Article

Technical and economic feasibility of the use of a commercial water heater based biogas in dairy stables

Víctor Manuel Molina Morejón[1]
Víctor Pedro Molina Romeo[2]
José de Jesús Espinoza Arellano[1§]
Juan Gabriel Contreras Martínez[1]
Adriana López Villanueva[3]

[1]Faculty of Accounting and Administration-Autonomous University of Coahuila-Torreón Unit. 153 East Boulevard Revolution, Col. Centro, Torreon, Coahuila, Mexico. CP. 27000. (vmolinaa2005@yahoo.com.mx; juan_gabriel_c@hotmail.com). [2]Faculty of Sciences of the Autonomous University of Coahuila Administration-Saltillo-Unit. Saltillo-Piedras Negras highway km 5. Saltillo, Coahuila. CP. 25107. (vitigabyfrida@gmail.com). [3]Bioremediation Laboratory-Faculty of Biological Sciences-Autonomous University of Coahuila-Torreón Unit. Torreón Matamoros highway km 7.5, Ejido el Águila, Torreón, Coahuila, Mexico. CP. 27275. (adriana.carax@gmail.com).

[§]Corresponding author: jesusespinoza_612@yahoo.com.mx.

Abstract

The purpose of this work was to analyze the technical and economic feasibility of using a commercial heater that works with biogas to obtain the necessary hot water in the sanitation of the milking area or to heat the milk that feeds the calves in stables of the Comarca Lagunera, Mexico. It is an economic and sustainable alternative to the widespread practice of using electrical resistors or liquefied petroleum gas (LPG) that generates an expense of approximately $300 000.00 pesos per year. The characteristics of the commercial heater acquired were determined using various heat transfer equations. The economic analysis of the investment was carried out over a period of five years using indicators that take into account the value of money over time such as the net present value, the internal rate of return and the cost-benefit ratio. In the experimental test, the energy required for water heating and efficient combustion was maintained. The technical feasibility of the proposal was shown by not rejecting the null hypothesis of equality of means ($p > 0.05$) of the 45 samples, which implies a consistency in the heating times. The financial analysis, in its different indicators NPV, IRR and R B/C, showed values in project acceptance ranges. This solution reduces the emission of greenhouse gases and production costs in operations. The option of using biogas is technically and economically viable.

Keywords: biodigester, dairy stables, financial analysis, manure, methane.

Reception date: January 2020
Acceptance date: March 2020

Introduction

The Comarca Lagunera, with an annual production of 2.448 million liters and a 21% share of the national production is the main dairy basin of the country (SADER-Laguna, 2017; García *et al*., 2019). The inventory of dairy cattle in the year 2018 in the Comarca Lagunera was 490 876 heads (García *et al*., 2019). In its different systems of cow's milk production coexist, predominantly the highly technical intensive system with stables of more than 6 000 animals and an average production per cow in milking of more than 32 liters per day (Espinoza *et al*., 2018).

The Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA, 2010), mentions that an area of 110 000 km^2 (11 x 10^6 ha) is used for livestock activity (SAGARPA, 2010) and this corresponds to 5.6% of the total area of Mexico. At regional level 7.5x10^6 t of total fresh excreta are generated, containing 12.3% of dry matter (DM) which is equivalent to a production of dry manure of 925 000 t per year (Figueroa *et al*., 2009). A characteristic of dairy cattle metabolism is a low efficiency in the use of nutrients, mainly nitrogen (N) (Figueroa *et al*., 2015).

Animal manure can be an effective and safe fertilizer if treated properly. If the treatment is inadequate or if no treatment is used, there is a high risk of contamination with pathogenic microorganisms, such as *Campylobacter* spp., *Escherichia coli*, *Salmonella* spp., *Clostridium botulinum*, *Giardia* spp., *Cryptosporidia* spp., *Microsporidia* spp. and *Fasciola* spp. (Acevedo *et al*., 2017). On the other hand, excreta generate highly polluting gases such as CO_2 carbon dioxide and CH_4 methane gases that contribute to the greenhouse effect (Barik *et al*., 2013).

In the Comarca Lagunera, biodigesters have been implemented in around 90 of the 251 specialized stables with the objective of sustainably using manure gases (López *et al*., 2017) of them, around 10 using biogas to produce electricity. Of the remaining 80 biodigesters about 50 burn methane into the atmosphere with torches specially designed for this function without any economic use. The lagoon type biodigesters were designed for capacities ranging from 20 000 to 30 000 m^3; however, 90% do not work properly and their methane production is below the optimum level of 60% (López *et al*., 2017).

A study by Hernández *et al*. (2015) points out that in the Comarca Lagunera the potential production of methane is 14 million m^3 $year^{-1}$, which is reduced to 8.4 million m^3 $year^{-1}$ when a conservative 60% efficiency is applied. The lack of information and specific studies by region makes planning and management of renewable technologies difficult, especially the biogas production system, whose process involves complex biological processes.

