Performance Evaluation of Hybrid Solar Photovoltaic/Biogas Systems Connected to the Grid: Case of Study of a Rural Community in Argentina

Juan Pablo Cecchini, Luis I. Silva, Luis E. Venghi, Carlos R. Rodríguez, and Ernesto E. Coutsiers

***Abstract*— This study models and evaluates a hybrid energy system for the Pujato Norte community, integrating photovoltaic solar, a biogas generator, and grid connection. Using HOMER Pro software, the project assessed economic feasibility, operational aspects, and maintenance costs over a 25-year projection, targeting a minimum 50% renewable energy contribution. Results indicate an optimal configuration comprising a 501 kW photovoltaic plant and a 50 kW biomass generator, capable of meeting the average daily load of 4,109 kWh. While the estimated initial investment is USD 997,029 and the resulting energy cost of USD 0.1738/kWh exceeds current grid rates, the system delivers a significant environmental benefit: a 41% reduction in carbon dioxide emissions, equivalent to 297,554.86 kg CO_2 annually. This substantial decrease underscores the hybrid system's potential to provide a more sustainable, long-term energy alternative by mitigating the environmental impact of local power generation.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/9866

***Index Terms*—Biogenerator, Connected hybrid system solar energy, HOMER Pro, Livestock waste.**

I. INTRODUCTION

THE increasing global concern regarding environmental degradation and climate change has driven a significant shift towards sustainable energy sources. Traditional energy systems, heavily reliant on fossil fuels, contribute substantially to greenhouse gas emissions and air pollution, making the transition to renewable sources essential. Renewable energy sources such as solar, wind, hydro, and biomass offer cleaner and more sustainable alternatives [1]. At the same time, solid waste management remains a pressing global challenge; the growing generation of municipal solid waste (MSW) poses substantial environmental and health risks. Inefficient waste management practices can result in pollution, greenhouse gas emissions (GHG), and the spread of diseases [2]. Additionally, poor electrical service quality in Latin America, marked by frequent interruptions and long outage durations, presents a significant challenge. Insufficient generation capacity, outdated infrastructure, and inadequate maintenance contribute to this issue, leading to frequent power outages that cause economic and social hardships, such as lost productivity, equipment damage, and public unrest. Sustainable policies incorporating renewable energy sources (RES) like hydroelectric, solar, wind, and biomass energy are essential to address these challenges. In central Argentina, solar energy and biomass are emerging as the renewable resources with the highest potential [3], [4]. Photovoltaic solar energy (PV) has seen significant development due to technological advances that reduce its levelized production costs. Biomass has also gained traction, with local availability supporting its potential as a viable energy source [5].

This study proposes a hybrid energy supply system that combines photovoltaic solar energy and biogas to provide a sustainable power source for a rural village in the Argentine interior, in conjunction with the public electricity grid (GRID) [6]. Photovoltaic solar energy, a renewable and clean energy source, will generate electricity during the day. Biogas, derived from diverse sources like local MSW, dairy farm waste, feedlots, and livestock activities, will provide complementary fuel to generate electricity at night and during low solar radiation periods. This approach indirectly addresses another pressing issue: the sustainable exploitation and use of waste from households and productive activities [7]. To assess the technical and economic feasibility of the proposed system, HOMER Pro software was used, a tool designed for the analysis and optimization of hybrid energy systems. This software helped determine the optimal system configuration, including component capacities (solar panels, biogas generator). The study's results provide valuable information for decision-making on the implementation of hybrid energy supply systems in the region, promoting sustainable development and enhancing the quality of life for local residents.

II. METHODOLOGY

A. Case Study

The small village of Pujato Norte is located at 31° 31.2'S and 60° 55.6'W. The climate in this area is temperate continental, with hot, humid summers and cold, dry winters. The average annual rainfall is about 1000 mm, distributed relatively evenly

---

The associate editor coordinating the review of this manuscript and approving it for publication was Pedro Moura (C*orresponding author: Juan Pablo Cecchini*).

This work was supported in part by the National Scientific and Technical Research Council (CONICET) and the National University of Rafaela (UNRaf)".

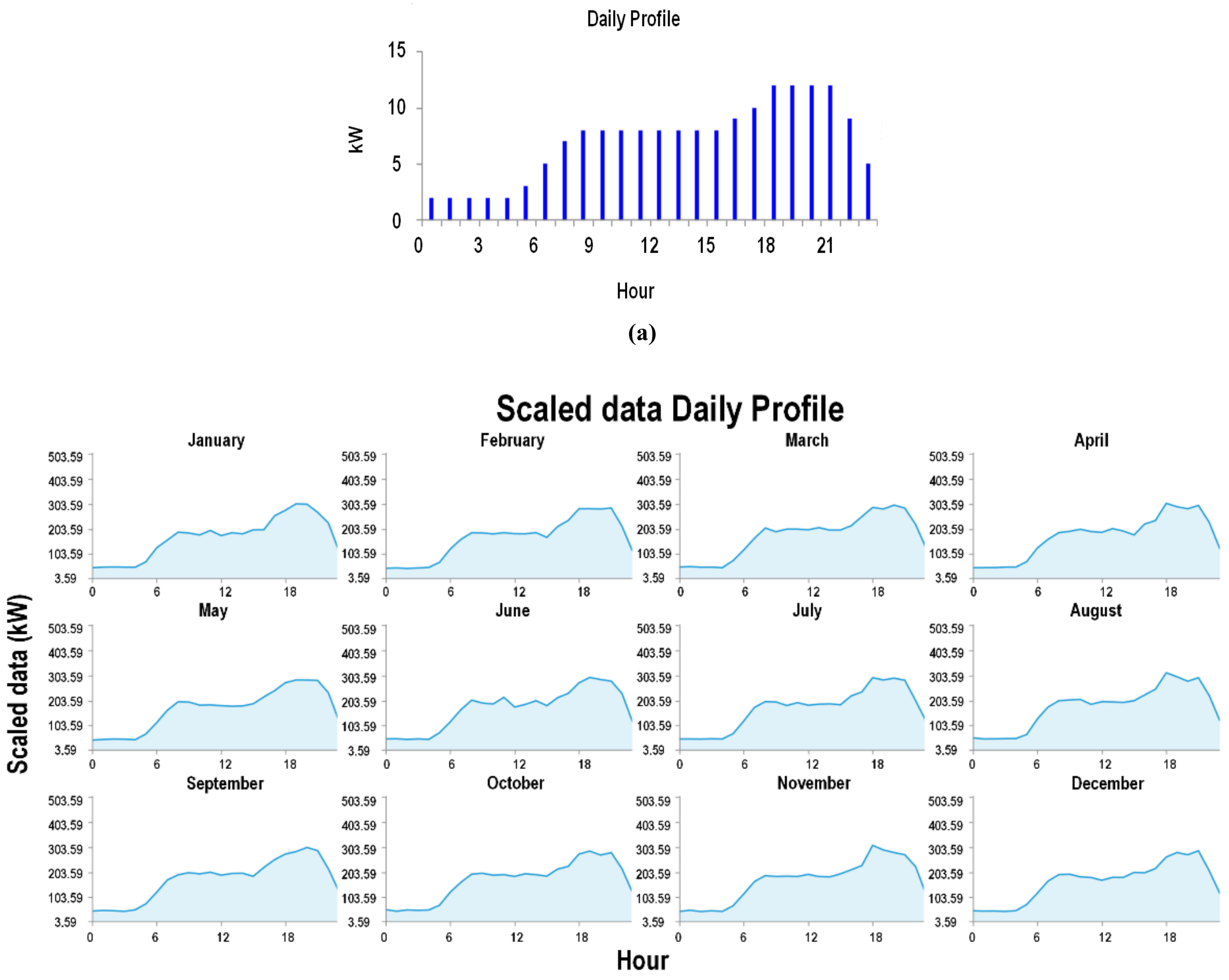
Juan Pablo Cecchini, L. I. Silva, and L. E. Venghi are with the National Scientific and Technical Research Council, and the National University of Rafaela, Rafaela, Argentina (e-mails: juanp.cecchinin@unraf.edu.ar, luissilva@unraf.edu.ar, and luisesteban.venghi@unraf.edu.ar).

