ISBN: 978-628-96613-3-0. ISSN: 2414-6390. Digital Object Identifier: https://dx.doi.org/10.18687/LACCEI2026.1.1.1245

Feasibility of Fuel Cells and Cogeneration Potential in Hotel Industry in Puerto Rico

Luis Guzmán Ceballos, Msc[1], and Amaury Malave Sanabria, PhD[2]
[1,2]Universidad Ana G. Méndez, Puerto Rico (U.S.), *lguzman142@email.uagm.edu, ajmalave@uagm.edu*

Abstract– This study evaluates the feasibility of using a solid oxide fuel cell (SOFC) as the primary mover in a cogeneration system for hotel applications. A 280kW SOFC system was proposed to meet both the electrical and thermal demands of a hotel, with the thermal energy utilized for hot water production and steam generation for laundry operations. The analysis revealed that, despite an installation cost of $840,000, the system offers significant cost advantages, producing energy at $0.12/kWh compared to the grid operator's $0.27/kWh, resulting in annual savings exceeding $300,000 and a simple payback period of 2.79 years. Power Purchase Agreements (PPA) further enhance the feasibility, where third-party investment in infrastructure reduces the financial burden of the high initial costs. Future work will explore integrating an absorption chiller for cooling, simulating SOFC performance with advanced tools, and assessing the viability of alternative fuels such as propane to improve flexibility and reduce costs.

Keywords-- Cogeneration, Hotels, Solid Oxide Fuel Cell and Feasibility.

I. Introduction

Climate change is an undeniable global issue that affects society in numerous ways, resulting in natural disasters such as droughts, floods, hurricanes, and more. These events cause extensive damage to ecosystems and infrastructure, increase mortality rates, and disrupt food availability [1]. In Puerto Rico, climate change has had a significant impact, particularly during hurricane season (June 1st to November 30th).

In September 2017, Puerto Ricans endured the devastating effects of Hurricane María, a Category 4 storm. María completely destroyed the island's electrical distribution system, leading to prolonged blackouts across the entire country for months. This crisis prompted the enactment of Law 17-2019 [2], which mandated the modernization of the power grid and established a goal for Puerto Rico to transition to 100% renewable energy by 2050.

Since Hurricane María, the electricity sector has remained a critical issue for residents. Continuous and prolonged blackouts, along with power fluctuations, have resulted in equipment failures and widespread dissatisfaction [3]. The hotel industry, like other sectors, has been severely affected by these deficiencies. Reliable and continuous energy is essential for hotel operations such as air conditioning, water heating, and other activities vital for maintaining guest comfort.

As an integral part of the economy, the hotel sector plays a key role in driving industrial growth. Since early 2021, the sector has experienced a 20% income increase [4]. To sustain this progress, increase profitability, and comply with renewable energy mandates, modern energy technologies must be explored and evaluated for feasibility.

One promising technology is fuel cells, which use an electrochemical process to convert the chemical energy in fuels into electricity without combustion [5]. Fuel cells are often integrated into cogeneration systems, which enhance energy efficiency by simultaneously producing two or more forms of energy from a single source [6].

This paper aims to investigate the application of cogeneration systems using fuel cells as primary energy converters in the hotel sector. By exploring this technology, we aim to address energy reliability challenges, reduce emissions, and contribute to Puerto Rico's renewable energy goals.

II. Literature Review

A. *Fuel Cell*

Fuel cell systems generate electricity through a fundamentally different mechanism compared to traditional combustion-based prime mover technologies. Instead of burning fuel directly, fuel cells use an electrochemical process to produce direct current (DC) electricity. This process operates continuously as long as a steady fuel supply is available, offering a reliable and efficient energy solution [7].

For stationary combine heat and power (CHP) applications, four main types of fuel cells are commonly utilized:

- Phosphoric Acid Fuel Cells (PAFC)
- Molten Carbonate Fuel Cells (MCFC)
- Solid Oxide Fuel Cell (SOFC)
- Proton Exchange Membrane Fuel Cell (PEMFC)

Additionally, two other types of fuel cells-Direct Methanol Fuel Cells (DMFC) and Alkaline Fuel Cells (AFC)-are primarily used for transportation and non-stationary applications, however, these technologies are beyond the scope of this study [7].

