Análisis de Factibilidad de la Tecnología de Trigeneración para la Eficiencia y Confiabilidad Energética en la Industria Salvadoreña

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Fecha de recepción: 2 de julio de 2024 - Fecha de aceptación: 25 de noviembre de 2024

Resumen

El sector industrial salvadoreño enfrenta desafíos relacionados con la confiabilidad y la rentabilidad de la energía. Este artículo explora la viabilidad de la tecnología de Trigeneración para mejorar la eficiencia energética y reducir la dependencia energética externa. La Trigeneración, que integra la producción de electricidad, calefacción y refrigeración a partir de una única fuente de combustible, se analiza en el contexto industrial salvadoreño. Aunque esta tecnología ha sido explorada ampliamente, hay una necesidad de estudiar su factibilidad en el contexto de países en vías de desarrollo, con altos costos de energía, sistemas de energía eléctrica poco confiables, y disponibilidad limitada de biocombustibles. La metodología incluye la recopilación de datos de una industria de fabricación de bebidas, abarcando el consumo de energía, las demandas máximas y los costos. El dimensionamiento y la modelización energética del sistema de Trigeneración determinan su viabilidad, con un enfoque en la generación de electricidad, los procesos térmicos y las fuentes de calor disponibles. El análisis financiero considera opciones de biogás y gas natural, revelando Periodos de Recuperación Simple y Valores Actuales Netos prometedores. El análisis de sensibilidad identifica parámetros críticos que afectan la viabilidad del sistema: el costo del biogás y la inversión de capital para la opción de biogás, y el costo del gas natural y la inversión de capital para la opción de gas natural. En conclusión, la tecnología de Trigeneración muestra un gran potencial para las industrias salvadoreñas, dependiendo de factores como la disponibilidad de combustible, el costo del combustible, el precio de venta de la electricidad y la demanda de energía para calefacción y refrigeración. Esta investigación puede animar a las empresas industriales a explorar proyectos piloto para validar los posibles beneficios de los sistemas de Trigeneración en su búsqueda de mayor eficiencia y confiabilidad energética.

Palabras clave: Trigeneración, eficiencia energética, enfriamiento calentamineto y potencia, estudio de factibilidad

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Nota: Este artículo de investigación es parte de Ingeniería–Revista Académica de la Facultad de Ingeniería, Universidad Autónoma de Yucatán, Vol. 28, No. 3, 2024, ISSN: 2448-8364

Feasibility Analysis of Trigeneration Technology for Energy Efficiency and Reliability in the Salvadoran Industry

Abstract
The Salvadoran industrial sector faces challenges related to energy reliability and cost-effectiveness. This paper explores the feasibility of Trigeneration technology to enhance energy efficiency and reduce external energy dependence. Trigeneration, which integrates electricity, heating, and cooling production from a single fuel source, is analyzed within the Salvadoran industrial context. Although this technology has been broadly explored, there is a need to study its feasibility within the context of developing countries, with high electricity costs, unreliable electrical grids, and limited availability of biofuels. The methodology includes data collection from a beverage manufacturing industry, covering energy consumption, peak demands, and costs. Sizing and energy modeling of the Trigeneration system determine its feasibility, with a focus on electricity generation, thermal processes, and available heat sources. Financial analysis considers both biogas and natural gas options, revealing promising Simple Payback Periods and Net Present Values. Sensitivity analysis identifies critical parameters affecting system viability: biogas cost and capital investment for the biogas option, and natural gas cost and capital investment for the natural gas option. In conclusion, Trigeneration technology shows significant promise for Salvadoran industries, depending on factors like fuel availability, fuel cost, electricity sales price, and demand for heating and cooling energy. This research could encourage industrial companies to explore pilot projects to validate the potential benefits of Trigeneration systems in their pursuit of enhanced energy efficiency and independence.