Despite the fact that internationally, there are studies that demonstrate the economic potential of manure use, there are no specific studies in the Comarca Lagunera related to the management of the biogas production system for efficient energy generation, so It is difficult to specify how much energy is lost in the 50 biodigesters that burn methane into the atmosphere without any use. The study presented in four dairy stables with a known population of 11 550 head of dairy cattle indicates that about 65 000 m^3 $year^{-1}$ of biogas is wasted (Molina *et al*., 2017).

Methane is a greenhouse gas 21 times more potent than CO_2 (Varnero, 2011). Greenhouse gas emissions when electricity is used equals 0.454 tons of CO_2 $(MWh)^{-1}$ (SEMARNAT, 2015). One of the stables studied consumes up to 235 000 kWh $year^{-1}$ equivalent to 107 t of CO_2 in the atmosphere. In the production process the main element is the biodigester, which when fed with raw material, after about 30 to 90 days, transforms it into biogas, mainly composed of methane gas, a potent greenhouse gas, used as fuel for generate heat or produce electricity. The use of biogas represents an area of opportunity in economic sectors that can potentiate sustainable development (Singh *et al*., 2013).

Overview of the use of bioenergy in the world and in Mexico

Bioenergy is the energy obtained from biomass, which is the constitutive matter of living beings, their excreta and their non-living remains. Biofuels are obtained from biomass, with a greater or lesser degree of processing, within them are distinguished gaseous biofuels such as biogas and biomethane, obtained from municipal waste and manure (García and Masera, 2016).

In 2015, biogas used to generate thermal energy worldwide in industrial and residential heating grew by only 3% compared to 2014. However, the installed bioenergy capacity grew 8%, mainly in China, Japan, Germany and England. At the close of 2015, of 23.7% of the total renewable energy produced, hydraulic energy occupied 16.6%, followed by wind with a 3% share and bioenergy with 2%, photovoltaic solar and geothermal energy, occupy 1.2 and 0.4% respectively.

Globally, the main producers of biogas are the United States of America, China and Germany as they generate approximately 69% of world production (40.8 million m^3), and in a complementary way it is reported that Europe contributes 45% of world production (26.2 million m^3) (REN21, 2016). The promotion of the use of biogas in heat generation is something that the United Kingdom has experienced. Bayar (2017) states that in his farms and other businesses in rural areas, anaerobic digestion plants with only thermal generation can be found as a ‘more viable opportunity’ than combined heat and electricity (CHP) plants for farmers and other energy users on the site.

In Mexico, renewable energy production accounted for 6.98% and biomass energy has the largest share with 3.79% (Alemán *et al*., 2014). The bioenergy potential of Mexico was calculated by Hernández *et al*. (2015) through the treatment of manure by anaerobic digestion, and approximately 5910.35 TJ was obtained, being able to generate 410.41 GWh of electricity and reduce methane emissions by 2240.64 Gg CO_2 Eq.

Operational parameters that affect biogas production

The final biogas performance depends on the composition and biodegradability of the organic food. The population of bacteria that break down organic matter, growth conditions and temperature decide the rate of biogas formation. The speed of digestion is affected by the temperature of the process and must be maintained in mesophilic ranges with an optimal digester design, nature of the substrate, pH, load size, hydraulic retention time and the proportion Carbon:Nitrogen (C:N) since all of them affect the production of biogas (Hagos *et al*., 2016).

A good biogas production should be found at a pH between 7 and 7.2 (Chawla *et al*., 1986). Likewise, for the process to develop satisfactorily, it indicates that the pH should not be lower than 6 or higher than 8 (Varnero, 2011). In Alvarado-Moreno (2016), the effect of temperature on biogas production is warned because an increase in temperature of 5 °C generated an increase in both pH and volatile fatty acids and methane production decreased 18%. The C:N ratio of 25-30: 1 is reported as optimal for biogas production (Mital *et al*., 1996).

Likewise, the presence of metals such as calcium, iron, magnesium, molybdenum and nickel, increase the production of biogas. In addition, it was reported that methanogens require ammonia for their specific growth rate and replication time. The presence of high concentrations of sulfate in the substrate can cause inhibition of the anaerobic process, especially of methanogenesis (Speece, 1996).

The importance of the subject of this work is reflected in the 'strategic technological program' of the state-owned company Petroleos Mexicanos (PEMEX, 2013), where the 'use of biogas' and 'as a technological need to evaluate the state of the art is considered as a technological challenge, identify, evaluate and implement technologies for the use of biogas'. Likewise, the antecedent of this work has its origin in a demand for research of the program of stimuli to innovation (PEI) on the efficient management of energy in the stables of the Comarca Lagunera (CONACYT, 2013).