C. R. Rodríguez is with Faculty of Exact, Physical and Natural Sciences, National University of Córdoba, Córdoba, Argentina (e-mail: ramiro.rodriguez@unc.edu.ar).

E. E. Coutsiers is with the Faculty of Exact Sciences, National University of Salta, Salta, Argentina and Calden Consulting SRL, Villa Allende, Córdoba, Argentina (e-mail: ecoutsiers@exa.unsa.edu.ar).

throughout the year. The predominant wind is from the northwest, especially during summer, the average speed is about 10 km/h, but can increase considerably during storms. Around 750 people live permanently and temporarily in this proposed area, where the commercial activity includes a couple of small businesses, a drinking water treatment plant, and beverage marketing. Furthermore, economic activities are the same as those that predominate in the region: agriculture, livestock and poultry, which provide waste such as wood, forestry, manure, etc.

Although the electrification of the region has access to the electrical distribution network, the quality of service is sometimes below standard. The aforementioned locality has a maximum daily energy demand of 4,109 kWh/day and a load factor of 0.34. Table I presents the monthly and annual energy consumption, categorized by consumer type. The main demand comes from residential consumers in the town and surrounding areas, and also to a lesser extent from businesses, industry and agricultural activities. As can be seen, almost 85% of the total annual load comes from the residential and rural categories, which mostly correspond to homes. The load curve is thought to be quite similar to that of other cities and towns in Santa Fe province and generally across Argentina [8]. It is assumed that the synthetic load from a community profile provided by HOMER is a fairly realistic approximation of the load profile to be analyzed (Fig. 1 a). Fig. 1 (b) shows how the daily load profiles vary, scaled by month, which were calculated considering the energy consumption detailed in Table I, where it can be seen that the consumption trend throughout the year remains practically unchanged.



(a)

(b)

Fig. 1. Daily load profile used in HOMER: (a) Baseline (b) Daily scaling broken down by month.

TABLE I
MONTHLY ELECTRICITY CONSUMPTION BROKEN DOWN BY CATEGORY ACCORDING TO THE PROVINCIAL ENERGY REGULATORY ENTITY (EPE) [9]

	Load (kWh)												
Category	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**Annual Total**
Residential	47,775	61,267	65,932	63,901	56,160	52,885	53,268	52,006	49,316	47,398	50,396	54,360	634,635
Commercial	2,986	3,001	3,017	3,025	3,036	3,048	3,062	3,078	3,096	3,116	3,138	3,162	37,765
Industrial	7,111	9,001	9,817	9,821	9,823	9,826	9,828	9,831	9,834	9,837	9,840	9,843	113,312
Street Lighting	7,728	7,707	7,686	7,665	7,644	7,623	7,602	7,581	7,560	7,539	7,518	7,497	91,350
NPO	1,803	1,803	1,803	1,803	1,803	1,803	1,803	1,803	1,803	1,803	1,803	1,803	21,636
Authorities	1,823	1,823	1,823	1,823	1,823	1,823	1,823	1,823	1,823	1,823	1,823	1,823	21,876
Rural (Isolated zones)	54,319	53,318	53,317	53,316	53,315	53,314	53,313	53,312	53,311	53,310	53,309	53,308	639,472
Monthly Total	**123,565**	**137,920**	**143,395**	**141,354**	**133,604**	**130,322**	**130,699**	**129,434**	**126,743**	**124,826**	**127,827**	**131,796**	**1,581,485**

B. Resource Assessment

This study considers solar and biomass renewable energy resources. HOMER synthesizes solar data according to the NASA Prediction of Worldwide Energy Resource database for simulation. The available biomass data for 12 months were considered constant throughout the year. The wind energy resource was estimated to have an average speed of approximately 5 m/s; the temporal variability observed throughout the day precluded its inclusion in the subsequent evaluation. Characteristics of both resources are discussed below.

C. Solar Energy Resource

The selected location has significant solar access with approximately 2,500 hours of sunshine per year and on average it is equivalent to 4.82 kWh/m^2/day. Fig. 2 shows the hourly global solar horizontal irradiation in the selected location. This quantity is obtained by adding the beam radiation (also called direct normal irradiance), diffuse irradiance, and ground-reflected radiation [10], [11]. The clarity index, representing atmospheric clarity, is also shown. This index is the ratio of solar radiation at the Earth's surface to that at the top of the atmosphere. The solar radiation reaching the Earth's surface is less than the radiation reaching the upper atmosphere due to humidity, dust, clouds or even temperature differences in the lower atmosphere. These data were taken from the National Aeronautics and Space Administration (NASA) [12] and were validated against real data obtained from photovoltaic systems in operation in this location [13]. January, the summer month, exhibits the highest daily radiation, while June, in winter, has the lowest. Based on data on monthly and global solar radiation in the village, it is shown that this resource has a high potential for use as an energy source in the region. Furthermore, as the clarity index remains constant at an approximate value of 0.55 throughout the year, it is possible to predict the energy calculation.