Keywords: trigeneration, energy efficiency, energy reliability, combined cooling heating and power, feasibility study

Introduction

Industries worldwide continuously search for technologies that enhance energy efficiency and reliability. The potential efficiency gains could be even more significant in developing countries, with high energy costs and generally unreliable electrical grids. Like in many other regions, industries play a pivotal role in El Salvador's economic growth. Industrial companies require electricity, fuels, and hot and cold fluids for their productive activities. Considering global competition, industries need to focus on improving the utilization of energy resources. In addition, energy supply reliability and cost-effectiveness have posed significant challenges to the Salvadoran industry. To address these issues, there is a growing interest in alternative energy solutions that enhance energy efficiency and reduce dependency on external energy suppliers. Trigeneration technology, also known as Combined Cooling, Heat, and Power Production (CCHP), is a concept that integrates electricity, heating, and cooling production and has emerged as an alternative. Trigeneration is the simultaneous production of electricity, heat, and refrigeration from a single fuel source, such as biogas or natural gas (Wu & Wang, 2006). Trigeneration can be a suitable technology for industries requiring large amounts of electricity and thermal energy (i.e., steam and cold water) for their processes.

For context, Cogeneration, or Combined Heating and Power (CHP) is a well-known technology that simultaneously produces electricity and heat. Trigeneration is a more efficient process that produces a cold fluid from excess heat from the cogeneration process. Figure 1 shows a Trigeneration system process, and describes how fuel energy is transformed into three energy services (electricity, steam and cold water). The prime mover, usually a turbine or internal combustion engine, produces electricity through a generator. In addition, heat from the flue gases is used as an energy source in a heat recovery boiler. Also, the thermal energy from the prime mover cooling system is used as an energy source in an absorption chiller. We hypothesize that this technology could be feasible in the Salvadoran context, considering the following developments: 1) The first Liquified Natural Gas (LNG) power plant started operation in the country in 2022, with an overall capacity of 380.7 MW, including the infrastructure for processing LNG. (Guzman, 2022) (Alemán, 2022) 2) Biomass and biofuels have gained space in the industrial sector. Energy from biomass is 15% of electricity production in El Salvador. (González Mercado et al., 2016), 3) There is local experience in implementing Cogeneration plants in the industry, including a 14 MW power plant in an electric facility, to gain independence from a generally unreliable electric grid. (Mancía, 2016).

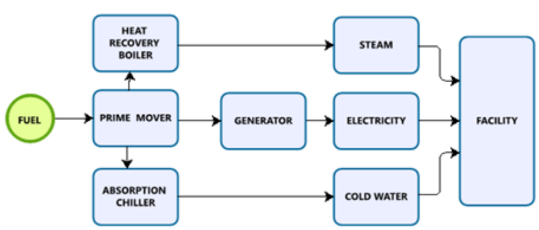

Figure 1. Trigeneration System Schematic.
Source: Authors

There are experiences outside the region for Trigeneration plants, mainly in the Food Industry, due to its constant demand for heating and cooling. For instance, a project in Rotterdam, including a 5 MW turbine producing electricity and steam, uses absorption refrigeration with a thermal load of 1400 kW and an evaporation temperature of -23°C. (Grupo Europeo de Ingeniería Agroalimentaria y Ambiental, 2024) . Another industry in Burgos, Spain, has a trigeneration plant, which produces process steam and cold water through an absorption refrigeration system. Ice storage technology is also included, with an evaporating temperature of -10 °C (Grupo Europeo de Ingeniería Agroalimentaria y Ambiental, 2024). A similar case study is reported in Logroño, Spain, with a 9 MW Trigeneration plant that produces hot water for an absorption refrigeration system, with a cooling capacity of 2500 kW and an evaporation temperature of -18°C. (Grupo Europeo de Ingeniería Agroalimentaria y Ambiental, 2024)

There is extensive literature on feasibility studies of Trigeneration Systems. Using biomass as a fuel for the process has been studied (Palomba et al., 2017), (Afonso & Rocha, 2016), along with solar energy (Khalid et al., 2021). Biogas is a popular fuel source as well (Leonzio, 2018), including landfill gas (Hao et al., 2008), Syngas (Segurado et al., 2019), in addition to waste heat (Baccioli et al., 2018). Other configurations include solar energy through parabolic trough collectors (PTC) (Khalid et al., 2021), Fuel cells (Genovese et al., 2023), geothermal energy (Qian et al., 2024). Other variations include hybrid systems, such as the one proposed by Cao (Cao et al., 2021), including a Kalina cycle, reverse osmosis desalination plus low temperature electrolisis powered by geothermal energy. The use of thermal storage has also been considered (Sandoval-Reyes et al., 2020).

