidized cost of electricity for the storage center	(**), [59]	USD/kWh	0.046
Subsidized cost of cooling		USD/kWh	0.074
Non-Subsidized cost of electricity for the storage center	(***)	USD/kWh	0.074
Non-Subsidized cost of cooling		USD/kWh	0.086

(*) Data from interviews conducted in Bolivia with staff of the dairy farmers’ association and federation (APL&FEPROLEC).

(**) The tariff of electricity for milk storage centers (considered as agricultural activity) is lower than the domestic category. That is established by the electric company [59].

(***) Hypothetical cost of a non-subsidized electricity based on a previous study [60].

in Eq. (1). These parameters are shown in Table 4; cost of refrigeration equipment (condensing units, compressors and storage tanks) considered as investment capital; cost of operation and maintenance; cost for use of the land; useful lifetime; and annual electricity cost required for the operation of the system. The sum of all these costs (for the lifetime of the project) divided by the total amount of useful cooling produced during the lifetime allows obtaining the current cost of refrigeration in units of USD/kWh. This was defined as the actual price for the cooling service in the conventional production case. Table 4 shows this current price of subsidized cooling which is provided when using subsidized fossil fuel-based electricity (in the refrigeration equipment) and the price that the cooling service (non-subsidized) would have when using non-subsidized electricity.

The lifetime of the conventional cooling system was set at 20 years, the discount rate at 6%, and the escalation factor of the prices at 3%. The annual O&M costs was assumed to be 2% of the investment capital and the annual increment of electricity cost was set at 3%. The coefficient of performance (COP) of the electric refrigeration systems collected from fieldwork was found to be 3.

Levelized cost of cooling provided by the polygeneration plant

To determine the cost of cooling produced by using an absorption refrigeration system (ARS) the same sequence and variables described for the conventional case applies (costs data was shown in Table 3). In this case, the heat required to drive the ARS has not cost since it is recovered from the exhaust gas of the IFMT/ICE. However, the investment capital cost for this equipment (shown in Table 3) is higher compared to the conventional one (Table 4), which influences in the final cost of cooling. This levelized cost of cooling supplied by the PP should be compared to the actual cost of cooling of the conventional system shown in Table 4.

Results and discussion

Levelized costs of the services supplied by the polygeneration plant and costs of the current energy services in the Bolivian market

Table 5 shows the levelized costs of the services determined for the proposed systems. These costs are shown together with the prices of

Table 5
Services costs of the PP and subsidized (S)/non-subsidized (NS) prices of services in Bolivia.

Service	PP-IFMT	PP-ICE	S-Prices	NS-Prices
Biogas/LPG (*)	USD/kWh	LCOB	S-LPG	NS-LPG
Electricity	USD/kWh	0.020	0.025	0.037
		0.160	S-EL	NS-EL
Cooling	USD/kWh	0.082	0.105	0.170
		0.083	S-CO	NS-CO
Fertilizer	USD/ton	0.081	0.074	0.086
		3.1	–	–
		3.1	–	–

(*) Biogas content is 60% methane/40% carbon dioxide (volume/volume) with a LHV of 17.8 MJ/kg. LPG content is 60% propane/40% butane (volume/volume) with a LHV of 46.1 MJ/kg.

similar competitive services in the Bolivian market i.e., LPG (sold in tanks by dealers), electricity (supplied by an electric company), and conventional cooling (obtained when using electricity from the grid in the refrigeration equipment). The subsidized price of LPG (S-LPG) is the current price in the market (0.32 USD/kg of LPG [61,62]). The non-subsidized price (NS-LPG) corresponds to the exportation price [63,64]. The price of natural gas for the Bolivian thermoelectric plants is subsidized with public funds. The consequence is a reduced cost of electricity for the final users. This cost of electricity (for residential tariff [24]) at which the electric company sell is defined as the subsidized electricity price (S-EL) while the non-subsidized price (NS-EL) is an approximation based on studies conducted in Bolivia that try to predict what the real price of electricity would be [60,65]. The refrigeration service is indirectly subsidized if subsidized electricity is used for its production, which is defined as the subsidized cooling cost (S-CO). The non-subsidized cost of cooling (NS-CO) corresponds when non-subsidized electricity is used (Table 4). The prices of dry fertilizers cannot be compared to the cost of other similar fertilizers (from bio-digestion processes) in the market because there is no evidence of its commercialization in the country.