Subsequently Molina *et al*. (2017) they conducted an experimental research at the laboratory level with a small heater that aimed to demonstrate the technical feasibility of using biogas as a source of thermal energy for water heating in which the need to use a larger heater was concluded ability to supply the volume of hot water necessary to meet the demand of the stable for sanitation purposes and preparation of milk for calves.

Materials and methods

Stage 1: Since biogas contains only 41% of the caloric value of liquefied petroleum gas LPG, the characteristics of the commercial heater that was acquired were previously determined using heat transfer equations to determine if it could meet the demand for hot water in the stable. The input data to start the calculations are shown in Table 1.

Table 1. Input data for the calculation of thermal load and biogas flow.

Known data	Acronyms and units	Values
Water temperature at the entrance of the heater	(T_{ent}) °C	18
Water temperature demanded, at the outlet of the heater	(T_{sal}) °C	70
Higher caloric value of biogas (VCS)	(VCS) kJ $(m^3)^{-1}$	20 880
Initial biogas flow	(Q) m^3 h^{-1}	1.5
Heater high	(L) m	1.7
Heater internal diameter	(D) m	0.54
Heater base area	(A) m^2	0.229

Calculation of the thermal load required for heating water in a heater using biogas

Experimental data: a) water temperature heater inlet zone (T_{ent}): 18 °C; b) water temperature exit zone (T_{sal}): 70 °C; c) higher caloric value of biogas (VCS) 20 880 kJ $(m^3)^{-1}$; d) initial biogas flow 1.5m^3 h^{-1}; e) water flow to be heated (Q): 1.02 m^3 h^{-1}; and f) high (L): 1.7 m, g) internal diameter: (D) 0.54 m. Material: stainless steel

Calculation considerations: the heater behaves like a vertical cylindrical tube. The temperature after 27 min. The heater surface is homogenized and constant allowing the use of average parameters of the water to be heated. There are no variations in the areas in the inlet and outlet sections and since the storage capacity of 0.2 m^3 is the replacement flow is considered small compared to the volume of the tank giving almost watertight flow conditions. There are stationary operating conditions. The calculations made from these data are presented in Table 2.

Table 2. Input data for the calculation of thermal load and biogas flow.

Name of the calculation	Basic equation	Obtained result
Calculation of heat transfer by radiation	$q_{Rad}= F_{12}*A_1*\sigma*(\Delta T_{12}) + F_{13}*A_1*\sigma*(\Delta T_{13})$	q_{Rad}= 15194.19 kJ h^{-1}
Water velocity calculation inside the heater	$V=\frac{Q}{A}$	V= 0.00124 m s^{-1}
Reynolds number calculation	$Re_D=\frac{V*\rho*D}{\mu}$	Re_D = 1209.22
Sieder and Tate correlation for laminar flow	$Nu_D=\frac{\bar{h}*D}{k}=1.86*\left(\frac{Re_D*Pr}{\frac{L}{D}}\right)^{\frac{1}{3}}*\left(\frac{\mu}{\mu_s}\right)^{0.14}$	Nu_D= 23.48
Determination of the heat transfer coefficient at the average fluid temperature	$Nu_D=\frac{\bar{h}*D}{k}$	$\bar{h}$= 27.7 W m^{-2} °C
Calculation of heat by convection in the heater	$q_{conv} = \bar{h} * P * L * \Delta T_{ml}$	q_{conv}=13287.24 kJ h^{-1}
Heat loss from conduction through the walls	$q_{cond}=\frac{\Delta T_{ml}}{R_1+R_2+R_3}$	q_{cond}= 1548 kJ h^{-1}
R_1 Inner wall resistance	$R_1=\frac{LN\left(\frac{r}{r_1}\right)}{2*\pi*k*L}$	R_1= 0.917865 °C/kW

Name of the calculation	Basic equation	Obtained result
R_2 Resistance in the metal wall of the tank	$R_2=\frac{LN\left(\frac{r_2}{r}\right)}{2*\pi*k*L}$	$R_2= 0.319862\ {}^{\circ}C/_{kW}$
R_3 External insulation resistance	$R_3=\frac{LN\left(\frac{r_3}{r_2}\right)}{2*\pi*k*L}$	$R_3= 106.15\ {}^{\circ}C/_{kW}$
Thermal load by convection and conduction.	$q_{total_{Con\text{-}Cond}}= q_{conv}+q_{cond}$	$q_{total_{Con\text{-}Cond}}= 14835.6\ kJ\ h^{-1}$
Total heat calculation required	$q_{total}= q_{Rad}+q_{total_{Con\text{-}Cond}}$	$q_{total}= 30037 kJ\ h^{-1}$
Calculation of the necessary Biogas flow	$q_{total}= VCS*Q_{bio}$	$Q_{bio}= 1.44\ m^3\ h^{-1}$

First, heat by radiation and convection was calculated by calculating the Reynolds number and the Nusselt number. For the calculation of heat by convection the possible loss of heat by conduction through the walls was calculated: interior, R_1; metal wall of the tank, R_2 and insulation resistance, R_3. Then the thermal load was obtained by convection and conduction. The total heat value needed (q_{total}) was: 30037 kJ h^{-1} and the necessary biogas flow (Q_{bio}) reached a value of 11.44 $m^3\ h^{-1}$.