As key points, Lai (Lai & Hui, 2009) emphasizes the importance of flexibility in the design of trigeneration systems, due to variable demands associated with climate and human factors. The reviewed studies collectively underscore the potential of trigeneration systems to enhance energy efficiency and sustainability. Key factors influencing their feasibility include the choice of fuel, integration with renewable energy sources, and supportive economic policies. Trigeneration stands out as a versatile and promising technology for meeting diverse energy needs while mitigating environmental impacts. The reviewed works highlight the importance of ongoing research and development to address technical challenges and optimize system performance, paving the way for broader adoption of trigeneration technologies. Although technical literature is abundant on the subject, there is a gap in understanding how the technology can be applied in contexts where the electrical grids are highly unreliable and fuel availability is limited. These two factors, we believe, are essential in various countries in the developing world, and understanding how the feasibility is affected by critical parameters, such as electricity and fuel costs, load factors, among others, can provide more clarity on how a broad implementation of the technology could be pursued in similar situations. If there is cost-effective alternative to the electrical grid that can provide sufficient power, steam, and cold water, we believe some industries might be interested in adopting Trigeneration.

This paper presents a comprehensive analysis of the feasibility of trigeneration technology in the Salvadoran industrial context, focusing on factors such as energy demand, cost-effectiveness, and sensitivity. This work is structured as follows: 1) Key insights on the sizing and energy modeling process of a Trigeneration System in a specific context; 2) Assessment of the economic viability of a Trigeneration System. 3) A Sensitivity analysis, identifying key variables that most significantly affect the feasibility of the technology.

Methods

The methodology used in this feasibility analysis consisted of using a local beverage industry as a case study and sizing a trigeneration system that could satisfy their power, cooling, and heating needs. We analyzed two fuel alternatives: Biogas, and natural gas, and conducted energy, economic and sensitivity analyses to determine how feasible this technology would be, and which variables affect the cost-effectiveness the most. We will present here the data collected from the industry, as a basis for the analysis, as well as the calculation methods and assumptions used.

A. Data Collection

Collaboration with an industry partner was essential to conduct a thorough feasibility analysis. A beverage manufacturing industry in El Salvador provided valuable energy consumption data, including electricity, heating, and cooling demands, peak electricity demands, total electricity consumption, annual electricity costs, annual fuel costs, and fuel consumption. These data formed the foundation for sizing the trigeneration plant and assessing its economic feasibility. The Beverage Industry is vital for the national economy since it produces 7.2% of national industrial production, steadily increasing its share (Asociación Salvadoreña de Industriales (ASI), 2023).

Input data consisted of the following: Energy consumption (kWh) per each electric connection analyzed, Electricity costs ($), Fuel costs ($), Steam consumption (Ton), and Air conditioning system inventory (Tons). The industry partner provided the research team with ten months of data from January 2022 to October 2022. A summary of relevant data regarding electrical energy consumption and peak demand is provided in Figures 2 and 3. Connections 1 and 2 refer to the circumstance that two grid connections exist in the industrial facility under study, with different electric meters. The study aimed at generating the electricity required by both connections. In Figure 4, monthly fuel oil consumption is presented.

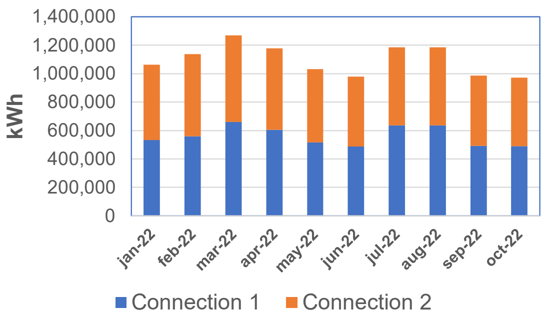

Figure 2. Annual energy consumption for each Electric Connection Trigeneration System Schematic.
Source: Authors