Fig. 5 (and Table 5) show that the levelized cost of biogas (LCOB) of the proposed systems (PP-IFMT and PP-ICE) was found to be lower than the LPG price either subsidized or not (first group of bars in Fig. 5). This comparison is done considering the equivalent energy content in both fuels. The levelized cost of electricity (LCOE) for the PP using an IFMT was found to be higher than the subsidized price (S-EL), but lower than the non-subsidized price (NS-EL). The cost of electricity supplied by a PP using an ICE was found even lower than the subsidized price (second group of bars in Fig. 5). The price of the cooling service produced in both proposed PP is close to each other and it was found higher than the subsidized price of the cooling (S-CO) service in the market, but lower than the non-subsidized price (NS-CO).

The cost of the dry fertilizer is proposed to be compared to the cost of dry cow manure in its natural state (stored in open space without any treatment), which is 10 USD/ton according to consultations. This is the price when the cow dung is sold to other farmers for agricultural purposes. This price was used to determine the cost of fresh cow manure used as feedstock for biogas production in the proposed plants. The feedstock cost was set at 1.8 USD/ton, which is slightly higher if

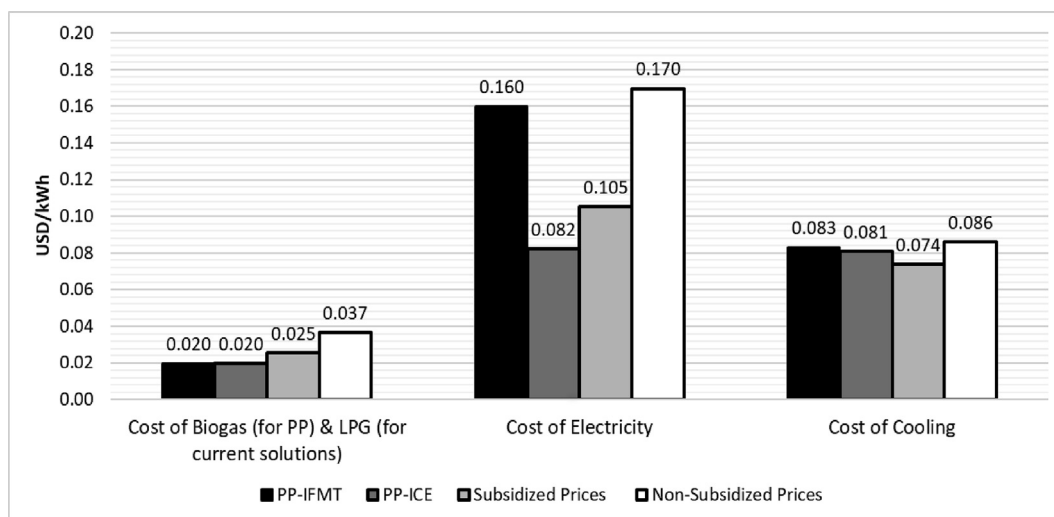


Fig. 5. Cost comparison of services supplied by the proposed PP's versus services in the market.

considering that the dry content of the fresh manure is only 16% [32].

The costs calculated for the dry fertilizer (3.1 USD/ton) were found to be much lower than the current dry cow dung price (10 USD/ton). That would allow having a greater margin of profit when selling it given that it has better quality than the cow dung in its natural state [30], which increases its economic value.

From the levelized costs of the services shown in Table 5 and Fig. 5 it can be concluded that in a non-subsidized (NS) scenario, which is not the current case, definitely both options are competitive. However, for a realistic scenario it is important to explore various economic variables, which would allow reducing the cost of the services until they are close (or equal) to the subsidized prices (S) and in this way being competitive under the current market conditions.

Sensitivity analysis for the cost of services supplied by the polygeneration plants

In this section, the levelized cost of biogas will be identified as LCOB-1 for the case of PP-IFMT and LCOB-2 for the case of PP-ICE and 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. Similarly, this applies to electricity (EL) and cooling (CO) services.