B. *Technology Description*

As previously mentioned, fuel cells generate direct current (DC) electricity through an electrochemical process similar to that of a battery. However, unlike batteries, fuel cells are continuously supplied with fuel, allowing them to operate indefinitely as long as the reactants are replenished. Typically, hydrogen (H_2) and oxygen (O_2) serve as the reactants. Hydrogen is often derived from hydrocarbon fuels such as natural gas or liquefied petroleum gas (LPG), while oxygen is sourced from ambient air [8].

Figure 1 depicts a single fuel cell unit, which consists of three main components: a cathode (positive electrode), an anode (negative electrode), and an electrolyte. Hydrogen is introduced to the anode, and oxygen at the cathode. In the presence of a catalyst at both electrodes, chemical reactions (1) and (2) occur, producing ions and electrons. These reactions generate direct current electricity along with water as a byproduct [8].

The voltage output from a single fuel cell unit is relatively low, typically less than 1 volt DC. For practical applications, hundreds of individual cells are assembled into a series, or "stacked," to achieve usable voltages, typically ranging between 200 and 400 volts DC [8].

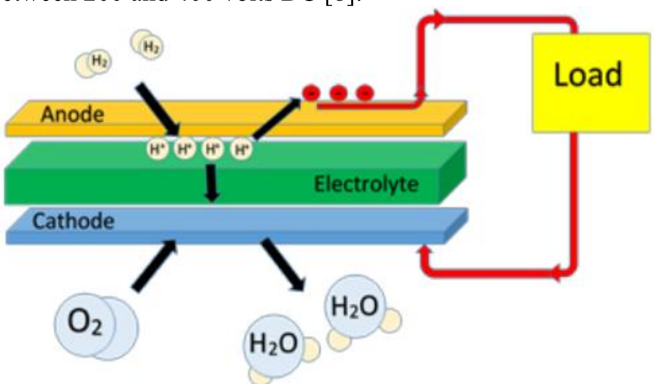

Fig. 1 Fuel Cell electrochemical process

At the anode, the hydrogen gas is electrochemically dissociated (in the presence of a catalyst) into hydrogen ions ($H+$) and free electrons ($e-$) [8].

$$\text{Anode Reaction: } 2H_2 \rightarrow 4H^+ + 4e^- \quad (1)$$

The electrons flow out of the anode through and external circuit. The hydrogen ions flow into the electrolyte layer and eventually to the cathode, driven by both concentration and potential forces. At the cathode the oxygen gas is electrochemically combined (in the present of a catalyst) with the hydrogen ions and free electrons to generate water.

$$\text{Cathode Reaction: } O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (2)$$

The overall reaction in a fuel cell is as follows:

$$2H_2 + O_2 \rightarrow 2H_2O \text{ (vapor)} + \text{Energy} \quad (3)$$

During power generation in a fuel cell, electrons travel through the external circuit, ions move across the electrolyte layer, and chemical reactants flow into and out of the electrodes. Each of these processes encounters inherent resistances, which reduce the operating cell voltage below its theoretical maximum. Additionally, irreversible processes can impact the open-circuit voltage. As a result, part of the chemical potential energy is converted into heat instead of electricity. The electrical power output of the fuel cell is calculated as the product of the current, measured in amperes, and the operating voltage [8].

C. *Applications*

Fuel cells are currently available or under development for a wide range of applications, including power generation. These applications encompass commercial and industrial combined heat and power (CHP) systems, pure electrical generation, residential and commercial CHP systems, backup power, and portable energy solutions. However, due to the high installation costs of fuel cell systems, the most practical and economically viable distributed generation (DG) application is CHP [8].

CHP systems generate on-site power while capturing and utilizing by-product heat. The quality of this heat depends on the type of fuel cell and its operating temperature. For instance, Proton Exchange Membrane Fuel Cells (PEMFC) and Direct Methanol Fuel Cells (DMFC) operate below 200°F, producing low-quality heat. This study focuses on Solid Oxide Fuel Cell (SOFC) technology, which operates at higher temperatures (1,200–1,800°F) and offers better heat quality for CHP applications [8].