Stage 2: purchase, installation and modification to the heater so that it could work with biogas. From the results of stage 1 a commercial heater of 1 800 L h^{-1} was acquired, capable of satisfying the demand of the stable of 1 000 L of hot water three times a day: after each milking, plus the seven hours that lasts the preparation of milk to calves, between 4 am and 11 am. Of this original heater, only the chassis and the water tank were used. The simplified scheme of the experimental work carried out is shown in Figure 1 where two pipes are seen from right to left, one conducts live biogas from the biodigester, which is filtered to reduce the H_2S content before entering the heater.

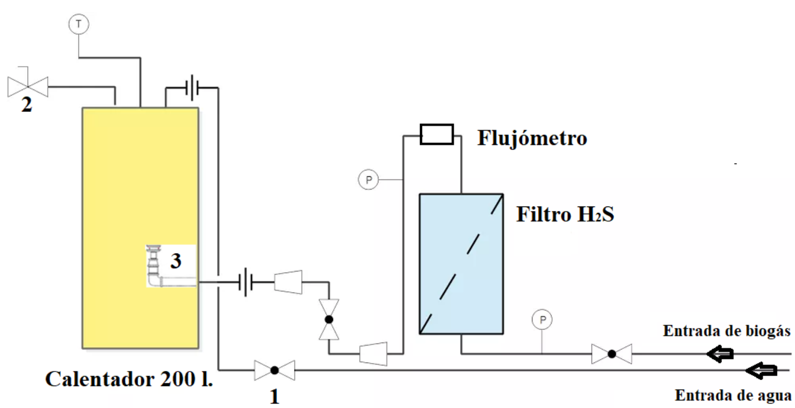

Figure 1. Simplified scheme of the test bench with 200 L heater.

The other pipe conducts local supply water at room temperature. In total, 15 tests were made, with a repeatability of 3 samples per test, in total 45 experimental samples during the months of November 2016 and January 2017 generally between 7:30 and 13:30 h. The null hypothesis

H_0 was formulated that formulates the non-existence of significant differences between the means of the different experimental runs taking into account the heating times as a function of the temperature reached by the water. Statistical analysis was performed based on the Anova analysis using Fisher's 'F' test to see if at least some mean was different; and if it were the case, apply the Tukey test to make the multiple comparison of means (Lind *et al.*, 2004; Levin and Rubin, 2010).

Stage 3: A new burner adapted to burn biogas with the ability to regulate the fuel air ratio to achieve better combustion was designed.

Stage 4: instrumentation of the test bench: a multiple gas detector, $CH_4/O_2/CO/H_2S$ was used. Brand Draeger-Grainger to obtain biogas values. Water temperature was measured with thermometers installed in the heater. The biogas flow was measured by a rotary flowmeter. The biogas pressure at the inlet of the heater was measured with a differential pressure gauge. The financial evaluation of the project was carried out; through the classic financial indicators in the evaluation of projects net present value (NPV), internal rate of return (IRR) and benefit/cost ratio (Baca, 2013; FAO, 2017). These indicators are based on the analysis of the value of money over time since it is a five-year project.

Results and discussion

To illustrate in a simplified way the ratio of heating time in minutes against water temperature in ºC, Figure 2 shows only the result of six experimental samples (series 1 to 6), where it is observed that the average duration time of the Experiment is about 230 min, this time is distributed as follows: the first 170 min is used so that the temperature of the water inside the heater reaches around 90 °C. Once this temperature is achieved, the No. 2 flow valve opens, hot water begins to flow out of the heater and at the same time the same amount of cold water begins to enter inside.

As in any passage heater, the hot water temperature begins to fall through the cold water inlet and stabilizes at a value of 70 °C, a sign that the volume of water contained in the 200 L tank has been homogenized and It stays in balance.

