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Hybrid power system for distributed energy deploying biogas from municipal solid waste and photovoltaic solar energy in Mendoza, Argentina

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Abstract. The emission of greenhouse gases (GHG) generated from landfill biogas causes critical environmental and social issues. However, efficiently capturing and using biogas can reduce its environmental impact. In the metropolitan area of Mendoza, around 1,300 tons of municipal solid waste (MSW) are generated daily, and 65% of it goes to the El Borbollón landfill. The aim of this study was to present the results of implementing the first hybrid system for electricity generation from biogas and solar energy in a landfill. This alternative solution allows responsible management of MSW and diversifies the regional energy matrix. The production of biogas, its collection, conduction, treatment, conditioning for combustion, and electrical engineering aspects are analyzed within the technological complex operating under a grid-connected generation system. The results of the study show that with an average annual generation of 6,387 MWh/year and a reduction of GHG emissions between 44.1% and 70.5%, the use of MSW biogas in small cities can also be carried out as a climate change mitigation strategy in the framework of distributed generation.

1 Introduction

In Argentina, the Urban Solid Waste (USW) generation rate per inhabitant is 1.15 kg/day, and the organic fraction constitutes between 40% and 50% of the total [1]. However, the organic waste generated in larger quantities is the least managed [2]. This leads to problems of a diverse nature, such as the production of greenhouse gases (GHG) and leachates, contamination of water bodies, proliferation of human disease vectors, and the loss of potential energy stored in Municipal Solid Waste (MSW).

To address this issue, Mendocina Energy Company SAPEM (EMESA) and Environmental Technology and Services S.A. (TySA) developed the Power Generation Hybrid System from Biogas and Solar Photovoltaic (PGHS) in the Gran Mendoza area. This area is made up

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of the departments of Ciudad de Mendoza, Godoy Cruz, Guaymallén, Maipú, Las Heras and Luján de Cuyo.

The PGHS project, which was commissioned in November of 2020, has the triple benefits of reducing energy consumption in MSW management in Mendoza, and therefore obtaining a high added-value product with environmental, economic, and social development benefits. These benefits include distributed electric energy of renewable origin, contributing to the energy security of the population of the province of Mendoza, as well as the diversification of its energy matrix. Currently, the electricity generated in the province is mainly based on fossil sources. In 2022, 69.52% of the generated electricity came from processes using fossil fuels, 29.89% from hydraulic processes, and only 0.59% from renewable sources using solar photovoltaic (PV) technology. The whole generation process involved the consumption of 542,677 TeP of natural gas and 4,065 TeP of fuel oil [3].

On a socio-environmental scale, the PGHS project promotes compliance with Sustainable Development Goals (SDG) 7, 8, 9, 11 and 13 of the United Nations Agenda 2023 [4] as the PGHS project aims to increase social awareness of the problem of open dumping of MSW as a global issue. It highlights the benefits and opportunities that come with a more efficient and responsible management of MSW disposal, with the environmental and economic incentives caused by renewable electricity generation. These incentives are achieved through the capture of GHG, mainly methane, reducing the environmental impact in the treatment and transformation of MSW. In Mendoza, MSW is generated in an average of 1,800 tons per day, 1,300 of which correspond to the metropolitan area or Gran Mendoza, and in turn, 65% of which are dumped in El Borbollón landfill [5]. These generation volumes align with the national average generation rate of 1.15 kg/inhabitants/day (kilograms per inhabitant per day) [6].

The overall objective of this work is to present the results of the implementation of the PGHS case study, based on the appraisal and use of MSW from El Borbollón landfill in the province of Mendoza, Argentina, as an alternative solution for responsible management of MSW. The particular objectives of the work are adjusted to set a precedent for the hybridization of renewable energy generation technologies in a context of technical, political, environmental and social complexities. The project serves as a model of a pioneer success case in the region, contributing with strategies and solutions in several aspects such as MSW biogas production -with its predictive model of potential production-, the biogas collection and conduction system, and its treatment and conditioning for its subsequent combustion and generation of electric energy. Finally, within the PGHS framework the methodology used for this work is intended to make a contribution to applied science in pilot scale developments at the regional level. The current project appeals to technology and knowledge transfer to society.

2 Materials and methods

Municipal Solid Waste landfills can be categorized into three types namely, open dumps, semi-controlled landfills, and sanitary landfills [7]. Open dumps are areas where MSW is dumped uncontrolled in the open air. Semi-controlled landfills are managed landfills where waste is dumped in cells, all crushed, leveled, and coverage with soil. Although these landfills generate less odor than open dumps due to the topsoil cover, they are not designed to capture gas emissions or leachate discharge [7].