Several studies have explored the potential of SOFC-CHP systems in different applications, highlighting their advantages and challenges. For instance, Mariella Provenzano examined their use in upscale European hotels, finding that while these systems can significantly reduce emissions and achieve energy independence, their high costs and long return on investment make government financial incentives crucial for widespread adoption [9]. In Hong Kong, Meng Ni and Julia Meng demonstrated that integrating an absorption chiller with a cogeneration system could increase efficiency from 84% to 94%, effectively transforming a CHP system into a Combined Cooling, Heating, and Power (CCHP) system, though the payback period ranged from 4 to 10 years [10]. Similarly, Alexandro Arsalis and George Georghiou investigated the combination of SOFC systems with photovoltaic (PV) systems for commercial buildings, including hotels, showing that this integration reduced CO_2 emissions by 36% and achieved an electricity generation cost of $0.1053 USD per kWh, illustrating its potential for energy independence and climate change mitigation [11].

For residential CHP applications, Braun et al. studied five different SOFC-CHP configurations tailored to meet the heating and water needs of U.S. households. Their research concluded that systems incorporating both cathode and anode gas recirculation, along with internal methane reforming, could achieve a CHP efficiency of 79% [12].

These studies collectively underscore the versatility and potential of SOFC-CHP systems in various settings, from hotels to residential applications. With continued innovation and financial support, fuel cell technology could play a pivotal role in achieving energy independence and reducing carbon emissions.

III. Methodology

A. *Data Collection*

The Puerto Rico Energy Center (PREC) provided utility consumption data from five hotels located in different regions of Puerto Rico, covering a complete fiscal year. The dataset was compiled from billing records issued by the corresponding utility providers: LUMA for electricity, the Puerto Rico Aqueduct and Sewer Authority (AAA, by its Spanish acronym) for water, and individual suppliers for gas. Each variable comprises 60 observations, reflecting monthly consumption across all sites. The coefficient of variation (CV) for total consumption is 27%, indicating a moderate level of dispersion among the measured variables. This level of variability suggests sufficient consistency in consumption patterns to support the development of an initial cogeneration model for hotel energy use in Puerto Rico, particularly for preliminary feasibility assessment and system sizing applications.

The primary goal of this study is to create a comprehensive load profile for the hotel sector, which will serve as a baseline for evaluating the feasibility of implementing a Solid Oxide Fuel Cell Combined Heat and Power (SOFC-CHP) system.

The load profile and gas consumption trends, analyzed in relation to hotel occupancy rates, are presented in Fig. 2 and 3, respectively.

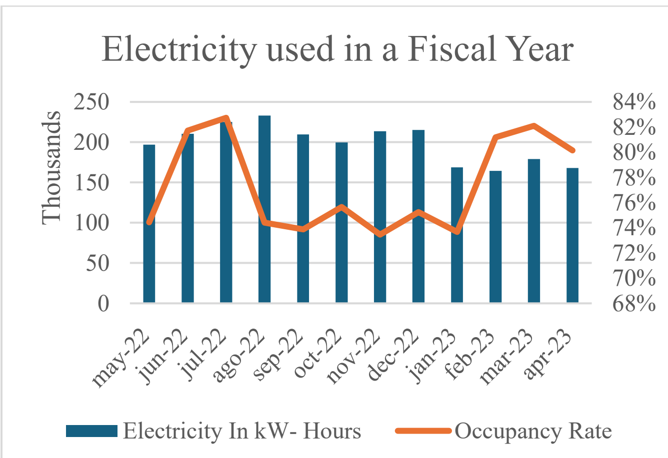

Fig. 2 Average electricity used vs Occupancy rate during a fiscal year

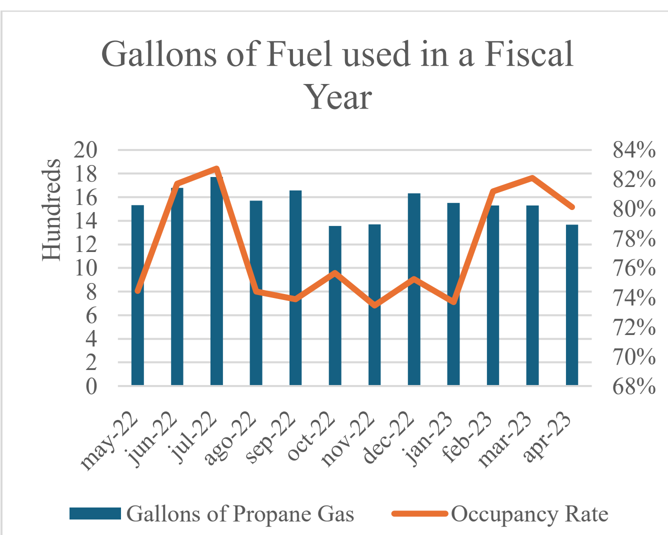

Fig. 3 Average gas consumption vs Occupancy rate during a fiscal year

Based on the data collected and the analysis of Fig. 2 and 3, it can be concluded that the occupancy rate of the hotels has a minimal impact on electricity and gas consumption, as the variation observed in the hotels studied is less than 10%.