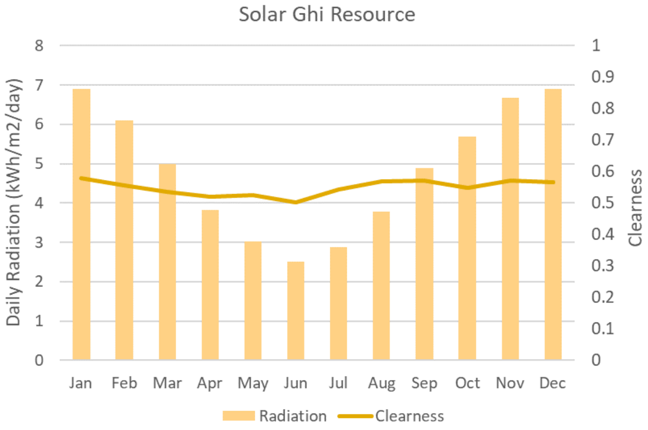


Fig. 2. Monthly solar radiation and clarity index of Pujato Norte.

D. Biomass Resource

The province of Santa Fe not only has a great diversity of biomass resources with potential energy use but also presents a surplus of resources for this potential purpose. The sources are diverse and, in the report, presented by the FAO (2018) each of them is detailed and accounted for. To minimize freight costs, this work only considered cattle manure from nearby areas and pre-separated organic MSW generated within the rural community [14].

Urban Solid Waste (MSW): Waste characterization was estimated based on national data from Martínez Waltos (2021) [15]. This data indicates an organic waste content of 50-60% (including food, garden, paper, and cardboard at 20-30%), plastics at 8-12%, glass at 5-7%, metals at 2-3%, and other materials at 2-3%. The communal government makes constant efforts to ensure that waste separation is carried out. Community contribution is the most economical option; however, it has the disadvantage that poor separation can result in a rejection rate of 17% in separated waste [16]. To avoid this, after collection, the separation is completed with the intervention of communal workers. The processing involves two lines, one for wet waste and another for dry waste. Dry waste is sent to a recycling plant, while wet waste, including biodegradable waste, will be used for biogas production. According to estimated data, 1 kg of waste is generated per inhabitant per day [17]. Considering 52% organic waste whose humidity is 70%, for a population of 750 inhabitants, that is, a net amount of dry biomass from MSW of 0.117 ton/day.

Livestock Waste: As for the department of Las Colonias, where the village is located, according to the FAO report [9], it has a supply of wet waste of 315,578 ton/year from dairy farms, bovine feedlots and pig establishments, among others.

E. Economic Considerations in a Volatile Environment

Argentina's economic landscape is characterized by recurrent periods of high inflation and significant macroeconomic shifts. While our financial modeling utilizes real U.S. dollar terms to neutralize the direct impact of inflation, and our Weighted Average Cost of Capital (WACC) explicitly incorporates Argentina's country risk alongside sector-specific characteristics, it is crucial to acknowledge the broader implications of such volatility on long-term project sustainability. Our deep familiarity with the local context allows us to highlight several key dynamics. High inflation, even when accounted for in financial metrics, can introduce operational challenges, such as difficulties in budgeting and forecasting, supply chain disruptions due to price uncertainty, and potential social pressures on wages and pricing. Furthermore, the broader economic and social dynamics, including changes in consumer purchasing power, policy shifts, and public sentiment, can indirectly influence project demand, operational costs, and regulatory frameworks. While precise quantitative projections of future economic conditions fall outside the scope of this study, this qualitative analysis serves to provide a more holistic understanding of the contextual factors that could affect the project's enduring viability and adaptability within Argentina's unique economic environment.

Considering that a better economy results in greater sustainability, HOMER Pro evaluates the optimal system using different economic parameters that include: Net Present Cost (NPC), Levelized Cost of Energy (LCOE), Cost of Capital (CAPEX), and Salvage Cost. The useful life of the project is considered to be 25 years with a nominal discount rate (NDR) of 21.4% and an inflation rate of 2.3%. The discount rate was determined following the calculation methodology outlined in Coutsiers et al. (2022) [18], which has the following characteristics:

- WACC
- Capital Asset Pricing Model (CAPM)
- Capital Asset Pricing Model for Debt (Debt CAPM)

The rate is calculated, and used in the flow of funds, in nominal terms, in US dollars and after taxes. The inflation considered is obtained as an average of the reference inflation projections according to the U.S. Federal Open Market Committee & Federal Reserve Bank of St. Louis [19].

III. SYSTEM DESIGN AND SPECIFICATIONS

The hybrid energy system is composed of photovoltaic (PV) panels and a biogas generator connected to the public electrical grid. It is worth mentioning that the biogas generator is connected directly to the grid through an alternating current (AC) bus, while the photovoltaic panels are connected to a direct current (DC) bus and then access the AC bus through a converter, as shown in the diagram in Fig. 3. This hybrid power system will supply the described load profile by counteracting the negative effects caused by supply instabilities, voltage dips or surges, and electrical distortion or noise in the signals of supply.

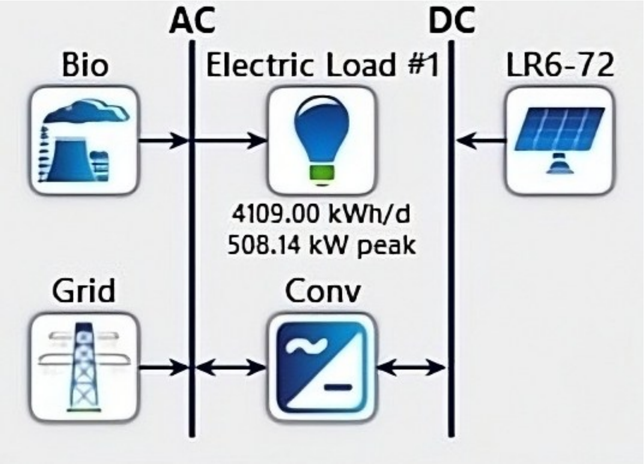


Fig. 3. Architecture of a hybrid energy system.