In contrast, the landfill in this case study, El Borbollón, is an improved version of the semi-controlled landfill. It allows for the classification, segregation, size reduction, and densification of MSW on-site. Moreover, it has facilities designed to capture the biogas generated by the natural anaerobic digestion of the decomposition of the organic fraction of MSW (OFMSW).

The production of MSW biogas or landfill gas is due to thermal, chemical, and biological conditions, which give rise to the mechanism of formation of this type of gas through various reactions such as hydrolysis, fermentation, anaerobic oxidation, acidogenesis, acetogenesis, and methanogenesis. Among the diverse and prolific bacterial communities involved in the anaerobic digestion of OFMSW in a landfill [8], methanogenic bacteria are mainly responsible for biogas formation. Biogas can contain approximately 40% methane (CH_4) and 45% carbon dioxide (CO_2) [9], followed by traces of carbon monoxide (CO), nitrogen (N_2), volatile organic compounds, benzene, toluene, xylene, carbon tetrachloride, hydrocarbons, organo-sulfur compounds [7], and non-methane organic compounds (NMOC) [10,11].

2.1 Predictive model for landfill methane production potential

This study utilizes LandGEM (Landfill Gas Emission Model) which is a predictive model developed by the United States Environmental Protection Agency in 2005 [12]. The model relies on a first-order kinetic decomposition equation (Eq. 1), assuming that methane generation is a direct function of the quantity of MSW (Municipal Solid Waste) landfilled. It also takes into account the previous years' methane generation by MSW landfilled, in addition to the current year's methane generation. This enables accurate estimation of methane generated by landfills, [13].

$$Q_{CH_4}= \sum_{i=1}^{n} \sum_{j=0,1}^{1} k \cdot L_0 \cdot \left(\frac{M_i}{10}\right) \cdot e^{-kt_{ij}} \qquad (1)$$

where Q_{CH4} is the annual methane generation in (m^3_{CH4}/yr); Mi is the average amount of waste disposed in the landfill in year i measured in (t/yr); k is the methane generation rate constant measured in (yr^{-1}), which depends on the location's rainfall; L_0 is the methane generation potential (m^3_{CH4}/t); i is the temporal increment of 1 year; j is a temporal increment of 0.1 years; and tij is the age of the jth waste section accepted in year i. In turn, the LadnGEM model intrinsically contemplates the f_{CH4} factor, the fraction of methane contained in the biogas (%) (this fraction for our case study is shown in the results section in Table 1). It was considered, in turn, within the model that the landfill's closure will be in the year 2040. By that time, the province of Mendoza will have reached a projected population of 2,328,963 inhabitants, of which 1,435,434 will corresponding to the Gran Mendoza area [14]. For our case study, the k factor takes the value 0.02 yr^{-1} and L_0 takes the value 60 m^3/t [15,12], in consideration of the location of the El Borbollón landfill, where the annual average accumulated precipitation remains at values close to the average of the last ten years (244.2 mm) [16].

2.2 Caption, conduction, treatment and conditioning system of urban solid waste biogas for combustion

Fig. 1 shows the main characteristics of the PGHS. In order to capture the biogas generated effectively, a collection system was designed. This system consists of vertical collectors made up of circular metallic structures with large diameters that are in direct contact with the waste. The collectors are also made up of concentric plastic pipes, one perforated inside and one outside, that enable the biogas to flow from the base of the cell to the surface. The biogas is then conveyed to a network of pipes on the surface that transport it to the treatment and conditioning stage.

The collected biogas is taken into the treatment and conditioning room, where it passes through a primary dehydrator, removing its moisture content partially or entirely. The biogas can be incinerated in two ways. Firstly, it can be burned entirely in a hidden flame torch, which was the only way before developed and commissioned the PGHS project. Alternatively, the biogas can be incinerated in microturbines that make up the electric power generation system. However, the biogas must be conditioned before entering this system. This involves filtering the content of solid particles, water, and lubricants using the compression assembly (Bio-Komp). It is also necessary to ensure that the biogas has a low siloxane content in all its families (maximum 5 ppb) and a biogas pressure of 5.5 bar at the microturbine inlet flange. [17,18].

2.3 Power generation hybrid system

This project was designed to comply with the Distributed Generation regulations in the Province of Mendoza, which have been in place since 2015 and are currently regulated by Resolution 01/2022 [19]. This regulation has allowed PGHS to become the first project in Mendoza and in Argentina to use the Injection Solely Point (ISP) format and the first project in Argentina to integrate distributed electricity generation from MSW biogas and solar sources. The ISP generation system is installed at a location other than the user's supply point, with at least one associated supply to apply the Compensation Mechanism (monetization), which considers the electricity tariff of the associated supply(s) in the proportion declared for each one in the Distributed Energy Resource Contract [19].