B. Data Analysis

To analyze the consumption data and begin evaluating cogeneration opportunities within the sector, the collected information was synthesized into the graphs shown in Fig. 4 and 5. These graphs provide a clear overview of the sectors utilizing the highest amount of resources and offer valuable insight into the approach that should be taken when assessing cogeneration potential. Based on these graphs, key factors can be identified to design the cogeneration system and evaluate its efficiency and feasibility.

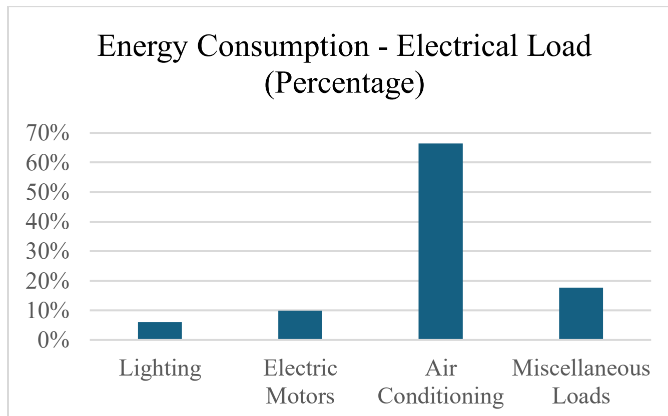

Fig. 4 Average distribution of energy consumption from the five hotels analyzed.

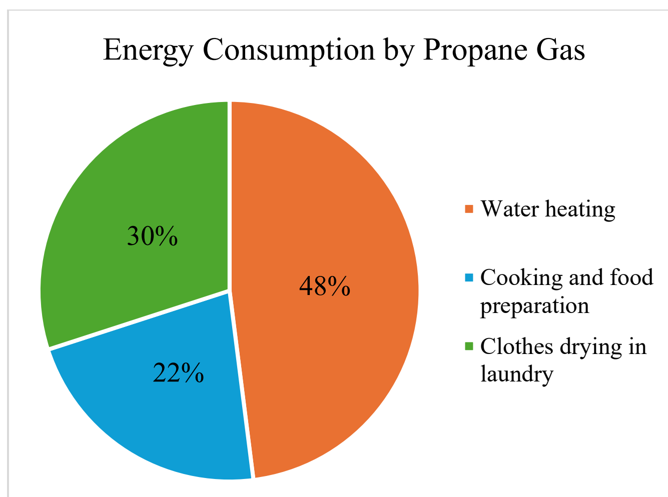

Fig. 5 Average distribution of propane gas consumption from the five hotels analyzed.

A significant potential for cogeneration systems emerges from the air conditioning demands of buildings, which account for over 60% of energy consumption in the industrial sector in tropical climates like Puerto Rico.

C. SOFC-CHP System

To achieve the highest possible efficiency in the CHP system, the following considerations were made [13]:

1. The proposed cogeneration system must align with the current heat requirements to ensure cogeneration plants operate with a higher capacity factor.
2. The primary mover (SOFC) should be capable of meeting total or partial energy requirements, provided the thermal demands are satisfied. Importing energy from the local grid (LUMA) is preferred when necessary.
3. The cogeneration plant was sized based on the yearly average of thermal energy requirements, rather than peak demand, to optimize efficiency.
4. Trigeneration systems are deemed viable due to the high air conditioning loads. In this setup, both air conditioning and/or chilled fluid will be generated from the waste heat of the fuel cell. Lithium bromide (LiBr) absorption chillers will primarily be used for air conditioning in the trigeneration system.

Based on the consumption data collected from the hotels, a summary of the annual average consumption has been compiled, as shown in Table I. This data will serve as the foundation for sizing the proposed system.