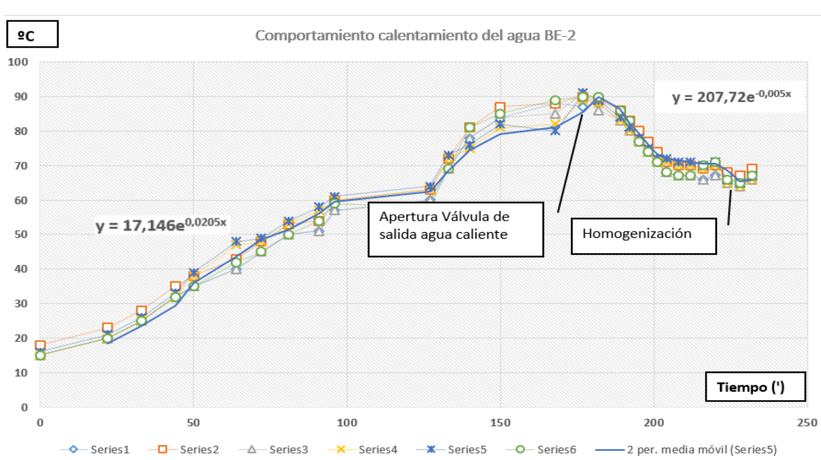

Figure 2. Result of two experimental runs with six samples: temperature vs. time.

All samples were measured with temperature values in 30 moments (with intervals of seven minutes), from the beginning of the experiment until homogenization. When comparing in the analyzed samples the relation heating time in minutes vs the temperature reached by the water in ºC, the results of the Anova indicate that the null hypothesis of equality of means ($p > 0.05$) was not rejected concluding that the heating times are equal. The behavior of the temperature (y) against time (x) was also modeled, obtaining the equation $y= 17.146e^{0.0205x}$ (from 0 to 170 min) and the behavior of the lowering temperature until its stabilization expressed as $y=207.72e^{-0.005x}$ (from 170 to 210 min).

The average values achieved, both of the flow of biogas and the resulting heat were sufficient to achieve water heating, which together with the non-rejection of the hypothesis of equality of means shows the technical feasibility of using biogas as a source of energy to obtain the hot water needed in the stable.

The final scheme of the heating system is presented in Figure 3 where it was observed that when the water in the heater (1) reaches its homogenization temperature, it is all stored in a storage or recovery tank (2) capable of keep this temperature beyond 24 h. The use of this water is mainly for sanitation (3) and as a milk preparation element for calves, using a plate exchanger (4) and as a heating medium (5) in times of low temperatures.

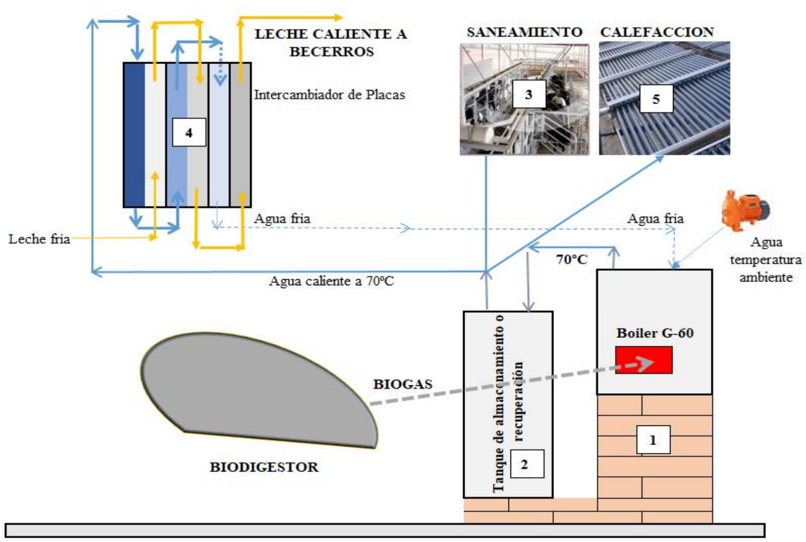

Figure 3. Final scheme of the use of water heated with biogas.

As part of the results, observations are made, which may have some practical implications for potential users of this technology: the option of using the filter to eliminate H_2S was finally discarded because as ADBA (2015) observes, no treatment is required to eliminate it if it is only burned. It is likely that in other works, the turning point of homogenization is not reached in 210 min because, for example, the average value of methane is different. However, these results are benchmarks and can be compared with future experiments.

Molina *et al*. (2017) mention that the stable where this research was conducted has a population of 4 600 head of dairy cattle and an estimated methane production of 25 500 m^3 $year^{-1}$, equivalent to 70 m^3 d^{-1} (2.9 m^3 h^{-1}). The commercial heater needed 3.5 h to reach 70 °C of water demanded by the stable and consumed at that time about 11 m^3 of biogas. Therefore, the heater required 11 hours of work to cover 1 000 L of water three times a day and consumed about 32 m^3 in its three work shifts. During the seven hours that the preparation of the milk lasts for the calves, 20 m^3 of biogas are consumed. In total the whole process consumes 74% of the estimated daily production.