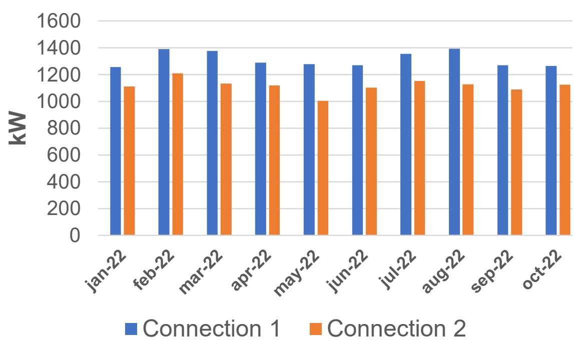

Figure 3. Peak Demand for each Electric Connection.
Source: Authors

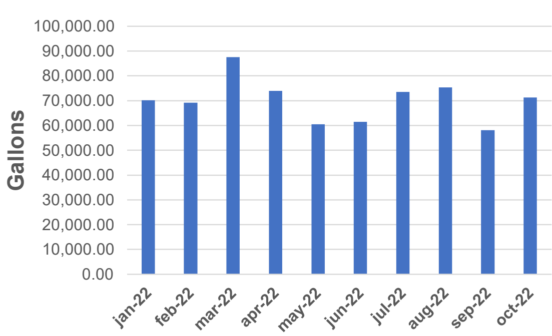

Figure 4. Fuel Oil Consumption
Source: Authors

Table 1 shows the monthly steam flow rates, enthalpy change, and thermal output used to estimate the plant's thermal requirements.

Table 1. Steam Requirements

Month	Tons	Flow rate (tons/h)	Flow rate [kg/s]	Enthalpy change at 8 bar [kJ/kg]	Thermal Output [kW]
January	3526.1	4.9	1.4		2786.1
February	3136.3	4.4	1.2		2478.1
March	4346.2	6.0	1.7		3434.1
April	3662.7	5.1	1.4		2894.0
May	3192.9	4.4	1.2		2522.8
June	2924.3	4.1	1.1	2048.0	2310.6
July	3657.9	5.1	1.4		2890.2
August	3730.6	5.2	1.4		2947.7
September	2840.3	3.9	1.1		2244.2
October	3702.0	5.1	1.4		2925.1
Average	**3471.9**	**4.8**	**1.3**	**Average**	**2743.3**

B. Sizing and Energy Modeling of the Trigeneration System

The core of the study involved sizing the trigeneration system, with a primary focus on electricity generation. The cogeneration plant was designed to meet the industry's entire electricity demand throughout the year. This analysis also determined the percentage of thermal processes that the trigeneration installation could supply or whether some existing elements, such as boilers, would need to be retained for heat generation.

As a system configuration, a prime mover consists of a Combined Heating and Power Unit (CHP). This unit is a heat engine that produces electricity from a fuel, and it generates excess heat that could be captured from the flue gases and the cooling system.

These heat sources will be used for generating steam through a heat recovery boiler and cold water via an absorption chiller. Firstly, a CHP was selected for each electrical connection based on peak electricity consumption during the study period. The primary sizing criteria consisted of meeting the overall electricity demand plus a significant surplus. There are two heat sources to consider when estimating the heating and cooling components of the Trigeneration System. The first heat flux to analyze is obtained from the CHP cooling system. The second one is the thermal energy contained in the flue gases. Upon analyzing temperatures and energy flows, the cooling system's heat energy would be the energy source of an absorption chiller. In contrast, the flue gas energy would be ideal for steam generation through a heat recovery boiler. The overall available heat for each thermal system depends on the load factor and is presented in Table 2 as follows.

Table 2. Overall available heat input for the Trigeneration System Steam requirements

Overall Available Heat	
Flue Gas Available Heat [kW]	1273
Motor Cooling Available Heat [kW]	1204
Overall Available Heat [kW]	2477

An estimated steam production flow rate is obtained by considering the heat recovery boiler efficiency, as presented in Table 3. On the other hand, heat recovery from the cooling system is used to activate the chiller. Using this information, an absorption chiller was selected, and using performance curves from the manufacturer, it was verified whether the chiller would produce the cold water required for the industry's cooling demand. The sizing exercise showed that the cooling demand could be met, but the heating demand would require some boiler capacity to be retained.

For sizing and calculation purposes, two alternatives were studied. First, a Trigeneration plant based on biogas fuels. Some industries are using organic waste from their processes to generate biogas through anaerobic digestion (i.e., Biodigestors). Second, Liquefied Natural Gas, considered a fuel alternative for local industries due to the recent implementation of a Natural Gas Power Plant, takes advantage of its processing infrastructure but depends on the legal and logistic viability of distribution.