A. PV System

The solar panel chosen for simulation is the LONGi Solar LR6-72 with a nominal power of 0.350 kW and an efficiency of 18.1%. Its capital cost is USD 1800/kW, and the same cost is assumed for replacement, the operation and maintenance cost of the same is USD 50/year/kW [20], for a period of 25 years, consistent with the useful life of the asset. Based on these panels, calculations were carried out with reduction factors set by default at 80%. Finally, the expected energy production by the panel system is expressed in the following Eq. (1):

$$E_{spv}(t) = G(t) \times \eta_{spv} \times A \tag{1}$$

where:

$G(t)$ = hourly irradiance in kWh/m^2

η_{spv} = photovoltaic panel efficiency

A = area of the photovoltaic modules

In the case of wanting to calculate the energy generated over a year, instead of the hourly irradiance $G(t)$, we are going to use a medium irradiance G_med = 1560 kWh/m^2/year. Therefore, for the panel under analysis that has an area of 2 m^2, those 350W are going to generate about 564.72 kWh/year.

Since the solar panels generate a DC output and the load under consideration is supplied by AC, it is necessary to use a DC/AC converter (Inverter). This makes it possible for the load to be supplied by the panels when the electrical network presents some damage, and by the electrical network and biodigester when the panels do not generate or present any damage. For this reason, the size of the converter is chosen based on the peak value of the demand, while the nominal power of the inverter ($P_{inv}(t)$) is calculated as follows (Eq. 2) [21].

$$P_{inv}(t) = P_L^m(t)/\eta_{inv} \tag{2}$$

where:

η_{inv} = inverter efficiency.

$P_L^m(t)$ = peak demand power

The capital and replacement cost of the converter are both considered USD/kW 100 and the operation cost as USD 0.1/kW/year [22], [23]. The useful life of the converter is 25 years, with an inverter efficiency of 95%.

Furthermore, it is considered important to highlight the recyclability alternatives for solar panels at the end of the project's lifespan, estimated at 25 years. By the projected decommissioning date, asset management under a circular economy model becomes crucial [24],[25]. While the current model presented in this study focuses on the operation and immediate energy and environmental benefits, future research and planning should integrate a robust end-of-life management method for the solar panels. This could include exploring agreements with specialized photovoltaic panel recycling companies, evaluating emerging technologies for the recovery of valuable materials (such as silicon, silver, and copper), and analyzing the economic and logistical feasibility of these options within the Argentinean context [26] and the local programs for recycling with a circular economy perspective [27]. Adopting a circular economy approach for solar panels will not only minimize waste generation but also enable the recovery of valuable resources, contributing to the long-term sustainability of the proposed hybrid energy system [28][29].

B. Biogas Generator

Based on the abundant availability of waste, as previously considered, its use as raw material for energy generation in a biogenerator (BG) was proposed, at the same time attacking the problem of waste in a sustainable and ecological manner. Energy can be extracted from waste using thermochemical conversion technologies (such as gasifiers coupled to engines) or biological conversion technologies (digesters). During the anaerobic digestion process of organic matter in a digester, the biomass is transformed into methane [30]. Then, the biogas generated can be used directly in internal combustion engines or purified for injection into the natural gas network. For the choice of conversion technology according to Al-Najjar et al. [31], anaerobic digestion is generally preferable in small-scale projects with high organic biomass, as it is a relatively simple and economical biological process. On the other hand, gasification is more suitable for large-scale projects or when greater control over the composition of the gas produced is required. With some modifications, a conventional diesel generator can be used as a BG. The cost of a newly modified BG (per kW) includes the cost of modification, transportation and installation, purifier and desiccant, as well as the cost of the control system. To this cost must be added the cost of the biodigester and the storage tank for the biogas generated. The investment, replacement, operation and maintenance cost of this biogas generation system is USD 900/kW, USD 900 and USD 0.10 per hour respectively [32], [33]. The generator is connected to the electrical grid through the AC bus and the projected useful life is 20,000 working hours [34]. Therefore, keeping the generator running continuously and indefinitely will result in frequent replacements throughout the life of the project. To avoid this, the work of the biodigester was scheduled at night from 8:00 p.m. to 7:00 a.m. when there is no photovoltaic generation [35], this also reduces the current net cost of the system because the operating costs are reduced as demonstrated in Ogunwo [36]. The total cost of running the generator is calculated based on the time spent during the year. Power search range: 0, 10, 20, 50, 100, 200, 500 kW. The composition of biogas comprises: 50-70% CH_4, 30-50% CO_2, and traces of H_2S, and the density is about 1.15 kg/m^3. Typical lower calorific values are between 21-24 MJ/m^3 [37]. Additionally, the price of biogas was set at 0.015 USD/kWh since it can vary depending on the variation in the raw material and the handling cost [38].

C. Grid

Argentina's primary energy matrix is mainly based on fossil fuels, with an 85.9% share in the total offer during 2023[1]. The main fossil fuels used are natural gas (53.0%), crude oil (31.3%) and coal (1.6%). The remaining primary energy is made up of biomass (5.8%), hydropower (3.4%), nuclear (2.6%) followed by wind energy and solar energy (2.3%) [39].

On the other hand, when we analyze the distribution of the energy sources used for the electricity available in the grid, the impact of renewable energies becomes much more significant, with a 17,1% share in the total production during 2023. The main renewable energies are wind (12.1%), solar (3.1%), hydropower plants smaller than 50MW (1.1%) and bioenergy (0.8%). Whereas the rest of the electric energy is produced with fossil-fuels (42.9%), hydropower plants larger than 50MW (32.7%) and nuclear (7.3%) [40].

Energy rates in Argentina are subsidized for most residential and commercial consumers. However, in recent years measures have been implemented to reduce subsidies, which has caused a gradual increase in rates. Current rates vary depending on the region, social category and type of user consumption, in addition to continuous corrections in the value of the local currency with respect to the dollar. The price of electricity varies depending on: type of home, area, amount consumed and activity, on average for residential consumption it is around USD 0.075 per kWh, while for industrial consumption it is around USD 0.100 per kWh [9]. Based on these criteria, in this model implemented in HOMER a value of USD 0.100 per kWh was introduced for purchase from the electrical grid and a value of USD 0.050 per kWh for sale to the electrical grid, assuming 1 USD = 1,165 ARS. Furthermore, as a restriction to the proposed hybrid generation system, a minimum of 50% renewable energy was set, therefore, at most the other 50% can be purchased from the grid.