Solid biomass represents the largest proportion of biomass used worldwide for heat generation with 77%, urban solid waste (MSW) represents 18%, biogas 4% and biofuels 1%. Biogas participated 20% of electricity generation, MSW 8% and biofuels in 1% electricity. E liquid biofuel represents the largest source in the transport sector (REN21).

Figure 4 (left) shows the 360 L h^{-1} heater (E_1) of the work mentioned in (Molina *et al*., 2017) and on the right, the 1 800 L h^{-1} heater of this study (E_2). The results of this work were recognized in the public file of the project 231389 (CONACYT, 2017).

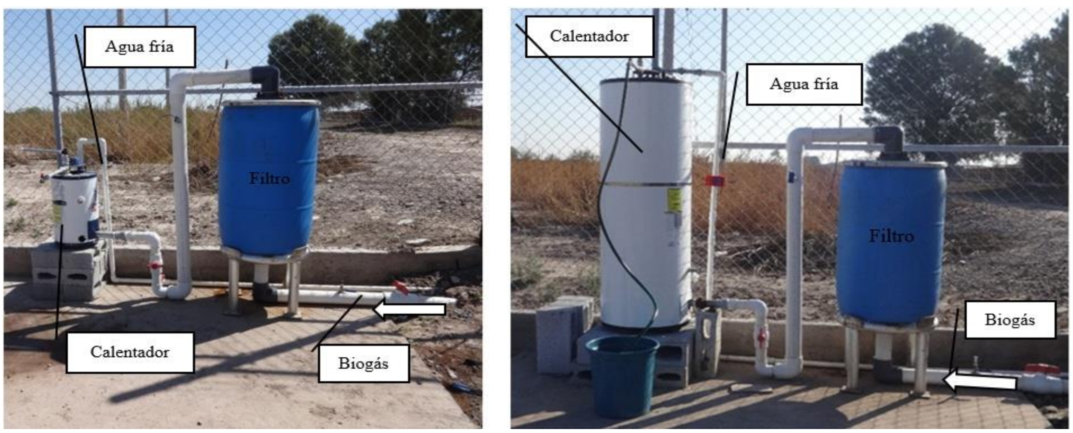

Figure 4. Heaters used in jobs E1 (left) and E2 (right).

Financial analysis

The financial analysis of the E_2 project was based on a five-year horizon with an initial investment of $400 000.00 and annual operating expenses of $18 000.00 plus $47 450.00 per year for the use of biogas for a total of $65 450.00 annually. According to García and Masera (2016), $USD 6.48 per day is spent on biogas (equivalent to $130.00 Mexican pesos per day multiplied by 365 days, giving us the $47 450.00 per year that are being added) (Table 3). The initial investment included the acquisition of the water heater, the storage tank, pipes and fittings, instrumentation and control, assembly, design and installation of the new biogas-adapted burner and the laying of hot water network.

Operating expenses included the annual inspection and maintenance of the equipment. The income is the savings that the company makes for the expenses of electric energy for water heating. Being a multi-year project, the flows of income and expenses have to be updated so that they are comparable over time. The update rate varies according to the type of project, some public agencies establish the rates at which the costs and income of the projects that request funds must be updated.

Table 3. Costs, income and cash flow of the water heating project with the use of biogas in dairy farms in the Comarca Lagunera.

Years of the project	Costs ($)	Income (%)	Current flow of funds ($)	Update factor (25%)	Updated costs ($)	Updated revenue ($)	Updated cash flow ($)
0	400 000	-	-400 000	1	400 000	-	-400 000
1	65 450	281 476	216 026	0.8	52 360	225 181	172 821
2	65 450	281 476	216 026	0.64	41 888	180 145	138 257
3	65 450	281 476	216 026	0.51	33 510	144 116	110 605
4	65 450	281 476	216 026	0.41	26 808	115 293	88 484
5	65 450	281 476	216 026	0.33	21 447	92 234	70 787
Sums	727 250	1 407 380	680 130		576 013	756 968	180 954

In our case we used a 25% update rate which seemed very high; However, it is the rate that the company that provides this type of equipment to the stables interested in its installation. It was about making it as real as possible. Being a high rate, it has the advantage that it puts the viability of the project under greater pressure, so that it is more robust in case the costs are higher than planned or the revenues lower than estimated.

The financial indicators used were the NPV, the IRR and the B/C ratio. The criteria to accept a project as viable is that the NPV> 0, the IRR> that the cost of money and the ratio B/C> 1 (Baca, 2013; FAO, 2017). The three indicators (Table 4) resulted in the acceptance ranges of the project, so it is concluded that the investment in water heaters using the biogas produced by the dairy farm itself as fuel is economically viable.

Table 4. Financial indicators of the water heating project with the use of biogas in dairy stables in the Comarca Lagunera.