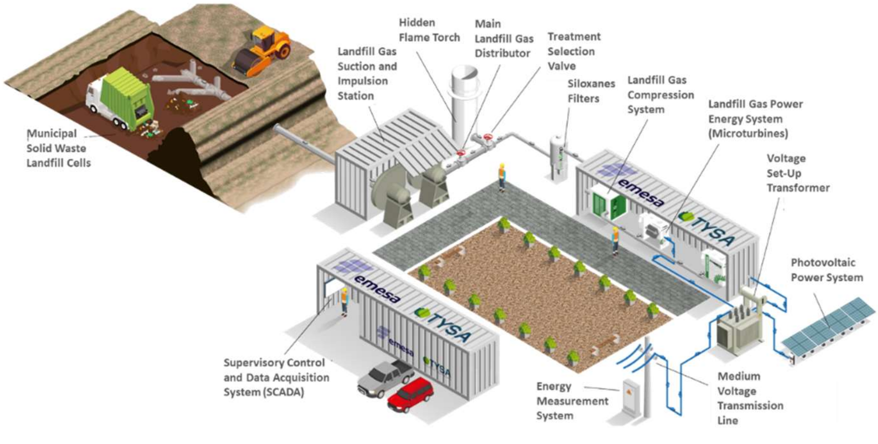

Fig. 1. Infographics of the Power Generation Hybrid System from Biogas and Solar Photovoltaic - El Borbollón. Mendoza. Argentina. Own work.

Several biological conversion technologies can be used to generate electric power from biogas from MSW, as stated by [20], and some studies, such as [21], and [22], have shown that landfill biogas can be used to generate electricity. This type of biogas is usually a viable technological alternative in municipalities with more than 200,000 inhabitants,

according to [23].

For our project, we calculated the theoretical potential of electricity generation by MSW biogas recovery (PEGLFG_MSW) using a mathematical model, Eq. 2 [24]. In this article, we have used energy units in MWh to simplify the analysis,

$$PEG_{LFG\_MSW} = LHV_{LFG\_RSW} \cdot Q_{CH_4} \cdot \gamma \cdot \eta \tag{2}$$

$$LHV_{LFG\_MSW} = f_{CH_4} \cdot LHV_{Methane} \tag{3}$$

where PEG_{LFG_MSW} is the theoretical potential of electricity generation by MSW biogas recovery measured in (MWh/year); LHV_{LFG_MSW} is the lower heating value of biogas in (MWh/m^3); Q_{CH4} is the annual methane generation in (m^3/yr) given by Eq. 1; γ is the efficiency of the biogas recovery system (%), which can be low (<50%), medium (60%) or high (80%). η is the electrical efficiency of the technology used to generate electricity (%). In our case, γ takes the value of 50%, according to [24], and η takes the value of 29%, according to information from the technology manufacturer [25]. Then, the lower heating value of MSW biogas is calculated with Eq. 3, where f_{CH4} (%) is the fraction of methane contained in MSW biogas, and $LHV_{Methane}$ is the lower heating value of methane. In our case, the value reported by National Gas Regulatory Entity [26] is taken. Since f_{CH4} and the lower heating value of biogas (LHV_{LFG_MSW}) can vary according to the age of the landfill and the quality of the municipal solid waste, it is advisable to take periodic samples of the biogas generated in order to verify its gas quality before combustion. The analysis methodology applied to perform this quality verification is by gas chromatography with thermal conductivity detector by the system of normalized areas using certified quality standards for the determination of response factors, where the equipment used is a SHIMADZU GC-9A gas chromatograph with thermal conductivity detector and 2-meter Porapac Q column. Considering the maximum value of the percentage of methane (f_{CH4}), indicated in Table 1 of the results section, and replacing the values we obtain,

$$LHV_{BG\_RSU} = 0{,}003204 \, {}^{MWh}\!/_{m^3} \tag{4}$$

The technology selected for this project was gas microturbines capable of operating with the particularities of landfill biogas, referring to its low heating value and possible siloxane content [27, 28]. Two Capstone Green Energy microturbines, model C65, are being used in a Grid Connect configuration, with each turbine having a capacity of 65 kW (under ISO conditions: 15°C; 14,69psia, 60% RH <Relative Humidity>). This technology is pioneering in the region, with these microturbines being the first to operate with landfill biogas in Mendoza, Argentina, and in Latin America. Capstone has only two similar projects in other parts of the world, one in Rubi, Spain and the other in La Ciotat, France [29].