TABLE I
SUMMARY OF ANNUAL AVERAGE CONSUMPTION

Yearly Hours	**Yearly Average Energy Consumed (kWh)**	**Yearly Average Energy Consumed in gas (MMBTU)**	**Yearly Average Energy Consumption for Hot Water and Laundry (MMBTU)**
8,760	2,436,232.80	1,697.63	1,324.15

Two models for a cogeneration system have been identified as the most promising. The first model uses a solid oxide fuel cell (SOFC) as the primary mover, with its waste heat repurposed to produce hot water and steam for water heating and laundry drying. The second model also employs an SOFC as the primary mover, but its waste heat is directed to power an absorption chiller.

For this feasibility study on the use of fuel cells in the hotel industry, the focus will be on the first model, which utilizes waste heat to generate hot water and steam. The feasibility assessment will rely on data from existing commercially available systems provided by the Department of Energy (DOE), as well as literature on simulated or studied SOFC systems.

The DOE has provided data for an SOFC combined heat and power (CHP) system with a capacity of 1.5 kW. As shown in Table II, we will use the fuel consumption inlet data from this system as the basis for our analysis.

TABLE II
COMMERCIALLY AVAILABLE FUEL CELL SYSTEM [8]

Performance Characteristics	System 1	System 2	System 3	System 4	System 5
Fuel Cell Type	PEMFC	SOFC	MCFC	PAFC	MCFC
Nominal Electricity Capacity (kW)	0.7	1.5	300	400	1,400
Net Electrical Efficiency (%), HHV)	35.3%	54.4%	47%	34.3%	42.5%
Fuel Input (MMBtu/hr), HHV	0.0068	0.0094	2.2	4.0	11.2
Total CHP Efficiency (%), HHV	86%	74%	82%	81%	82%
Power to Heat Ratio	0.70	2.78	1.34	0.73	1.08
Net Heat Rate (Btu/kWh), HHV	9,666	6,272	7,260	9,948	8,028
Exhaust Temperature (°F)	NA	NA	700	NA	700
Available Heat (MMBtu/hr)	NA	NA	0.78 (to 120°F)	0.88 (to 140°F)	3.73 (to 120°F)
Sound (dBA)	NA	47 (at 3 feet)	72 (at 10 feet)	65 (at 33 feet)	72 (at 10 feet)

For the 1.5 kW SOFC system, no data is provided regarding the availability of heat recovery. However, according to [11], it can be estimated that 40% of the fuel input energy is available for heat recovery. This estimation is based on the average thermal-to-energy efficiency and the operating temperature, which is approximately 1,380°F. This provides a thermal output of 0.00376 MMBtu/hr for every 1.5 kW system, with a corresponding fuel input of 0.0094 MMBtu/hr.

A SOFC system was sized to meet the peak electrical demand of the hotel, ensuring that the unit can supply the full on-site electrical load under all operating conditions, with no reliance on grid electricity during normal operation. Given that SOFC systems achieve optimal performance and durability under steady-state conditions, selecting a capacity above the maximum hotel demand allows continuous operation without part-load efficiency penalties. Larger SOFC systems were favored due to economies of scale, which reduce installation costs and lower the cost of electricity generation [14].

In addition to electrical considerations, the system capacity was selected to produce a level of recoverable thermal energy compatible with the hotel's year-round domestic hot water and auxiliary thermal demands, thereby maximizing combined heat and power (CHP) utilization. Based on the hotel load characteristics and the availability of commercially scalable SOFC systems, a 280 kW unit was selected as a representative and technically appropriate primary mover for this study. The operating parameters of the selected SOFC system are summarized in Table III.

TABLE III
PARAMETERS OF THE SOFC PRIMARY MOVER

Net Power (kW)	280
Fuel Input (MMBtu/hr) HHV	1.755
Net Electrical efficiency	54%
Available Heat (MMBtu/hr)	0.702
Total CHP efficiency	74%

IV. Financial Considerations

The most effective way to assess the feasibility of the project is by analyzing its economic benefits. To do this, two fundamental factors must be considered. The first is comparing the cost of the generated energy with the purchasing cost from the grid operator. The second is evaluating the project's return on investment (ROI).

To achieve this, it is essential to account for the costs associated with equipment, installation, and ongoing operation and maintenance. Based on references from the Department of Energy (DOE), the capital and O&M costs are summarized in Table IV.