Financial indicator	Indicator value	Project decision
NPV	180 954	It is accepted
IRR	46%	It is accepted
B/C	1.31	It is accepted

The payback period was also calculated. According to the updated cash flow data (Table 2) at the end of the second year, $311 078.00 has been recovered, so an additional 0.8 years are required for a total of 2.8 years to recover the initial investment. The investment or capital costs of renewable energy have significant variations not only in a global context but also among countries in the same region.

Conclusions

The proposal of heating water with a commercial heater, which uses methane generated by anaerobic digestion of manure produced in the stable, showed technical feasibility by showing consistency in the heating times of the 45 samples studied. The economic analysis, with its different indicators, NPV, IRR and R B/C, observed values in ranges of acceptance of the project. Therefore, it is concluded that the heating of the water in the dairy stables for the purpose of sanitation and heating of milk for calves, with a commercial heater, is technically and economically viable.

At the level of dairy farm managers in the Comarca Lagunera there is no clear concept of what efficient energy management is, there is no culture of assessing the importance of being efficient in the use of this resource. It will be necessary to spread this type of technologies; through different means, such as the demonstration stations with the main leading farmers where the goodness of the system is appreciated and its use can be increased.

Acknowledgments

The authors thank MVZ Jose Antonio Romero Martínez of the Stable 'El Coronel' for the facilities provided for the fieldwork during this study.

Cited literature

Acevedo, I.; Leos, J. A.; Figueroa, U. y Romo. J. L. 2017. Política ambiental: uso y manejo del estiércol en la Comarca Lagunera. Acta Universitaria. 27(4):3-12. https://dx.doi.org/10.15174/au.2017.1270.

ADBA. 2015. Anaerobic digestion & biogas association. Producing and using biogas. Chapter 5. In The practical guide to AD. London, UK. 59-80 pp. http://adbioresources.org/search/eyjyzxn1bhrfcgfnzsi6innlyxjjacisimtlexdvcmrzijoiq2hhchrlcia1libqcm9kdwnpbmcgyw5kihvzaw5nigjpb2dhcy4ifq.

Alemán, G. S.; Casiano, V.; Cárdenas, D. R.; Díaz, N.; Scarlat, J.; Mahlkencht, J. F.; Dallemand, A y Parra, R. 2014. Renewable energy research progress in Mexico: a review. Renewable and Sustainable Energy Reviews. 32:140-153.

Alvarado-Moreno, J. 2016. Efecto de la temperatura en la producción de biogás en un bioreactor tipo batch a través de la descomposición anaeróbica de residuos sólidos orgánicos. ENGI Revista Electrónica de la Facultad de Ingeniería, Universidad Buenaventura, Colombia 3(1):16-19.

Baca, U. G. 2013. Evaluación de proyectos. Séptima edición, McGraw Hill. México. 387 p.

Barik, D.; Sah, S. and Murugan, S. 2013. Biogas Production and Storage for Fueling Internal Combustion Engines. Inter. J. Emerging Technol. Adv. Eng. an ISO Certified Int. J. 3(3):193-202.

Bayar, T. 2017. Heat-only biogas plants could edge out UK CHP, firm says. http://www.pennenergy.com/articles/cospp/2017/05/heat-only-biogas-plants-could-edge-out-uk-chp-firm-says.html.

Chawla, O. 1986. Advances in biogas technology, Indian Council of Agricultural Research, New Delhi. https://www.worldcat.org/title/advances-in-biogas-technology/oclc/692066363.

CONACYT. 2013. Eficiencia energética de bombas de pozo profundo y ordeños mecánicos en establos de Comarca Lagunera. https://www.conacyt.gob.mx/index.php/sni/fichas/2013/5617-196007-ficha-publica/file. (10 de junio de 2019) ó 196007-ficha-publica/file.

CONACYT. 2017. Gestión eficiente del biogás para generar energía térmica. https://www.conacyt.gob.mx/index.php/transparencia/transparencia-focalizada/fichas-publicas/fichas-publicas-2016/15761-ficha-publica-231389/file.

Espinoza-Arellano, J. J.; Carrillo, A.; Molina, V.; Torres, D. y Fabela, A. 2018. Características técnicas y socioeconómicas de establos del sistema de producción intensivo de leche de vaca de la Comarca Lagunera. Revista Agrofaz. 18(1):101-109.

FAO. 2017. Food and Agriculture Organization of the United Nations. Guía para la formulación de proyectos de inversión del sector agropecuario Ministerio de Desarrollo Agropecuario. Ciudad de Panamá. http://www.fao.org/3/I8097ES/i8097es.pdf.