D. Analysis of Social Aspects

While these hybrid systems offer clear technical and environmental benefits, their social implications often do not receive the same attention. Acceptance, accessibility and equity in access to these new forms of energy are crucial factors that can determine the success or failure of their implementation in

---

[1] The 2024 annual report is not yet available.

local communities. In this context, the Trilemma Index is presented as a comprehensive tool to evaluate the balance between three fundamental pillars: energy security, energy equity and environmental sustainability [41]. It is widely used at a macro level in national energy evaluations, for example, for Argentina its qualification for the year 2023 has been reported with a Trilemma Score of 70, positioning itself in the ranking 32 of countries, with 66.4% in Energy Security, 85.3% in Energy Equity and 69.3% in Environmental Sustainability. This index can also be adapted to analyze renewable energy systems at a micro level, such as hybrid microgrids. Evaluating these systems through the lens of the Trilemma Index allows not only to address the technical and economic challenges, but also to offer a broader vision of their social impact. Particularly, the social dimension of hybrid renewable energy systems, which includes factors such as community participation, equity in energy access and cost perception, is crucial to ensure that the proposed solutions are sustainable and acceptable in the long term. Vulnerable communities, especially in rural and isolated areas, present specific challenges related to energy affordability, lack of adequate infrastructure and lack of knowledge about new energy technologies [42], [43]. This study evaluated the social impacts of the use of hybrid renewable energy systems in microgrids through the Trilemma Index, after the optimization of HOMER Pro. For this, the data of the optimal configuration of the system was extracted and the scoring mechanism based on the Three Core Factors of the Energy Trilemma was used, namely, to calculate the factors of the formulas developed by Lacea et al. [44].

- To obtain the Reliability Factor (RF), which in this study refers to the system's ability to satisfy current and future demand, the following was used:

$$Reliability\ factor\ (RF) = \left(1 - \frac{f_{unmet}}{5}\right) \times 100\% \quad (3)$$

$$f_{unmet} = \left(\frac{E_{unmet}}{E_{demand}}\right) \times 100 \quad (4)$$

Where E_{unmet} is the electricity that cannot be served by the system and it was set at a maximum of 5% of the total demand, E_{demand}, in which for that value the RF = 0.

- To calculate the affordability factor (AF), the following equation was used:

$$AF = \left(1 - \frac{LCOE}{2C_t}\right) \times 100\% \quad (5)$$

Where LCOE is the levelized cost of energy, which refers to the average cost per kWh of useful electrical energy produced by the system. The denominator $2C_t$ is the maximum assumed limit value for the COE. In this case, 5% of the average per capita income per day is taken for a household with a regular consumption of 1 kWh/day [45], which according to the National Institute of Statistics and Census of Argentina (INDEC) amounts to 12.7 USD/day (1 USD ~ 1,165 ARS) [46], as equivalent to the affordability threshold of the cost of electricity (Ct) (USD 0.635 per kWh). Therefore, AF would result in a zero value (0%) when the COE is equal to two times the Ct value. Likewise, the lower the COE value than C_t, the higher the AF will be. The COE acceptance criterion is for AF values between 50 and 100%, while an AF below 50% means that the COE is greater than the threshold value and the system configuration is no longer affordable.

- For environmental sustainability (ES) the following were used:

$$RPF = \left(1 - \frac{E_{nonren}}{E_{served}}\right) \times 100\% \quad (6)$$

Where RPF is the % renewable penetration factor, E_{nonren} refers to the production of non-renewable electrical energy (kWh/year), and E_{served} refers to the electrical load served (kWh/year).

The total Energy Trilemma score was calculated using the weighted average shown in equation (7) assuming that each factor of the Three Core Factors had equal weight [47].

$$ET = a \times RF + b \times AF + c \times RPF \quad (7)$$

IV. RESULTS AND DISCUSSION

A. Sensitivity Analysis

Sensitivity analysis monitors the effect of certain variables. Different values are assigned to these variables within a certain range to evaluate their influence on the system. In this study, as detailed in Table II, different daily flows of waste to be treated were analyzed 1; 5 and 10 tons/day, thus considering the increase in future activity. For example, the logistics of waste collection from more remote places are improved. In this way, freight costs also increase; for this, different prices ranging from 0 to 5 USD/ton were foreseen. The variation of the gasification factor or ratio (f) was also considered, which depends on the type of waste to be treated and its capacity to produce biogas. Considering only municipal solid waste (MSW) and cattle manure as substrates, the following biogas production rates were established: 0.074 m^3 per kg of dry MSW and 0.037 m^3 per kg of cattle manure [48]. Assuming an average biogas density of 1.15 kg/m^3, the resulting gasification ratios were calculated: 0.0851 for cattle manure and 0.04255 for MSW. These factors allow us to estimate the amount of biogas produced from a certain mass of each type of waste.

TABLE II

BIOMASS INPUT DATA INCLUDING MSW AND CATTLE WASTE

Parameter	Value
Feed biomass	1*; 5; 10 tons/day
Price	USD 0; 1; 2; 3; 4; 5
Carbon content	50 %
Gasification factor	0.0426; 0.0851 kg biogas/ kg biomass
Lower Heating Value (LHV) of biogas	21 MJ/kg

*A minimum of 1 ton/day is considered easily achievable with the estimated flow of MSW and livestock waste in the area.

The system was analyzed and optimized considering the sensitivity parameters focused on biomass previously described, such as the variation in biomass supply and its characteristics that are reflected in the gasification ratio and price. As a result of the simulations carried out in HOMER Pro, two feasible configurations were generated with and without a biogenerator, since the possibility of supplying the system only with biogas is limited.

From the results it can be highlighted that by increasing the amount of biomass the operating costs and LCOE vary between USD/year 93,398 and 114,484 and between USD/kWh 0.174 and 0.183 respectively. The NPC varies between USD 1,527,609 and 1,740,813 and the CAPEX between 997,029.4 USD and 1,114,296 USD. In all systems the renewable fraction barely exceeds 50%. As expected, kWh production is strongly linked to the flow of available biomass and the higher the gasification ratio, the greater the amount of energy obtained from waste. By increasing the waste flow, a decrease in NPC, LCOE and CAPEX is also observed.

When the price of biomass is 5 USD/ton and f = 0.0426, the most convenient system architecture does not use a biogenerator, covering all demand with solar panels and energy purchased from the grid. The same happens for higher prices.

At flows of 1 ton/day of waste the electrical contribution is minimal, depending on the f it will be 0.380% or 0.777% and the systems analyzed are almost identical (whether or not the biogenerator is used). As the flow increases to 5 ton/day and 10 ton/day, the percentage of electricity production through biogas and, depending on the parameters f and price of the ton of biomass, can increase up to 4.2% and 8.6%. respectively, also increasing the nominal capacity of the generator.