TABLE IV
SOFC CAPITAL AND O&M COST

Total Installed Cost ($/kW)	3,000
Non-Fuel O&M ($/kWh)	0.055
Total kW	280
Total kWh	2,452,800
Total Installed Cost ($)	840,000
Total Non-Fuel O&M ($)	134,904
Energy Rate ($/kWh)	0.27
Total Natural Gas Consume (MMBTU)	15,371
Total Gallons/year of Natural Gas	153,709
Gas Rate ($/MMBtu)	7.19

A key criterion for deciding to self-generate energy instead of purchasing it from the grid operator is the comparison between the current purchasing price and the self-generation cost. To calculate the cost of energy production for self-consumption, the Levelized Cost of Energy (LCOE) can be used as follows [15]:

$$\left(\frac{\$}{kWh}\right) = \frac{Total\ Inst.\ Cost*(\%\ Annuity)+Total\ O\&M\ Cost+Fuel\ Cost}{Total\ Energy\ Produce\ (kWh)} \quad (4)$$

In this case, the annuity is assumed to be 5% of the total installation cost of the project, as cogeneration projects often benefit from reductions in pollutants and increased energy efficiency. Using this percentage, we calculate an energy cost of $0.12/kWh. Comparing this value with the current purchase cost of $0.27/kWh from the grid operator yields a promising result.

The second factor to evaluate is the simple rate of return, which requires calculating annual savings and comparing them with the installation costs. Since the SOFC-CHP system can produce slightly more energy than needed, no energy is purchased from LUMA in this analysis. Additionally, excess energy is not considered for sale to LUMA in this evaluation. However, this represents a future point of analysis that could further reduce the project's simple payback period.

The current system, without self-production of energy, relies on propane gas as the fuel for combustion and purchases the entire energy demand from the grid operator. The price of propane is provided by the supplier, while the cost of energy is determined by LUMA. The current costs for energy and propane gas are presented in Table V.

TABLE V
CURRENT COST OF ENERGY AND GAS

No Cogeneration	
Total Energy Used from the Grid (kWh)	2,436,232.80
Price ($/kWh)	0.27
Total Price of Energy ($)	657,782.86
Total Gas Used (gal)	18,553.33
Price ($/gal)	2.10
Total Price of Gas ($)	38,962.00
Summing Energy and Gas ($)	696,744.86

As previously established, the cogeneration system will not produce excess energy. The performance results and the annual estimated savings from implementing the self-generated SOFC-CHP system are presented in Table VI.

TABLE VI
ESTIMATED COST FOR THE INSTALLED SYSTEM AND SAVINGS

Cogeneration	
Total Energy Used from the Grid (kWh)	-
Price ($/kWh)	0.27
Total Energy Produced (kWh)	2,436,232.80
Price ($/kWh)	0.12
Total Price of Energy ($)	285,479.27
Total Gas Used (MMBtu)	15,371
Price ($/MMBtu)	7.19
Total Price of Gas ($)	110,516.63
Summing Energy and Gas ($)	395,995.90
Annual Estimated Savings ($)	300,748.96

$$Simple\ Payback = \frac{Total\ Installation\ cost}{Annual\ Estimated\ Savings} \quad (5)$$

Using the total installation cost of $840,000 and annual savings of $300,349, we calculate a simple payback period of 2.79 years. Despite these promising results, projects involving CHP systems often use Power Purchase Agreements (PPA). Under a PPA, a third party invests in the infrastructure and installation, then sells the generated energy to the hotels over a fixed term. These agreements make the project even more attractive by addressing the high initial costs of installation and implementation.

V. CONCLUSIONS

This study analyzed the use of a solid oxide fuel cell (SOFC) as the primary mover in a cogeneration system for hotel applications to evaluate its feasibility. Due to the higher installation costs of low-nominal-power SOFC systems, a 280kW system was proposed based on the hotel load profile data. This system would meet both electrical and thermal needs, with the thermal output used to provide hot water and generate steam for laundry purposes.

The results indicate that an installation cost of $840,000 is required. However, the energy produced by the SOFC-CHP system is significantly cheaper than the current energy price from the grid operator ($0.12/kWh compared to $0.27/kWh). This substantial difference results in annual savings of over $300,000, yielding a simple payback period of 2.79 years for the system.

Additionally, projects involving SOFC-CHP systems often benefit from Power Purchase Agreements (PPA). Under the PPA, a third-party funds the infrastructure and installation costs and sells the energy to the hotel at a fixed rate over an agreed period. This arrangement significantly reduces the financial burden of the high initial installation cost, making the project even more attractive while maintaining the long-term benefits of reduced energy expenses.