Influence of the feedstock and biodigester costs variations on the price of biogas

The impact of using cow dung for the production of multiple services in a polygeneration plant can make farmers give more monetary value to this resource. This can generate an increase in the feedstock cost when it comes to supply the polygeneration plant. On the other hand, the collection and handling of cow dung can be seen as a dirty and unattractive task. These two aspects are addressed when looking at the effect of different feedstock costs on the final biogas price. That is illustrated in Fig. 6 for the current feedstock cost (used to determine the levelized cost of biogas, LCOB, of the proposed plants), which is 1.8 USD/ton and two alternative costs, 2.2 USD/ton and 2.6 USD/ton. Although the calculation of the LCOB has already considered an annual increment of 2% in the cost of the feedstock, this graph shows the trend of the biogas cost for these three different prices. Additionally, Fig. 6 shows the variation of LCOB when the cost of the biodigesters moves in a range of plus or minus 20%.

At the current cost of the biodigesters (0% variation) the feedstock cost can be increased even at values higher than 2.6 USD/ton without reaching the referential price of the subsidized cost of LPG (S-LPG) as it

can be seen in Fig. 6. That means that better payments can be offered to the farmers while improving their economy and maintaining a competitive cost of biogas. However, this increase will also influence in the final cost of electricity and the other services supplied by the plant. Regarding the variation of the cost of the biodigester, it can be seen that at around 10% of increment in its cost and for a feedstock cost of 2.6 USD/ton, the LCOB equals the price of S-LPG. If the feedstock cost is 1.8 or 2.2 USD/ton and the biodigester cost increases by 20%, the LCOB is still lower than the S-LPG. On the other hand, the LCOB for the three feedstock costs considered (1.8, 2.2 and 2.6 USD/ton) maintains a considerable distance from the non-subsidized price of LPG (NS-LPG) even if the biodigesters cost increases by 20%. This shows that the production of biogas is already competitive compared to the current costs of LPG (subsidized or non-subsidized).

Effect of subsidizing the initial investment capital on the services costs

The costs of some of the services shown in Table 5 were found lower than the subsidized referential prices of similar services in the market. However, the electricity cost for the case of the polygeneration plant that uses a microturbine (PP-IFMT) was found higher than the subsidized electricity price (S-EL). In addition, the cost of cooling for both options (PP-IFMT and PP-ICE) was found to be slightly higher than the subsidized price of conventional cooling (S-CO). Subsidizing the initial investment cost of the PP solutions (e.g., incentives given by the government) can be a way to reduce the services costs while making them more competitive in the market. That is shown in the following graphs for the case of electricity and cooling services. The graphs also show the subsidized and non-subsidized prices of electricity and cooling in the market as reference. Finally, the application of this subsidy can be also interpreted as a reduction in the technology cost.

Electricity: Fig. 7 shows that the electricity cost for the case of PP-IFMT (LCOE-1) is higher compared to: (i) the current subsidized electricity price (S-EL) and to (ii) the electricity cost of the PP-ICE (LCOE-2), which shows a much lower cost. That is mainly due to the high investment capital for the microturbine (IFMT) used for electricity production and its lower electric efficiency when compared to the internal combustion engine (ICE). At around 60% of subsidy, the LCOE-1 reaches the subsidized price of electricity (S-EL) of the market. However, this relatively high subsidy can be seen as a barrier for an eventual implementation.

Interestingly, the cost of electricity for the case of PP-ICE (LCOE-2) is lower even than the subsidized price of electricity (S-EL) that is due to the lower investment capital cost and the higher electric efficiency when compared to the IFMT case. This option does not require any