Each microturbine is a stationary power generation system that provides on-site electrical power. Each turbine can generate power in parallel with the utility grid (Grid Connect mode) or isolated from it (Stand Alone mode). The unit consists of a turbine, a solid-state power electronics system, and a fuel system. Because the microturbines are confined in a 12m long (40ft) sea container, an external fan is provided to blow excess air inside the enclosure. This ensures that the microturbines have the required amount of air for the correct combustion of the biogas and cooling of the power electronics. The standard litres per minute for the air and the power electronics are 26,300 slpm and 14,200 slpm, respectively. The main components of the turbine are shown in Fig. 2 in its cross-section and Fig. 3 in its simplified functional diagram. The compressor runner, turbine, and generator rotor are mounted on a single shaft [25], as noted below.

On the other hand, electric power from solar PV technology is generated in a grid-connected photovoltaic system, involving voltage and frequency references from the public power distribution network [30].This system, which was designed just for the merely goal of accomplish the “hybrid” feature of the project, not to accomplishing a generation or efficiency target, is composed of 16 LV-Energy PV modules, model LVE72PSe, with a peak power of 330 Wp (in STC conditions), which are connected to a SMA inverter, model Sunny

Tripower 5000TL, in two strings of 8 modules each. The PV modules are arranged on a metallic structure directly driven on the surface of a landfill cell already closed, with a fixed inclination of 30º, which allows optimal use of the incident solar radiation of the site [31]. In this case study, the electricity generated by this technology was self-consumed by the project's building and auxiliary service facilities. In the event of energy surpluses, it was fed into the public distribution network, generating an economic credit on the contracted electricity service [19]. Likewise, worldwide, photovoltaic systems in distributed generation are conceived as an energy efficiency strategy since they allow taking advantage of the availability of electricity generated mainly by renewable sources to improve the efficiency of using other energy sources [32].

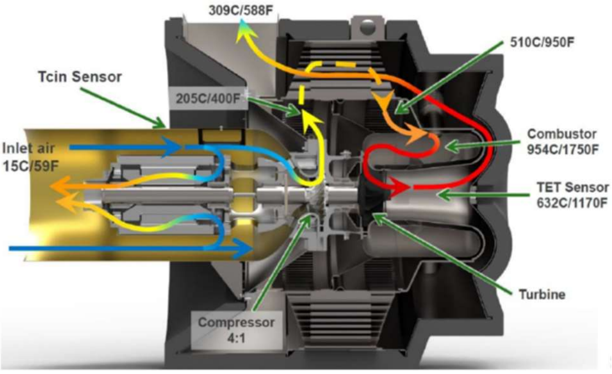

Fig. 2. Cross section of the turbine with airflow indication. Source: Capstone Green Energy (2021).

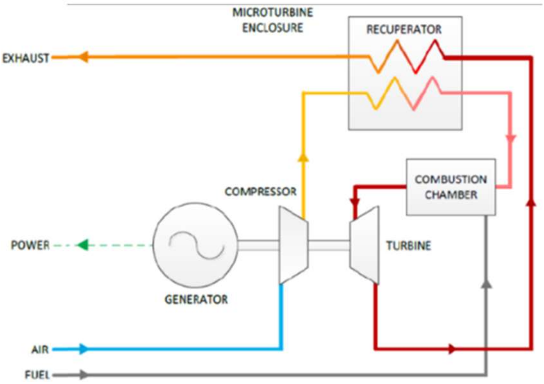

Fig. 3. Simplified functional diagram. Capstone Green Energy Microturbine, model C65-GC. Source: Capstone Green Energy (2021).

Each stage or subsystem of the technological set had its independent electrical protections, and, in turn, the whole set has power electrical protection systems that hybridize generation technologies while providing safe operation conditions for personnel and equipment. In turn, the electrical protections, field sensors, current inverters, variable-frequency drivers, and emergency shutdowns of both the biogas generation system and the PV system are linked to a Supervisory Control and Data Acquisition (SCADA) system, which is responsible, through a Programmable Logic Controller (PLC), for automatically coordinating all the electrical protections, field sensors, current inverters, frequency variators, and emergency shutdowns of both the biogas generation system and the PV system. The SCADA system is responsible, through a PLC, for automatically coordinating all the systems and elements mentioned above, as well as for managing the interlocks, permitting the closing of power switches, indicating alarms and taking the system out of operation in the event of failure or an explosive atmosphere due to methane accumulation.

The electrical energy generated by both renewable sources is evacuated through a step-up power transformer, which takes the generation output voltage (0.4 kV) to the 13.2 kV required to transport such energy through a 1.2 km long medium voltage line (MVL) to the measurement point outside the project site under analysis. Likewise, in order to comply with the requirements demanded by the electricity distribution company and the provisions of EPRE Resolución 01/2022 on technical matters, two Tavrida model Rec15/25_Al1_5p medium voltage automatic reclosers were installed at both ends of the MVL, one at the transformer outlet (generation side) and the other at the interconnection of the internal MVL with the distribution service MVL (distribution side).