Figueroa, U.; Núñez, G.; Delgado, J. A.; Cueto J. A. y Flores, J. P. 2009. Estimación de la producción de estiércol y de la excreción de nitrógeno, fósforo y potasio por bovino lechero en la Comarca Lagunera. *In*: Orona C. I.; Salazar, S. M. E. y Fortis H. (Eds.). Agricultura orgánica. 2ª (Ed.). FAZUJED. SMCS. Gómez Palacio, Durango. 128-151 pp.

Figueroa, U.; Núñez, G.; Reta D. y Flores, H. 2015. Balance regional de Nitrógeno en el sistema de producción de leche-forraje de la Comarca Lagunera, México. Rev. Mex. Cienc. Pec. 6(4):377-392.

García, C. A. y Masera, O. 2016. Estado del arte de la bioenergía en México. Publicación de la red temática de bioenergía (RBT) del CONACYT. http://rtbioenergia.org.mx/wp-content/uploads/2016/12/Divulgacion_Estado-del-arte-de-la-bioenerg%C3%ADa-en-M%C3%A9xico.pdf.

García, G. O.; Figueroa, U.; Cueto, J. A.; Núñez, G.; Gallegos, M. y López, J. D. 2019. Disponibilidad de nitrógeno usando dos tipos de estiércol de bovino lechero en cultivos de maíz forrajero y triticale. Rev. Nova Scientia. 11(1):124-141 doi.org/10.21640/ns.v11i22.1709.

Hagos, K.; Zong, J.; Li, D.; Liu, C. and Lu, X. 2017. Anaerobic co-digestion process for biogas production: Progress, challenges and perspectives. Renewable and Sustainable Energy Reviews https://doi.org/10.1016/j.rser.2016.11.184.

Hernández De Lira, I.; Huber, D.; Espinosa, T. and Balagurusamy, N. 2015. Methane emission and bioenergy potential from livestock manures in México. J. Renewable and Sustainable Energy. 7(5):1-10. Retrieved from https://www.researchgate.net/publication/283851321.

Levin, R. y Rubin, D. 2010. Estadística para administración y economía. Ed. Pearson. 7ª (Ed.). revisada. México, DF. 799 p.

Lind, D.; Marchal, W. y Mason, R. 2004. Estadística para administración y economía. Ed. Alfaomega. 11 (Ed.). México, DF. 830 p.

López, A.; Hernández de Lira, I. y Molina, V. 2017. Propuesta de proceso de gestión eficiente del sistema de producción de biogás para la cogeneración de energía en establos lecheros de la Comarca Lagunera. CienciAcierta. (51):1-17.

Mital, K. 1996. Biogas systems: principles and applications, new age international (P). Limited Publishers, New Delhi. 412 p.

Molina, V.; Molina, V. P.; García, F. and Gutiérrez, O. 2017. Efficient biogas management to generate thermal energy. Inter. J. Eng. Innov. Res. 6(5):235-239.

PEMEX. 2013. Petróleos Mexicanos. Programa estratégico tecnológico 2013-2027, Petróleos Mexicanos y sus Organismos Subsidiarios. http://www.pemex.com/acerca/informes_publicaciones/Paginas/tecnologico-estrategico.aspx.

REN21. 2016. Renewable energy policy network for the 21st Century. Renewables 2016 Global Status Report. Paris, France. 272 p. http://agricultura.gencat.cat/web/.content/de_departament/de02_estadistiques_observatoris/27_butlletins/02_butlletins_nd/documents_nd/fitxers_estatics_nd/2016/0179_2016_ERenovbles_Energia-renovable-mon.pdf.

SADER-Laguna. 2017. Estadísticas del sector agropecuario y forestal de la Comarca Lagunera. Delegación de SAGARPA en la Comarca Lagunera. Subdelegación de Planeación. Cd. Lerdo, Durango.

SAGARPA. 2010. La producción de carnes en México. Claridades Agropecuarias. 207:19-33.

SEMARNAT. 2015. AViso para el reporte del registro nacional de emisiones. http://www.geimexico.org/image/2015/aviso_factor_de_emision_electrico%202014%20 Semarnat.pdf.

Singh, A.; Pant, D. and Olsen, K. 2013. Importance of life cycle assessment of renewable energy sources. *In*: Singh, A.; Pant, D. O. (Eds.). Life cycle assessment of renewable energy sources. Green Energy Technol. 13-37 pp. Doi: 10.1007/978-1-4471-5364-1.

Speece, R. 1996. Anaerobic biotechnology for industrial wastewaters. Archae Press, Nashville, Tennessee, USA. https://www.worldcat.org/title/anaerobic-biotechnology-for-industrial-wastewaters/oclc/35335903. 394 p.

Varnero, M. 2011. Manual de biogás. Proyecto CHI/00/G32. Chile: remoción de barreras para la electrificación rural con energías renovables. http://www.fao.org/3/as400s/as400s.pdf.