B. System Optimization

The preceding analysis revealed that the PV/Bio/Grid scenario with a flow rate of 10 ton/d, a price of USD/ton, and f = 0.0851 was the optimal hybrid system for supplying the town. It receives the lowest NPC with USD 1,527,609 and an LCOE of USD/kWh 0.1738. The operating cost of the system is USD 99,892 and capital cost is USD 997,029. Fig. 4 shows how both the flow rate and the cost of biomass influence the CAPEX in the most unfavorable gas generation condition (where the type biomass produces less amount of biogas) with f = 0.0426. The project becomes cheaper by increasing the flow of waste to be processed and by decreasing the price per ton.

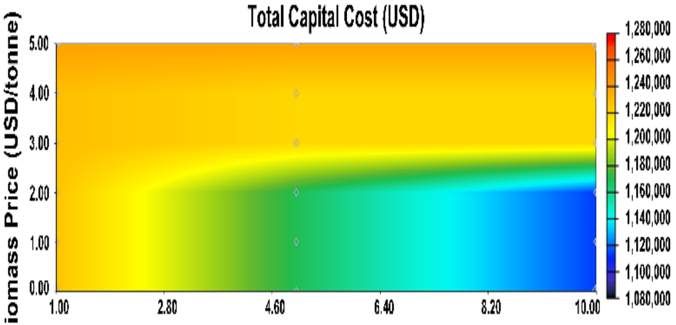


Fig. 4. Surface graph of the total Capital Cost depending on the flow of biomass (ton/day) and its price (USD/ton).

The cash flow shown in Fig. 5, indicates that the highest expenditure occurs in the initial year, primarily due to the capital investment required for the photovoltaic (PV) system installation. Following this upfront cost, the ongoing expenses over the remaining years of the project's lifespan are dominated by operational costs, mainly attributed to electricity purchases from the grid. This pattern aligns with the decision to restrict biogenerator use to nighttime hours, which helps extend its operational life and minimizes replacement costs, as referenced in [49]. It is also evident that a higher energy contribution from the biogenerator would decrease reliance on grid electricity and thereby reduce associated costs. However, this potential is limited by the biogenerator's maximum input capacity, set at 10 tons of biomass per day. Additionally, Fig. 5 suggests a relatively stable cash flow pattern over the project's life, indicating predictable operational expenses and the potential for long-term cost savings due to reduced fuel dependency. Furthermore, the use of the grid in combination with renewable sources like PV and biogas enables the system to achieve a balanced cost structure, although this configuration does incur some periodic costs associated with maintenance and operational adjustments, particularly for the PV system and the biogenerator. This hybrid approach also helps to mitigate the variability in renewable energy generation, providing a stable and resilient power supply to the system.

In hybrid energy projects like this, a consistently positive cash flow is challenging to achieve due to recurrent operational and maintenance expenses, alongside the amortization of initial capital investments. However, factors such as reducing grid dependency, increasing biogenerator capacity (beyond the current 10 tons/day limit), securing governmental incentives, or selling surplus energy to the grid could potentially improve cash flow. Even if positive cash flow is not attained, the project remains viable by meeting sustainability and resilience goals, such as emission reduction and enhanced energy access in rural areas.

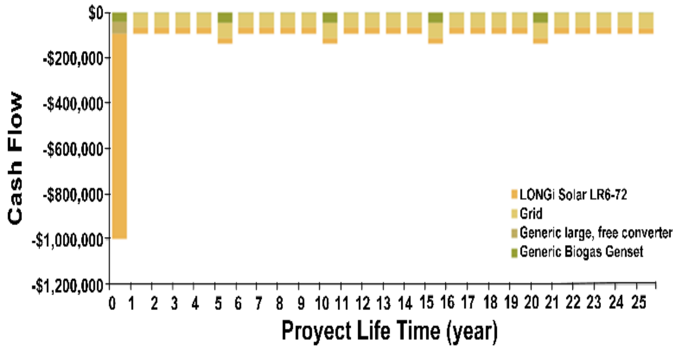


Fig. 5. Nominal cash flow by component.

The resulting configuration consists of a 501 kW photovoltaic module, a 50 kW biogas generator and 494 kW capacity inverters. The energy production throughout the year is shown in Fig. 6, resulting from 42.9% (724,581 kWh/year) of the panels, from the biogenerator 8.6% (145,179 kWh/year) and purchases from the network represented 48.5% (820,925 kWh/year).

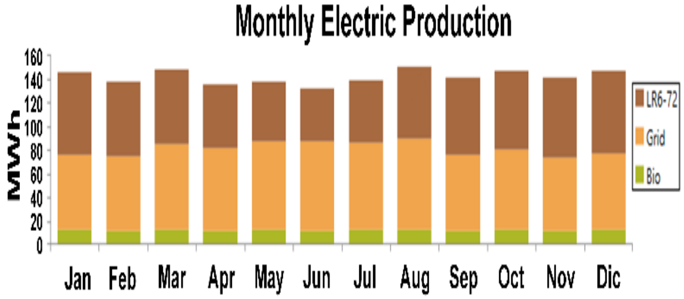


Fig. 6. Average monthly electrical production of the hybrid photovoltaic/biogenerator system.

C. Emission Analysis

Table III summarizes the emissions. For the optimal PV/Bio/Grid system, annual CO_2 emissions amount to 427,749 kg CO_2, with an emission factor of 0.2503 kg CO_2/kWh. By contrast, under the same flow, biomass fraction, and price conditions, the PV/Grid system produces 378,888 kg CO_2/year with an emission factor of 0.2035 kg CO_2/kWh. The difference in emission factors is due to the emissions from the biogenerator itself; however, this system also addresses municipal solid waste (MSW) disposal issues. Simulating using only the grid as the energy source results in 947,864 kg of CO_2/year, with an emission factor of 0.632 kg of CO_2/kWh. When comparing the emission factor of this hybrid system with Argentina's National Interconnected Electric System (SEIN), whose average value for the last 12 months was 0.2335 kg of CO_2/kWh, there is no significant difference with the simulated model [40]. However, looking at the grid-only simulated model is noticeable. This discrepancy can be mainly attributed to the energy mix, which in the simulated model could rely heavily on fossil fuels such as coal or natural gas, and to simplifications in the simulations, such as plant efficiency, transmission and distribution losses, and weather conditions. However, it is important to note that the hybrid system's emissions factor is similar to that of the SEIN and considerably lower than that of the grid simulated by HOMER Pro.

TABLE III
GHG EMISSION OF THE OPTIMIZED SYSTEM

Compound	Value	Units
Carbon Dioxide CO_2	427,749	kg/year
Carbon Monoxide CO	7.3	kg/year
Sulfur Dioxide SO_2	1,826	kg/year
Nitrogen Oxides NO_x	897	kg/year

D. Analysis of Social Aspects

Following the methodology described below, the Energy Trilemma Index obtained was 77.5 indicating a relatively high performance. While studies applying the Energy Trilemma Index to microgrids are limited, this score can be compared to a certain extent with the findings of Quitoras et al. [50], who reported similar values using HOMER Pro parameters in optimizing the quality of electricity supply by integrating microgrids in remote areas of Canada.