The parameterization of the protection functions of the recloser's electronic controller first required the realization of a Study, Calculation and Adjustment of Protections (SCAP) that allowed the coordinated operation between the protections of both ends of the MVL and also between the closest protections of the distribution network, verifying in both cases the electrical and thermal behaviour of the system components before three-phase, two-phase and single-phase faults in them [33].

The calculations of settings of both reclosers were performed for the following protection functions (in brackets the ANSI standard C.37 nomenclature C.37 .2 of the same) [34]:Directional Overcurrent (67/67N); Phase Overcurrent (50/51); Ground Overcurrent (50N/51N); Overvoltage (59); Undervoltage (27); Reverse Power (32); Anti-islanding or Vector Shift Protection (78); Underfrequency and Over frequency Protection (81). With the results of the adjustments, the Factory Acceptance Test (FAT) are performed, and then, with the electronic protections mounted in their cabinets, the Site Acceptance Test (SAT) are replicated.

2.4 Greenhouse gas emissions

It is possible to determine the net greenhouse gas (GHG) emissions of the Hybrid System for Electric Power Generation from Biogas and Solar Photovoltaic by using Eq. 7, which is measured in tons of CO_2 equivalent (t_{CO2eq}). These emissions consist of two main components. Firstly, the emissions generated during the production of MSW biogas from the controlled disposal of MSW, which can be calculated using Eq. 5. Secondly, the GHG emissions avoided or reduced (not emitted) due to the capture of landfill biogas incineration and the PV generation of the Hybrid System, which can be calculated through Eq. 6. By using these equations, we can accurately quantify the environmental benefits of this project.

$$T_{CO_{2eq}_{LFG\_MSW}} = T_{CO_{2}_{LFG\_MSW}} + F_{CO_{2eq}_{CH_4}} \cdot Q_{CH_4} \tag{5}$$

$$T_{CO_{2eq}_{AVOIDED}} = \gamma \cdot F_{CO_{eq}_{CH_4}} \cdot Q_{CH_4} + F_{CO_{eq}_{EE_{PV}}} \cdot E_{PV} \tag{6}$$

For Eq. 5, $T_{CO2eq\_LFG\_MSW}$ is the tons of carbon dioxide equivalent from landfill biogas generation (t_{CO2eq}/year); $T_{CO2\_LFG\_MSW}$ is the amount of carbon dioxide emissions generated by MSW from the landfill, i.e. the amount of CO_2 contained in the biogas produced (t_{CO2eq}/year). This value is obtained from the modelling results in LandGEM for our case study; F_{CO2eq_CH4} is the methane characterization factor to bring it to carbon dioxide equivalent (t_{CO2eq}/t_{CH4}) (Krey et al., 2014). As for avoided emissions, in Eq. 6, we have $T_{CO2eq\_AVOIDED}$ as the total avoided GHG emissions of the PGHS (t_{CO2eq} /year); γ is the efficiency of the biogas recovery system (%); F_{COeq_EEFV} is the characterization factor of the electric energy of the PV system injected into the grid, considered as energy substituted from that of our national energy matrix (t_{CO2eq}/MWh$_{EE}$) according to the GHG Inventory of the Republic of Argentina, Years 2010 and 2012 (Moreira et al., 2019). E_{PV} is the electric energy generated by the PV system (MWh/year). It is worth mentioning that a complete combustion of the methane entering the hidden flare and microturbines is considered. Therefore,

$$T_{CO_{2eq_{NET}}} = T_{CO_{2eq_{LFG\_MSW}}} - T_{CO_{2eq_{AVOIDED}}} \qquad (7)$$

where T_{CO2eq_NET} are the net avoided GHG emissions from the Hybrid Biogas and Solar Photovoltaic Electricity Generation System (t_{CO2eq}/year) Eq. 7, the other variables being as described above.

3 Results

3.1 Chromatography results from El Borbollon landfill site

Table 1 shows the results of the biogas chromatography analysis of the El Borbollón landfill, carried out in two measurement campaigns with a two-year difference. Chromatography results from El Borbollon landfill site.