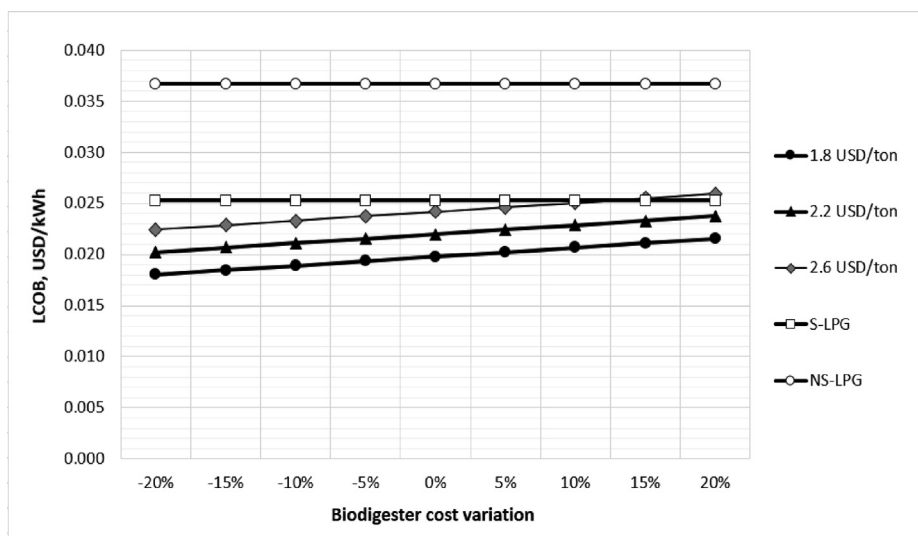


Fig. 6. Influence of feedstock cost on the LCOB.

subsidy. However, if applied, the cost of electricity reduces much more as it can be seen in Fig. 7. It makes this option more interesting to evaluate carefully in case of implementation.

Refrigeration: the cost of cooling (refrigeration) for the proposed solutions (LCOC-1 and LCOC-2) was found to be between the subsidized and non-subsidized (S-CO and NS-CO) prices of cooling provided by conventional systems. Fig. 8 shows that this cost decreases drastically when a subsidy to the investment capital increases. In the case of the proposed solutions, the cost of the energy for cooling production is zero due to the use of thermal energy recovered from the exhaust gases of the prime movers. This implies that the cost of cooling is more sensitive to variations in investment capital, which is given by applying subsidies. At a subsidy of around 10%, the cooling cost of any of the proposed plants (LCOC-1, LCOC-2) equals the subsidized price of conventional cooling (S-CO), reducing even more when the subsidy increases.

From the sensitive analyses we have that, in the case of the PP-IFMT, the cost of electricity (LCOE-1) will reduce up to the subsidized electricity cost of the market if a subsidy of around 60% is applied to the investment capital cost of the plant. That subsidy will allow reducing also the cost of biogas and cooling. However, such a high subsidy makes this option less attractive.

In the case of the PP-ICE, the cost of biogas and electricity are already lower than the subsidized prices of similar services in the market

while the cost of cooling (LCOC-2) is slightly higher than the subsidized service in the market. This cost will reduce up to the cost the subsidized cooling service in the market (S-CO) if a subsidy of around 10% is applied to the investment capital. This subsidy will reduce the cost of biogas and electricity supplied by this plant even more. If no subsidy is applied, this option is still attractive due to the low costs of biogas and electricity compared to the existing conventional services in the market.

Sale prices of services/products and discounted payback period for the proposed polygeneration solutions

An eventual implementation of the proposed solutions will require defining the prices at which the services/products supplied by the plants will be sold. For this, three scenarios with different prices are presented. The sale prices, in the first scenario (1), are defined to be equal as the levelized costs determined (LCOB, LCOE and LCOC) for the proposed solutions (PP-IFMT and PP-ICE). 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. For each scenario a discounted payback period (in years) was determined, that is shown in Fig. 9.

The variation of fertilizers prices, which are additional products supplied by the plant (dry and liquid fertilizers), greatly influences in

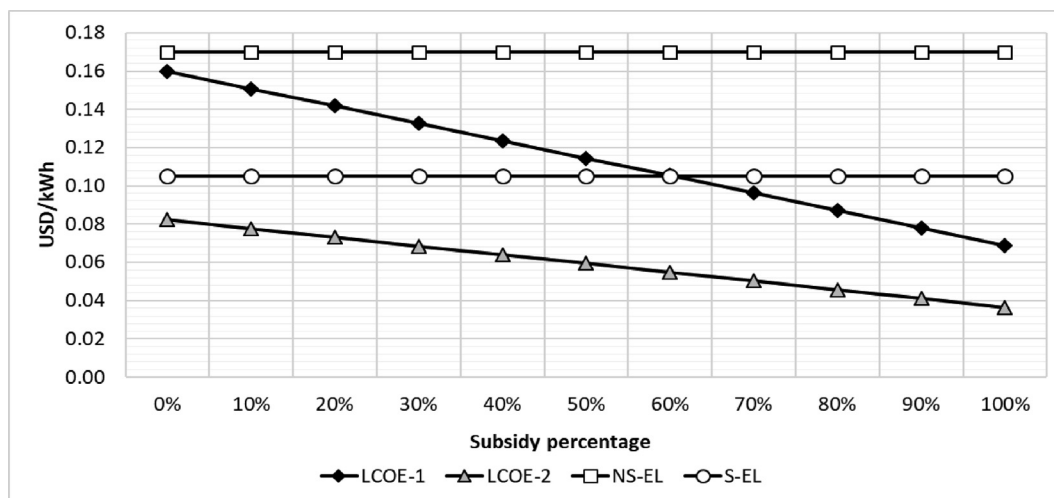


Fig. 7. Influence of subsidizing the investment capital cost on the LCOE.