Breaking down the Energy Trilemma Index, it is observed that the RF value was approximately 100%, since this connected microgrid would reinforce the current service, assuming that accessibility had been achieved; As a result, the E_{unmet} obtained in HOMER Pro was zero. The high reliability of the microgrid contrasts with certain problems in the stability of supply at the national level, where infrastructure, generation capacity and diversification of sources influence.

The AF obtained from the LCOE (price taken by the best hybrid system) was 86.3%, within the acceptance range; however, the LCOE of the microgrid was more expensive than the current price per kWh. In this sense, Jing et al. mentions that the three factors are difficult to reconcile and the search for a sustainable energy transition may entail additional costs that affect the affordability of electricity, which must be carefully evaluated by those responsible for the formulation. of policies [51].

Finally, the RPF was 50.4%, representing the renewable energy served. Compared to the national score, this variable does not fully reflect the improvements in sustainability because the contribution of the grid was considered as non-renewable for calculus. However, in reality, the Argentine electrical matrix includes renewable energies. Furthermore, the variables calculated in this work are representative in a basic context for calculating the Trilemma Index in microgrids, being simplifications that may not capture all the complexity of each dimension of the energy trilemma. At the national level, the ET provided by the World Energy Council includes other indicators and factors, such as the macroeconomic climate, governance and stability for investment and innovation [52].

Despite these limitations, it is clear that traditional cost-benefit analysis, focused solely on financial returns, is insufficient for evaluating complex projects. Socioeconomic benefits and broader project objectives must be integrated into the decision-making process. The energy trilemma model serves as a valuable tool to measure the progress of local energy policies, identify obstacles, and foster cooperation in the energy transition [53], [54], [55].

V. CONCLUSIONS

Solar energy and biomass present significant, underdeveloped sustainable resources in Argentina's central region. This study demonstrates the substantial potential for rural communities to integrate diverse renewable sources, thereby reducing operational costs and enhancing energy system robustness during peak demand. Our objectives were to decrease grid dependence using local renewables and to mitigate the environmental impact of urban solid waste and cattle manure by transforming them into an energy source, thus addressing a critical social issue.

The abundant local solar radiation (4.82 kWh/m²/day average) and readily available animal manure underscore the viability of these resources. Utilizing HOMER software, the optimal hybrid PV-biomass grid-tied system was modeled, featuring 501 kW photovoltaic panels, a 50-kW biomass generator, and a 494.96 kW inverter. This configuration can potentially meet the site's load demand with a 50.4% renewable fraction.

Economically, the Capex is approximately USD 997,029, resulting in an energy cost of USD 0.1738/kWh, which is 73.8% higher than the local grid rate. While acceptable within the established Trilemma Index parameters, affordability remains a challenge. Nevertheless, the true value of such microgrids extends beyond direct cost, encompassing crucial non-quantifiable benefits: increased local employment, economic growth, improved education, enhanced energy resilience, and greater source diversification. These social and strategic externalities align with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (affordable, reliable, sustainable, and modern energy) and SDG 11 (sustainable cities and communities), thereby justifying the system's relevance for local energy development and long-term sustainability.

ACKNOWLEDGMENTS

This work was carried out thanks to the financing granted by the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) and by the Centro de Investigación y Transferencia de Rafaela (CIT-Rafaela) of shared responsibility corresponding to the Universidad Nacional de Rafaela (UNRaf) and CONICET.

REFERENCES

[1] R. Seminario-Córdova, "Latin America towards Sustainability through Renewable Energies: A Systematic Review," *Energies*, vol. 16, no. 21, pp. 7422, 2023, doi: 10.3390/en16217422.

[2] U. A. Dodo, E. C. Ashigwuike, and J. N. Emechebe, "Techno-economic evaluation of municipal solid waste–fueled biogas generator as a backup in a decentralized hybrid power system," *Process Integration and Optimization for Sustainability*, vol. 6, no. 2, pp. 431–446, 2022, doi: 10.1007/s41660-022-00223-9.

[3] M. Bellini, P. Bonini, M. Dallo, F. Garreta, C. Navntoft, and P. Vejrup, "Mapa de recursos energéticos alternativos de la República Argentina. Primera versión, aprovechamiento de energía eólica y solar," *Avances en Energías Renovables y Medio Ambiente*, vol. 9, 2005. [Online]. Available: https://sedici.unlp.edu.ar/handle/10915/83072.

[4] Q. Tang, J. Wu, J. Xiao, F. Zhou, and X. Wu, "A Case Study of Renewable Energy Resources Assessment Results in Argentina," in *2021 IEEE 4th Int. Electr. Energy Conf. (CIEEC)*, Wuhan, 2021, pp. 1-5, doi: 10.1109/CIEEC50170.2021.9510993.

[5] S. Bhattacharjee and A. Dey, "Techno-economic performance evaluation of grid integrated PV-biomass hybrid power generation for rice mill," *Sustainable Energy Technologies and Assessments*, vol. **7**, pp. 6-16, 2014, doi: 10.1016/j.seta.2014.02.005.

[6] F. C. Robert and S. Gopalan, "Low cost, highly reliable rural electrification through a combination of grid extension and local renewable energy generation," *Sustain. Cities Soc.*, vol. 42, pp. 344–354, 2018, doi: 10.1016/j.scs.2018.02.010.

[7] G. C. Plaza, M. N. Pasculli, and A. L. Moya, "Análisis energético de los residuos sólidos urbanos en el área metropolitana de la ciudad de Salta en un escenario futuro," *Avances En Energías Renovables y Medio Ambiente*, vol. 25, pp. 246–256, 2022. [Online]. Available: https://portalderevistas.unsa.edu.ar/index.php/averma/article/view/2419

[8] A. Jurado, E. Vinson, and F. Nicchi, "Demand statistical characterization of low voltage users in Argentinian distribution networks for distributed generation studies purposes," in *CIRED 2021 - The 26th International Conference and Exhibition on Electricity Distribution*, Viena, 2021. [Online]. Available: https://digital-library.theiet.org/content/conferences/10.1049/icp.2021.1773

[9] Empresa Provincial de la Energía (EPE), "EPE Users," Accessed: Ago. 9, 2024, [Online]. Available: https://www.epe.santafe.gov.ar/institucional/usuarios.