Table 3. Heat recovery boiler performance

Heat Recovery Boiler / Estimated CHP Load Factor	
Available Heat for Steam Production [kW]	1273
Boiler Efficiency [-]	0.85
Steam Thermal Output [kW]	1082
Energy Needed to Evaporate Water [kJ/kg]	2048
Steam Flow Rate [kg/s]	0.5
Steam Production [ton/h]	**1.90**
Unmet Capacity [ton/h]	2.92

The selected equipment specifications and performance curves provided vital information for estimating electricity, steam, and cold water production. For instance, Figures 5 and 6 show the selected CHP 2 system performance curves. These curves allowed the estimation of available heat as a function of load factor. Similar performance curves allowed for estimating electricity generation, steam, and cold water thermal outputs, which were key for determining energy performance and savings.

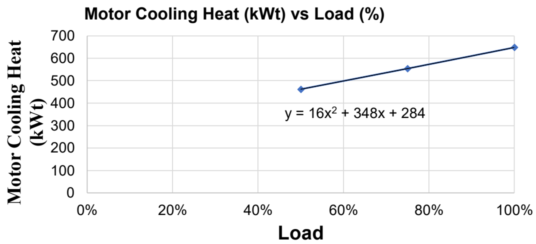

Figure 5. CHP 2 Motor Cooling Heat Performance Curve
Source: Authors

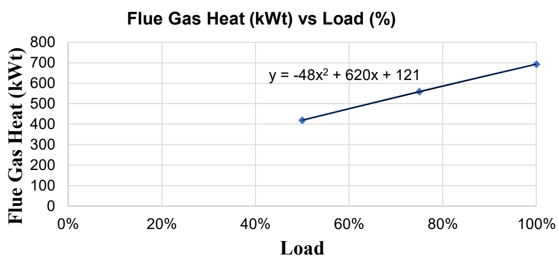

Figure 6. CHP 2 Flue Gas Heat Performance Curve
Source: Authors

C. Financial Analysis

A comprehensive financial analysis was conducted for both the biogas and natural gas trigeneration systems. Critical factors considered included the implementation cost of the trigeneration plant, current energy costs, projected annual fuel costs, annual energy savings, electricity savings for cooling, and projected revenue from electricity sales.

As a foundation, the values compiled in Tables 4 and 5 were assumed to analyze the Biogas and Natural Gas Trigeneration Systems.

Table 4. Assumptions for the Analysis of the Biogas Trigeneration System

Factor	Base Value
CHP 1 Load Factor	75%
CHP 2 Load Factor	75%
Biogas Cost [$/Nm^3]	$0.25
Fuel Oil Cost [$/l]	$0.510
Electricity Sales Cost [$/kW-h]	$0.100
Minimum Attractive Rate of Return (MARR)	9.00%
Capital Cost per Installed kWe	$1,526.84

Table 5. Assumptions for the Analysis of the Natural Gas Trigeneration System

Factor	Base Value
CHP 1 Load Factor	80%
CHP 2 Load Factor	80%
Natural Gas Cost [$/MMBTU]	$12.68
Fuel Oil Cost [$/l]	$0.51
Electricity Sales Cost [$/kW-h]	$0.10
Minimum Attractive Rate of Return (MARR)	9.00%
Capital Cost per Installed kWe	$1,526.84

D. Sensitivity Analysis

A sensitivity analysis was conducted to analyze the variability of the results depending on parameter changes. The factors included in the study are the CHP load factor, fuel price, electricity sales price, and capital investment costs per installed kWe.

Results and Discussion

This section presents the results obtained by applying the methodology just described. It is important to note that the results correspond to a specific company used as a case study. The numbers obtained do not necessarily represent the totality of the Salvadoran industry or the beverage production sector; however, we argue that they provide evidence of how a Trigeneration system would perform in this context. They would highlight potential implementation challenges and provide a basis for understanding what parameters are critical for a system of this type to be feasible.

An energy and economic model was developed to determine the system's feasibility. The model takes into account capital investment costs and savings. Capital costs were estimated based on actual Trigeneration projects. The overall capital investment cost is estimated as $1,526.84 per installed kWe. Table 6 breaks down this cost assumption.

Table 6. Biogas trigeneration system capital cost assumptions

Item	Cost (US$)
Engineering Cost [$/kWe]	42.99
Equipment Costs [$/kWe]	927.37
Installation Costs [$/kWe]	556.48
Estimated Unit Cost [$/kWe]	**1,526.84**

The following results correspond to the Biogas Trigeneration System, unless stated otherwise. The sizing process provided the results summarized in Table 7.