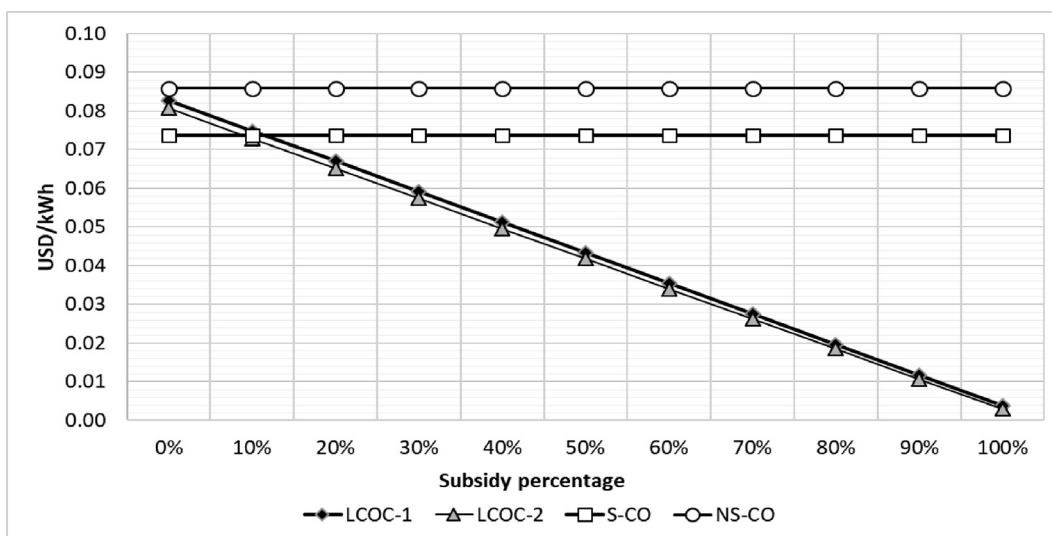


Fig. 8. Influence of subsidizing the investment capital cost on the LCOC.

the payback period. These prices should be adequate and competitive for their commercialization in the market. For the proposed scenarios and according to consultations, the cost of the dry fertilizer was set at 15 USD/ton, which is 5 USD more than the dry cow dung in its natural state. Additionally, the resulting liquid from the bio-slurry dryer system (BSD) is proposed to be sold at a price of 4 USD/m³ for all scenarios.

Scenario 1 for both solutions, PP-IFMT and PP-ICE, is referential since it is not feasible to sell the services at higher costs than those of the existing conventional services. That is the case of the higher cost of the electricity (for the case of PP-IFMT) and the slightly higher cost of cooling (for both solutions) when compared to the subsidized prices of the existing conventional services. However, this scenario can be valid for the application of either of the solutions in remote rural areas where there are no other alternatives to supply the proposed services.

Scenario 2 considers the application of a subsidy (to the investment capital of the plant) to lower the costs of the services until they are equal to the subsidized services existing in the market. The subsidy required by the PP-IFMT is 60% (Fig. 7). In a real context, this high subsidy can make this option unattractive. In the case of PP-ICE, the subsidy for the investment capital has to be around 10% to reduce the cooling service cost. This scenario seems to be the closest to the reality and shows that the most promising solution is the PP-ICE option since the subsidy required is low. This solution shows a high potential to be implemented under the current conditions of the Bolivian market.

In scenario 3, the hypothetical non-subsidized case, none of the

proposed polygeneration solutions require subsidy having a great advantage over the other presented scenarios. That is reflected in the shorter payback periods shown in Fig. 9. Although a market without subsidies will also influence on the fixed and variable costs involved in the calculation of the final prices of services, this scenario shows a referential trend. Finally, comparing the proposed solutions in the different scenarios, the PP-ICE option appears to be the most attractive.