Table 1. Results of MSW biogas analysis at El Borbollon landfill. NA states for "Not Analysed"

Analysed Parameter	Unit	Measurement Campaign Registered Values		Methodology
		12/4/2020	12/26/2022	
Methane	% v/v	35,10	20,14	EPA 18
Nitrogen + Oxygen	% v/v	NA	71,09	ASTM D 1945 y ASTM D 2597
Carbon Dioxide	% v/v	34,20	8,76	EPA CTM-034
Hydrogen Sulfide	mg/m³	22,70	NA	EPA 11
Dodecamethylcyclohexasiloxane	mg/m³	1,20	NA	EPA 0010/ 8260 D

It is important to note that the obtained results for MSW biogas are between 12.25% and 49.65%, which is lower than the minimum value of 40% as suggested [9]. Moreover, microturbines need at least 35% methane in the biogas to function properly. If the methane content is lower than this threshold, the firing sequence becomes impossible due to the control system. It is worth mentioning that the methane values obtained from chromatographic analyses differ significantly from cases where the surface biogas piping system is well-maintained. Instances of poor maintenance, such as loose pipe connections, condensate drainage in pipes, and siphons in pipes due to differential soil settlements, can affect the methane values.

3.2 Results of the theoretical potential for methane production and electricity generation from biogas from El Borbollón landfill

The data on the methane production potential of the landfill is presented in Fig. 4, obtained from the LandGEM model by inputting the values that are applicable to our landfill. Fig. 5 also displays the results of the plant's methane production under operating conditions, where the volumes of methane that have been burned in the hidden flare during the facility's operation years have been deducted from the theoretical methane production potential calculated by Eq. 1. This figure also shows the methane projection up to the year 2040, with a maximum value of 11.46x10^6 m^3/year expected in 2041. This corresponds to an accumulated amount of 7.07 MMt (million tons) of MSW between 2022 and 2040.

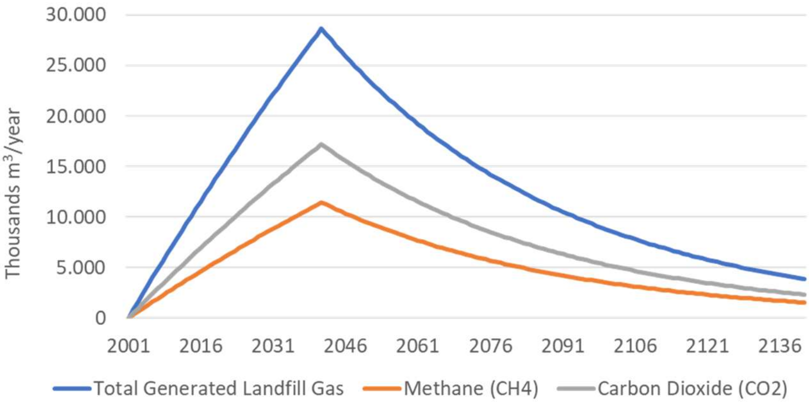

Fig. 4. Comparison of the theoretical potential of biogas production with CO_2 and CH_4 emissions. Own work.

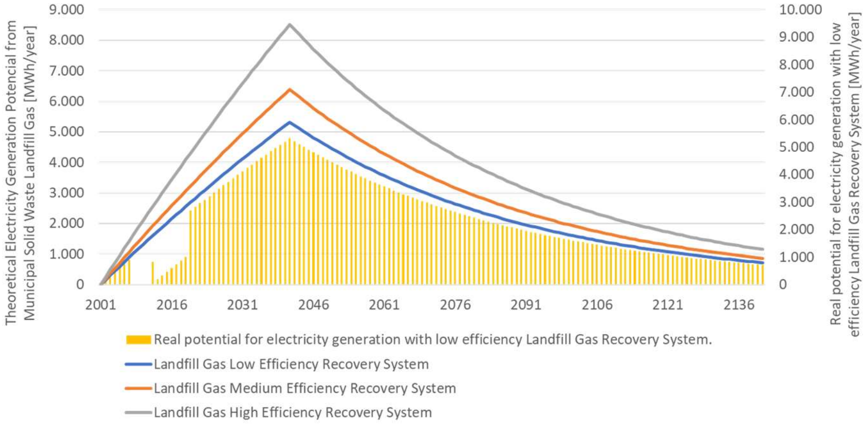

Fig. 5. Theoretical and real potential for electricity generation. Own work.

3.3 Decreased yield of electricity generation potential from landfill biogas recovery

Microturbines, like all gas turbines, operate efficiently based on the mass density of the intake air. The efficiency values provided by the manufacturer [25]. are based on full-load power at ISO conditions [37]. These conditions are defined at 15°C, 60% relative humidity, and a sea level pressure of 101.3 kPa. It is important to note that a decrease in efficiency may occur if the ambient temperature and elevation differ from the ISO conditions [25].