Table 7. Biogas trigeneration system capacity

Variable	CHP1	CHP2
CHP Load Factor	75.00%	75.00%
Electric Power [kW]	1461.0	1172.0
Thermal Output [kW]	1364.0	1113.0
Biogas Consumption [Nm^3/h]	582.8	470.0
Equivalent Energy Consumption [MJ/h]	12588.5	10152.0
Electric Energy produced in 1 h [kW-h]	1461	1172
Thermal Energy produced in 1 h [MJ]	4910	4007
Biogas used in 1 h [Nm^3]	582.8	470.0
Equivalent Fuel Cost [$/h]	$ 145.70	$ 117.50

By using equipment specifications and performance curves, an energy model of the Trigeneration System allowed an estimation of the annual costs and benefits. Table 8 provides an estimation of electricity and steam production. Table 9 provides a summary of costs, savings, and benefits. It is worth noting that the system has been oversized in terms of electricity production, and includes a significant surplus, which should be sold to the grid. Also, electricity savings from cold water production are included in the analysis. As mentioned earlier, this sizing arrangement allowed for the satisfaction of the cooling demands but did not allow for the satisfaction of the heating demands. There is a balance to be found between electricity and thermal outputs when sizing a Trigeneration System.

Table 8. Production Estimates

Production Estimates		
Electricity	Annual Electricity Production [kWh]	23,065,080.00
	Electricity Consumption [kWh]	12,166,921.39
	Net Sale [kWh]	10,898,158.61
Steam	Trigeneration Steam [ton]	16,661.88
	Fuel Oil Boiler Steam [ton]	25,001.47

Table 9. Summary of annual costs, savings, and total benefits

Annual Costs	Electricity	Fuel Oil	Total	
	$1,926,618	$1,624,232	$3,550,850	
Projected Revenue and Savings	Electricity Sales	Electricity Savings (Self-Consumption)	Electricity Savings for Refrigeration	Total Benefits
	$1,089,816	$308,242	$143,165	**$1,541,223**

The financial analysis results are summarized as follows. For the Biogas Trigeneration System, an investment of $5,359,208 yielded a Simple Payback Period (SPB) of 3.48 years, an Internal Rate of Return (IRR) of 13.47%, and a Net Present Value (NPV) of $635,612.07. In contrast, for the Natural Gas Trigeneration System, an investment of $5,246,222.94 yielded an SPB of 3.85 years, an IRR of 9.37%, and a NPV equal to $50,340.14. The simple payback period is within the four-year range in both cases. Also, a positive net present value indicates that both options are economically feasible, considering the assumptions used for the analysis. Overall, the economic results yield a promising outlook for implementing the Trigeneration system. This is so because the benefits outweigh the costs, and the investment is recovered in the medium term.

To test how stable these results are, the sensitivity analysis allowed a deeper understanding of how the parameters affect the outcome. Figures 7 and 8 present sensitivity charts for the biogas and natural gas systems. To interpret the charts, consider deviations from base case values for each variable and the impact of such variations on the system's net present value. The system is economically unfeasible if the net present value is below zero. The biogas system's most sensitive parameters are biogas cost and capital investment cost. As observed in Figure 7, a 7% increase in the biogas cost would make the NPV zero, implying an inflection point for the investment. Additionally, an 11% increase in the capital investment cost would make the investment neutral in terms of NPV. Also, decreasing the assumed electricity sales price by 15% ($0.085/kWh) would level the NPV to zero. The Minimum Attractive Rate of Return (MARR) and CHP load factor were the parameters that least impacted the result.

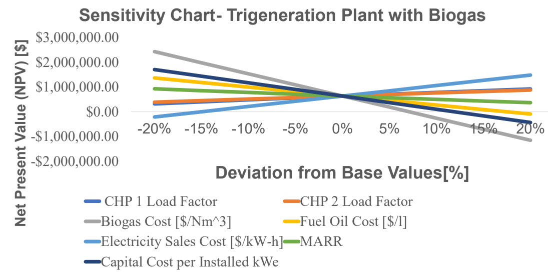

Figure 7. Sensitivity Chart for the Biogas Trigeneration System
Source: Authors

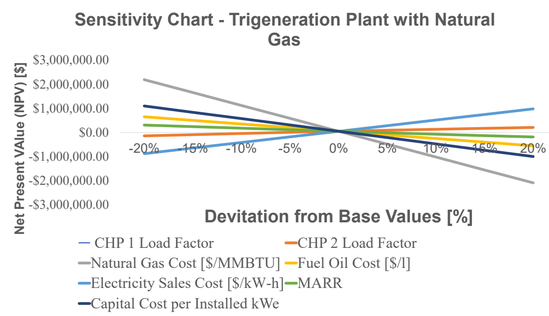

Figure 8. Sensitivity Chart for the Natural Gas Trigeneration System
Source: Authors