Future work is needed to further improve the feasibility and applicability of the system. Areas for exploration include integrating an absorption chiller to utilize waste heat for cooling applications, simulating SOFC performance using advanced modeling tools, and evaluating the use of alternative fuels such as propane to enhance flexibility and reduce operational costs.

ACKNOWLEDGMENT

The author would like to thank the supervisor, Professor Amaury Malavé, for his guidance, support, and insightful feedback throughout the research process. His commitment to academic excellence, attention to detail, and involvement in off-campus research projects played a significant role in the development of this paper

The author also acknowledges the faculty and staff of the Department of Mechanical Engineering and the Graduate Program at Universidad Ana G. Méndez–Gurabo for providing valuable resources and technical support.

REFERENCES

[1] National Oceanic and Atmospheric Administration (NOAA), "Climate change impacts," Nov. 8, 2023. Available: https://www.noaa.gov/education/resource-collections/climate/climate-change-impacts

[2] U.S. Department of Energy, "Recuperación y modernización de la red eléctrica de Puerto Rico." Available: https://www.energy.gov/gdo/recuperacion-y-modernizacion-de-la-red-electrica-de-puerto-rico

[3] A. Santa, "En aumento la cantidad de apagones y su frecuencia, revela informe trimestral de LUMA," Metro Puerto Rico, Apr. 26, 2024. Available: https://www.metro.pr/noticias/2024/04/26/en-aumento-la-cantidad-de-apagones-y-su-frecuencia-revela-informe-trimestral-de-luma/

[4] EFE S.A., "Puerto Rico sobrepasa en un 24% los ingresos en hospederías frente a datos de 2021 y 2022," Swissinfo, Aug. 22, 2023. Available: https://www.swissinfo.ch/spa/puerto-rico-sobrepasa-en-un-24-los-ingresos-en-hospederías-frente-a-datos-de-2021-y-2022/48753614

[5] U.S. Environmental Protection Agency, "Combined Heat and Power Partnership," Mar. 2019. Available: https://www.epa.gov/chp

[6] M. Mankour and M. Koulali, "Simulation and characterization of SOFC fuel cell model," *Przeglad Elektrotechniczny*, no. 7, pp. 1–6, 2022.B.

[7] B. Magro and S. P. Borg, "A feasibility study on CHP systems for hotels in the Maltese Islands: A comparative analysis based on hotels' star rating," *Sustainability*, vol. 15, no. 2, Art. no. 1337, 2023.

[8] U.S. Environmental Protection Agency, "Catalog of CHP technologies: Section 6—Technology characterization—Fuel cells," Mar. 2015.

[9] M. Provenzano, "Analysis of the energy consumption in the hotel sector and feasibility study for the installation of SOFC-based cogeneration systems," M.S. thesis, 2021.

[10] J. M. P. Chen and M. Ni, "Economic analysis of a solid oxide fuel cell cogeneration/trigeneration system for hotels in Hong Kong," *Energy and Buildings*, vol. 75, pp. 160–169, 2014.

[11] A. Arsalis and G. E. Georghiou, "A decentralized hybrid photovoltaic–solid oxide fuel cell system for application to a commercial building," *Energies*, vol. 11, no. 12, Art. no. 3512, 2018, doi: 10.3390/en11123512.

[12] R. J. Braun, S. A. Klein, and D. T. Reindl, "Evaluation of system configurations for solid oxide fuel cell-based micro-combined heat and power generators in residential applications," *Journal of Power Sources*, vol. 158, no. 2, pp. 1290–1305, 2006, doi: 10.1016/j.jpowsour.2005.10.064.

[13] M. R. Pelaez-Samaniego et al., "Potential and impacts of cogeneration in tropical climate countries: Ecuador as a case study," *Energies*, vol. 13, no. 20, Art. no. 5254, 2020.

[14] M. L. Pierre, T. Abdelwahed, A. O. Eric, and R. Nabila, "Mathematical modeling of re-electrification by green hydrogen storage through the PEM fuel cell integrating a 10-year economic study applied to a hotel," in *E3S Web of Conferences*, vol. 246, 2021, Art. no. 01038.

[15] P. Duffy et al., "Wind energy costs in Puerto Rico through 2035," Nat. Renew. Energy Lab. (NREL), Golden, CO, USA, Tech. Rep. NREL/TP-5000-83434, 2022.