We utilized the manufacturer's data on power reduction and efficiency of microturbines [25] to conduct a simple linear regression analysis. The purpose was to determine the operating parameters of the microturbines under daily average ambient temperature conditions

[38]. This helped us understand the extent of performance loss in our case study, as shown in Fig. 6.

The findings presented in Fig. 6 illustrate how the nominal generation power changes based on the average daily outdoor temperature because an increase of air temperature implies decreasing its density and reducing the cooling capacity of the electronics.

To determine the available generation power, the power of the peripheral systems is subtracted from the nominal generation power. The lowest available generation power observed is 70.6 kW, occurring at an average daily outdoor temperature of 33.2ºC, while the highest available power is 103.4 kW, observed at an average daily outdoor temperature of 4.0ºC, which means that should be considered microturbines technology will deliver a 20.4% less output power that rated, but functioning at a lower methane concentration, agreeing with [39]. Moreover, the annual average available power is 87.8 kW, which means 32.4% less output power than rated, functioning at an average 27.6% methane concentration between 2020 and 2021.

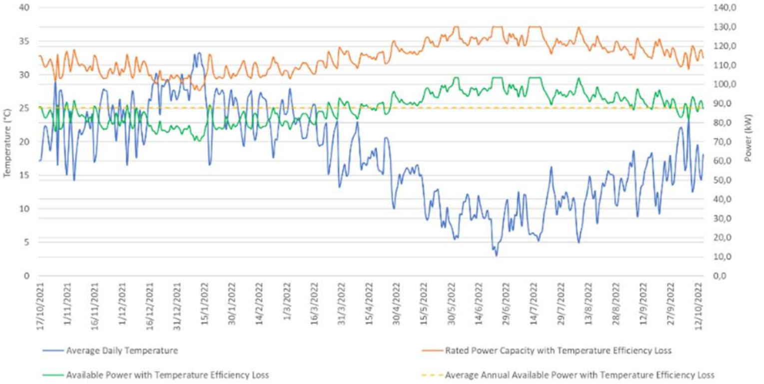

Fig. 6. Annual average temperature variation. Nominal, available and average available power generation with loss of yield. Own work.

3.4 Results of Electricity Generation from Solar Photovoltaic Technology

In the first year, the photovoltaic (PV) system generated 8,179 kWhac of electric power. The energy indicators resulting from this were: i) DC Side Capacity Factor of 17.6%; ii) Power Quality Ratio of 1,542 kWh/kW; iii) Efficiency of 74%; and iv) DC/AC Ratio of 1.06. The PV modules are estimated to degrade annually by 0.5% from year 1 onwards [40]. This degradation is expected to be similar in magnitude to the reduction in electric power generation, resulting in an estimated power generation of around 7,252 kWhac/year by the 25th year of installation.

3.5 Results on avoided greenhouse gas emissions

Fig. 7 displays the greenhouse gas (GHG) emissions, measured in thousands of tons of carbon dioxide equivalent (kt_{CO2eq}), associated with biogas production in its carbon dioxide, methane, and total components.

In 2041, the maximum carbon dioxide, methane, and total GHG emissions are 31.4 kt_{CO2eq}/year, 233.1 kt_{CO2eq}/year, and 264.5 kt_{CO2eq}/year, respectively. The cumulative values for these emissions up to 2041 are 671.5 kt_{CO2eq}, 4,976.4 kt_{CO2eq}, and 5,648.0 kt_{CO2eq}, respectively. Additionally, the graph shows the cumulative avoided GHG emissions by 2041 from biogas capture and incineration for the low (-2,488.2 kt$_{CO2eq}$), medium (-2,985.8 kt$_{CO2eq}$), and high (-3,981.1 k$_{tCO2eq}$) capture efficiency ranges, demonstrating a genuinely efficient environmental alternative solution for responsible management of MSW disposal.

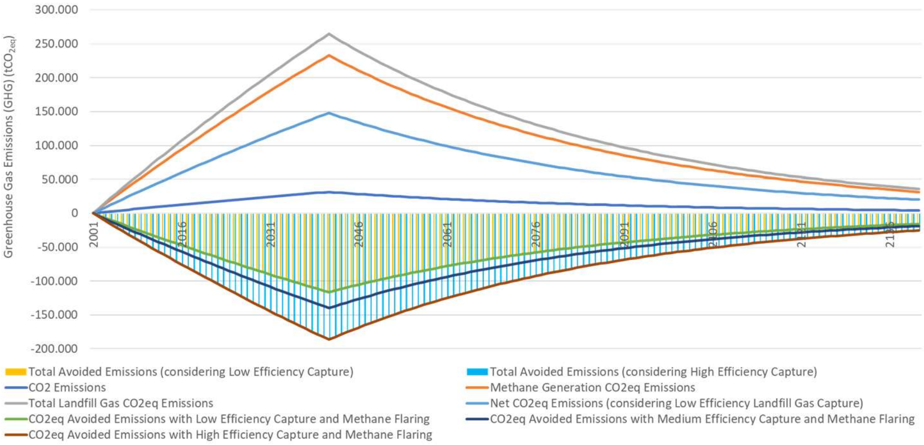

Fig. 7. Results on greenhouse gas (GHG) emissions generated, avoided and net. Own work.