For the Natural Gas Trigeneration System, the parameters that most affect the NPV are the natural gas cost and capital investment costs, as shown in Figure 8. In this case, the investment is much more sensitive to parameter changes. A slight increase of 0.47% in natural gas prices would equal the NPV to zero. Also, a 0.96% increase in capital investment cost, or a 1.085% decrease in electricity sales price, would also make the investment neutral in terms of NPV. The Minimum Attractive Rate of Return (MARR) and CHP load factor were the parameters that least impacted the result.

Results indicate that the Trigeneration technology is feasible but highly sensitive to critical parameters for the natural gas option. The Biogas option seems to be more stable in terms of cost-effectiveness. Notably, the two variables impacting feasibility more critically (fuel and capital investment costs) depend on the markets. However, there is a dynamic between electricity costs and feasibility. Higher electricity costs would make the system more feasible; an unreliable electrical grid also carries significant costs for industries. On the other hand, as technology becomes more mature, capital costs should be expected to decrease. If the fuel supply is improved, their costs will also be reduced. Those dynamics could make Trigeneration a more viable alternative in the future decades in El Salvador.

Conclusions

Salvadoran industrial companies have been aiming to improve energy efficiency for many years. Although the Trigeneration technology is yet to be tested in the country and region, there are viable experiences elsewhere where the concept has been demonstrated. The present paper analyzes, within the Salvadoran context, how feasible the technology is and which parameters would be vital for achieving that feasibility. High energy costs and unreliable energy services are also two aspects to consider. One key element of the viability analysis is that the industry would depend on a single fuel source instead of electricity and fossil fuel supply. However, as the analysis showed in this case study, not all requirements may be met. In this case, the steam production could not meet all the industry needs. Also, the cooling processes in industries are sometimes limited by temperature, which could be too low for the Trigeneration system to replicate.

In general terms, the case study revealed that the Trigeneration system is feasible. However, this depends on the availability of biogas or natural gas. The biogas option, although possible, depends on the steady and abundant availability of organic matter that can be used to produce the biogas. On the other hand, the natural gas option depends on regulatory and commercial developments, considering the appearance of the first natural gas power plant in El Salvador in 2022. The combination of factors that would facilitate the viability of a Trigeneration system are: 1) Fuel availability (i.e., biogas or natural gas). Also, fuel cost is a parameter that significantly affects the system's cost-effectiveness. 2) The analysis indicates that it is convenient to produce more electricity than needed and sell some surplus. Therefore, electricity sales price becomes a critical parameter in the analysis. 3) High demand for heating and cooling energy. A higher demand for cooling and heating energy makes the project more cost-effective because the fuel energy is better utilized, and more savings are obtained. Trigeneration offers a new paradigm for industries to become more independent of the electrical grid and produce their energy needs at higher efficiency rates. In this paradigm, the company's bottom line could improve. Although this paper presents a case study for one industrial company, the results indicate that the Technology is potentially feasible in this context. Beyond the Salvadoran context, these results could hold, with some caveats, in the Central American and Caribbean Regions, fostering energy independence and efficiency. This paper should encourage industrial companies to design and develop pilot projects for Trigeneration System technology, test the assumptions, and validate estimated benefits.

Acknowledgments

The authors thank the industrial firm that provided the data for the present research, and Rene Ariza, for reviewing an early version of the manuscript.

Author contributions

Luis A. Martínez : Conceptualization, methodology, supervision, writing review and editing. Javier E. Chávez : Investigation, formal analysis, writing original draft. Roberto C. Mendoza: Investigation, formal analysis, writing original draft. Edwin N. Salinas: Investigation, formal analysis, writing original draft. Ricardo I. Valiente: Investigation, formal analysis, writing original draft.

Conflicts of interest

During the elaboration of this work, the authors declare no conflicts of interest.

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