Measuring the supplied energy services

The costs of the proposed energy services have been defined in units of USD/kWh. This is valid for electricity since the measuring equipment available in the market use energy units. In the case of cooling (for milk refrigeration), there is currently a control of the daily amount of milk deposited by each dairy farmer to the milk storage center. The costs of cooling determined in this study, which is expressed in USD/kWh should be converted into USD/L (of milk), considering the amount of thermal energy that is required to refrigerate a certain amount of milk in a given period of time. Finally, the measurement of biogas, proposed to be sold for local distribution, can be done through a flow meter, for which the determined costs of biogas in USD/kWh should be converted into units of USD/m³. All these measurements are proposed to be done at a delivery point of services located in the plant.

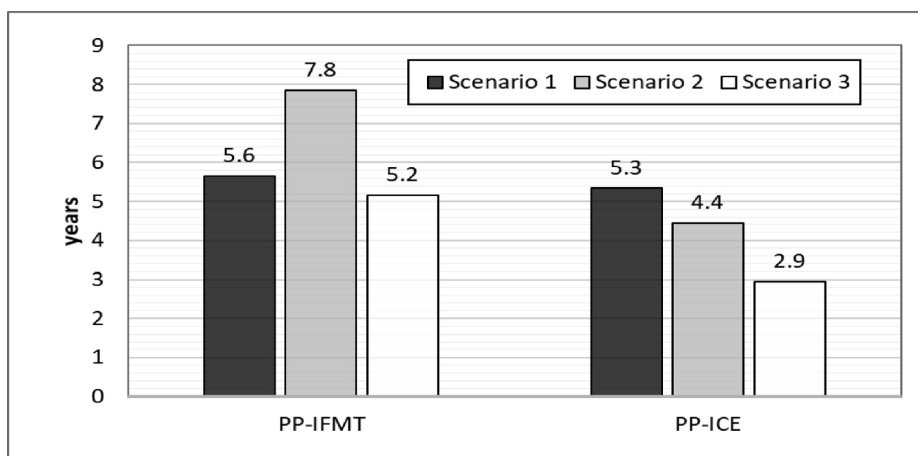


Fig. 9. Payback period for the proposed systems (for different sale prices).

Limitations, further work challenges and final remarks

The results of this study should be seen in the light of some limitations that were identified. The main limitation is that the approach of this research is only technological/economic and does not consider social, legal and regulatory barriers. However, the present research can be considered as a first step that may allow future studies that address these issues.

The estimation of the operation and maintenance (O&M) costs of the equipment can be seen as the second limitation of this study since they were taken from referential studies; therefore, they could be different in a real situation for the particular case of the Bolivian market. This is mainly because the technologies proposed in this study are not common in Bolivia. Accordingly, there is a lack of knowledge about the implementation/operation of this equipment, difficulties for finding spare pieces in case of failures, and lack of permanent technical support. All these aspects have high influence in the operation and maintenance costs and, consequently, can affect the feasibility of the solution.

The assumption that all the surplus services of the plant will be sold, can be seen as the third limitation. There may be different scenarios where not all the surplus services will be allowed to be sold in the market. It can happen because of the lack of regulatory framework in the country (institutions that control and regulate the market of energy services do not consider this type of solutions), which in turn can influence the economic performance of the project. The production/supply and distribution of energy services such as gas for cooking and electricity (or sale of surplus electricity to the grid) requires compliance with various technical and administrative requirements in Bolivia. Besides there is no clear regulation for sale of electricity to the grid by small producers that have a surplus of electricity production. As future work, it would be necessary to study the feasibility of implementing these solutions within the framework of existing regulations in the Bolivian energy sector. It would allow identifying gaps that can be addressed by policymakers. Finally, future studies can explore the financing possibilities for this type of initiatives when applied to productive sectors.

In order to overcome these identified limitations and barriers, further work is proposed. Three main actors have been identified, their future work/actions can help in an easy implementation of this type of solutions; (i) the government by providing an adequate regulatory framework and by offering economic (loans, incentives and/or subsidies for these solutions) and technical (qualified technicians who can follow up these solutions once they are implemented) support. (ii) The academics (research institutes and local universities) and the manufacturers; working together in the research and development of these technologies with an economic approach. This can help local companies be able to manufacture some equipment, spare pieces and be specialized in the operation and maintenance of the equipment. Local universities in coordination with these companies can help training technicians that would be able to follow up the implementation of these solutions. (iii) On the part of the productive sectors, in this particular case the dairy sector, it should be improved the management of waste and energy resources in the farms. For this, dairy farmers should be adequately trained by competent institutions, this can be done in the framework of policies promoted by government institutions.