Furthermore, the cumulative avoided GHG emissions from the injection of electricity from photovoltaic (PV) technology into the public distribution grid over 25 years are -0.108 kt$_{CO2eq}$, that compared to the cumulative avoided GHG emissions from biogas capture and incineration representing a relation of approximately 23.000 times lower, despite the fact the power relation between the microturbines and the PV technology systems is of 26 times. Therefore, the total avoided GHG emissions considering a low capture efficiency level are -2,487 kt$_{CO2eq}$, and for a high level, they are -3,981 kt$_{CO2eq}$. These values represent 44.1% and 70.5% of the total emissions without the biogas generation project, respectively, validating that the technology hybridization accomplished within the PGHS project could serve as a reasonable energy transition strategy.

4 Conclusions

The purpose of this project was to support a hybrid system in Mendoza, Argentina that uses biogas from municipal solid waste and solar photovoltaic technology to generate electricity. The PGHS is the first hybrid system of its kind in the country and the region capable of achieving the triple purposes of reducing energy consumption in MSW management in the province, obtaining a high added-value product with environmental, economic, and social development benefits at the same time contributing to the energy security trough out distributed renewable energy. Equally important, the project aims to demonstrate that, although the amount of electricity generated by this pilot project is not significant compared to the electricity generated from conventional thermal and renewable sources in the province of Mendoza, it is important for mitigating climate change.

However, the project is paramount in environmental issues as it helps to avoid greenhouse gas emissions. The cumulative net emissions of the project in 2041, assuming the most unfavorable scenario of low capture efficiency, would be 3,160 kt$_{CO2eq}$. If we consider the most favorable scenario of high efficiency, the cumulative net emissions of the hybrid system would be 1,667 kt_{CO2eq}. In other words, if the methane from MSW biogas had not been captured and combusted, MSW management in Greater Mendoza would have released 0.147 kt_{CO2eq} to the environment in 2022 and 5,648 kt_{CO2eq} accumulated to 2041.

The total avoided emissions, which include emissions avoided through the controlled management of MSW and subsequent combustion of the methane generated, as well as those avoided by the electric energy of PV origin, represent 4% and 6% of the emissions of Mendoza's net electricity generation in 2022, for low and high collection efficiency, respectively. That represents a significant environmental contribution for a single pilot project but can effectively handle the generated landfill gas of Gran Mendoza MSW controlled disposal.

If all of the methane produced in 2022 had been used, the electricity generated by the hybrid system would have represented only 0.007% of the total net generation and 1.4% of Mendoza's renewable generation for a low-efficiency condition of the capture system. For a high-efficiency condition, it would have represented 0.10% and 2.2% respectively. If Mendoza's thermal and renewable generation remained constant in 2041, the hybrid system would be expected to contribute 0.12% and 2.5% of total electricity supply to renewable generation at low collection efficiency, and 0.19% and 4.0%, respectively, at high efficiency.

Efficient collection and use of MSW biogas require maintenance activities to prevent biogas leaks. Leaks can be detected visually and confirmed by measuring low methane content in the biogas. However, chromatographic monitoring of biogas needs to be improved in the future.

This project supported various Sustainable Development Goals (SDGs) as well. For SDG 7, we increased renewable energy share and facilitated clean energy access. For SDG 8, we improved resource efficiency and supported labour rights and safe working conditions. SDG 9 was addressed by upgrading the waste industry for sustainability, promoting clean technologies, and encouraging innovation. Under SDG 11, we strengthened development planning, responding to population dynamics for balanced territorial development. Lastly, for SDG 13, we integrated climate change measures into regional policies, considering yearly greenhouse gas emissions. In conclusion, projects such as this pilot hybrid system, in which the methane values differ significantly from cases where biogas capture, conduction, treatment and conditioning systems are well-maintained but can effectively avoid GHG emissions from MSW disposal, at the same time, can generate renewable electricity to contribute to the energy transition, should not only focus on technical-economic success but also serve as a tool for educating the community about responsible management of urban solid waste and the importance of incorporating renewable sources of local electricity generation. We need to learn to live together without harming others and damaging the environment if we want to leave a livable world for future generations.

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