The results obtained in this study serve as an initial reference for a possible implementation of polygeneration systems in Bolivian dairy farms. However, a more precise and detailed study should be carried out in the future. That study should consider the negative effects on the performance of the equipment due to the ambient conditions, energy losses and variable energy demands among others aspects. Additionally, the pros and cons, in terms of operation and maintenance, of the internal combustion engine compared to the microturbine should be evaluated. This will allow to know which one is the best option for a particular case.

These solutions promote improvements in the economic situation of low-income dairy farmers (because they are paid for the cow's manure), reinforcement of community work and reduction of the conventional power grid dependence. The latter reduces the consumption of fossil fuels in large power plants and, consequently, the subsidies they receive from public funds decreases. On the other hand, the reduction of fossil fuels consumption and the use of waste resources for supplying energy services contribute to the reduction of greenhouse gas emissions.

The results of this study also permit to know the maturity of the polygeneration proposal applied to an impoverished productive sector, in this particular case, small dairy farms. We found some limits, usually linked to governmental subsidies to energy services. In this sense, our results shows that in other context (in countries without subsidies or with reduced subsidies to fossil fuel-based energy services) the polygeneration proposal is probably feasible for small and medium applications not only in the dairy sector but also in other productive sectors. However, probably the high investment cost and the complexity of the technology can still be seen as the main barriers towards a real implementation.

Finally, the methodology used in this research is not limited only to the dairy sector since it can be used in other studies in order to determine the techno-economic feasibility of polygeneration applications with similar characteristics. These applications can be proposed in sites where there is the availability of organic waste that can be used for biogas production; this biogas can be the energy source to meet demands of electricity and thermal services.

Conclusions

Two biogas-based polygeneration solutions have been proposed for an association of low-income dairy farmers in central Bolivia. The first solution considers a microturbine as prime mover, and the second an internal combustion engine. They both are integrated with an absorption refrigeration system and a bio-slurry dryer. The source of energy is based on the utilization of cow's manure for centralized production of biogas. The final services from the plants are biogas, electricity, refrigeration (for milk preservation) and fertilizers. The economic analysis has focused on determining the levelized cost of these services in order to observe their competitiveness in the Bolivian market. For this, the resulting costs were compared to the current subsidized and non-subsidized prices of similar competitive services existing in the market (LPG, electricity from the grid and cooling provided by conventional systems). The main conclusions are summarized as follows:

- The cost of biogas for both solutions was found to be 0.020 USD/kWh, which is lower than the subsidized and non-subsidized price of LPG, in terms of its energy content. The production of this service is already competitive under the Bolivian market conditions.
- The cost of electricity for the first option (microturbine as prime mover) was found to be 0.160 USD/kWh, which is higher than the subsidized price of electricity in the market but slightly lower compared to the non-subsidized price.
- The cost of electricity for the second option (internal combustion engine as prime mover) was found to be 0.082 USD/kWh. This cost of electricity is the most competitive option since it is lower than the subsidized price of electricity in the market.
- The cost of cooling for both solutions was found to be around 0.082 USD/kWh. This cost is slightly higher than the subsidized price of this service in the market.
- From a sensitivity analysis, it was found that the feedstock cost (payment to the farmers for fresh manure) can be increased from 1.8 USD/ton up to values of around 2.6 USD/ton while maintaining a biogas cost production lower than the subsidized price of LPG.
- The application of subsidies to the investment capital (amounting to 60% for the internally fired microturbine plant and about 10% for the internal combustion engine plant), allows reducing the services

costs to be competitive in the market. In this case, the subsidies allows reducing the production costs to be equal to the prices of subsidized services.

- In the scenario closest to reality, the discounted payback period was found to be 7.8 years for the microturbine based plant and 4.4 years for the internal combustion engine plant.

From this analysis, the polygeneration plant that implies the use of an internal combustion engine was found as the most promising option because the investment cost is low, it has high electric efficiency, it requires less subsidies to be competitive in the market and it has shown shorter payback periods than the microturbine plant option.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seta.2019.100571>.

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