[10] G. Rohani and M. Nour, "Techno-economical analysis of stand-alone hybrid renewable power system for Ras Musherib in United Arab Emirates," *Energy (Oxford, England)*, vol. 64, pp. 828–841, 2014, doi: 10.1016/j.energy.2013.10.065.

[11] HOMER Energy, *"Microgrid Power System Design Services Using HOMER PRO®,"* Accessed on: Sep. 10, 2024, [Online]. Available: https://www.homerenergy.com/products/pro/index.html.

[12] NASA, *"NASA POWER. Prediction of Worldwide Energy Resources,"* [Online]. Available: https://power.larc.nasa.gov.

[13] L. I. Silva, C. Berrino, and D. Ferreyra, "Grid-Connected Photovoltaic System in Educational Building. Overview and Preliminary Data Analysis," in *2018 IEEE ANDESCON*, Santiago de Cali, Colombia, 2018, pp. 1-6, doi: 10.1109/ANDESCON.2018.8564614.

[14] Food and Agriculture Organization of the United Nations (FAO), *"Spatial analysis of the energy balance derived from biomass. WISDOM Methodology. Province of Santa Fe. Technical Documents 8,"* 2018, [Online]. Available: http://www.probiomasa.gob.ar/_pdf/WISDOM_SantaFe_interior-web.pdf.

[15] F. Martínez Waltos, *"Report on the state of the environment 2020,"* Buenos Aires, Argentina: Ministerio de Ambiente y Desarrollo Sostenible de la Nación, 2021. [Online]. Available: https://www.argentina.gob.ar/sites/default/files/iea_2020_digital.pdf.

[16] A. Singh and P. Basak, "Conceptualization and techno-economic evaluation of municipal solid waste based microgrid," *Energy (Oxford, England)*, vol. 238, no. 121711, pp. 1-12, 2022, doi: 10.1016/j.energy.2021.121711.

[17] AIREDIGITAL, "Con conciencia ciudadana, Santa Fe podría reducir hasta en un 82% la cantidad de residuos que terminan enterrados en el relleno sanitario," 2024. [Online]. Available: https://www.airedesantafe.com.ar/.

[18] E. Coutsiers, M. Gea, and R. Rodríguez, "Estimación de la tasa de costo de capital para proyectos de energía renovable en Latinoamérica," *Avances en Energías Renovables y Medio Ambiente*, vol. 26, pp. 369–380, 2022. [Online]. Available: https://portalderevistas.unsa.edu.ar/index.php/averma/article/view/3852

[19] U.S. Federal Open Market Committee & Federal Reserve Bank of St. Louis, "FOMC Summary of Economic Projections for the Personal Consumption Expenditures Inflation Rate, Central Tendency, Midpoint [PCECTPICTM]," St. Louis, MO, USA: Federal Reserve Bank of St. Louis, Mar. 20, 2024. [Online]. Available: https://fred.stlouisfed.org/series/PCECTPICTM.

[20] National Renewable Energy Laboratory (NREL), "U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, With Minimum Sustainable Price Analysis: Q1 2023," Golden, CO, USA: NREL, 2023. [Online]. Available: https://www.nrel.gov/docs/fy23osti/87303.pdf.

[21] S. Singh, M. Singh, and S. C. Kaushik, "Feasibility study of an islanded microgrid in rural area consisting of PV, wind, biomass and battery energy storage system," *Energy Conversion and Management*, vol. 128, pp. 178–190, 2016, doi: 10.1016/j.enconman.2016.09.046.

[22] M. R. Hasan, "Feasibility study to design a Biogas-Photovoltaic hybrid system for electricity generation in vicinity to urban areas in Bangladesh," M.S. thesis, Halmstad University, Halmstad,

Sweden, 2019. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:hh:diva-40060

[23] M. R. Akhtari and M. Baneshi, "Techno-economic assessment and optimization of a hybrid renewable co-supply of electricity, heat and hydrogen system to enhance performance by recovering excess electricity for a large energy consumer," *Energy Conversion and Management*, vol. 188, pp. 131–141, 2019, doi: 10.1016/j.enconman.2019.03.067.

[24] Y. R. Maghraby, A. H. Ibrahim, A. Tayel, H. M. El-Said Azzazy, and T. Shoeib, “Towards sustainability via recycling solar photovoltaic Panels, A review,” *Solar Energy*, vol. 285, pp. 113085, 2025, doi: 10.1016/j.solener.2024.113085.

[25] K. Sivagami, S. Bosea, A. Vinayak, M. Sreenivas, A. Ghosh, M. Narasimhan, and A. Gurumoorthy, “Solar Panel Recycling from Circular Economy Viewpoint: A Review,” *Applied Solar Energy*, vol. 60, no. 2, pp. 328–345, 2024, doi: 10.3103/S0003701X23601862.

[26] P. Orosco, O. Barrios, F. Tunez, and L. Barbosa, “Sustainable Recycling of Silicon from End-of-Life Photovoltaic Panels for the Synthesis of Porous Cordierite Via Bischofite-Assisted Chlorination,” *Silicon,* vol. 17, pp. 889–903, 2025, doi: 10.1007/s12633-025-03244-4.

[27] M. E. Vidal and G. Loza, “Urban Policies in Argentina and Their Territorial Planning in the Context of SDG 11: The Case of Rafaela and Villa María” In *Urban Policy in the Framework of the 2030 Agenda: Balance and Perspectives from Latin America and Europe,* M. Á. Huete García, A. Rodríguez Miranda, V. Ugalde, R. Merinero Rodríguez, Eds. Cham, Switzerland: Springer Nature, 2023, pp. 9-35, doi: 10.1007/978-3-031-38473-8_2.

[28] F. Iseri, H. Iseri, E. Iakovou, and E. N. Pistikopoulos, “A circular economy systems engineering framework for waste management of photovoltaic panels,” *Industrial & Engineering Chemistry Research*, vol. 64, no. 30, pp. 14986-14997, 2025, doi: 10.1021/acs.iecr.5c00588.

[29] A. K. Tripathi, M. Aruna, A. K. Thandlam, S. Sharma, A. Jhalani, and R, Kumar, “Recovery strategies for EoL solar panels: sustainable and circular economy practices,” *Green Materials*, pp. 1-10, 2025, doi: 10.1680/jgrma.24.00153.

[30] A. Kasaeian, P. Rahdan, M. A. Rad, and W. M. Yan, "Optimal design and technical analysis of a grid-connected hybrid photovoltaic/diesel/biogas under different economic conditions: A case study," *Energy Conversion and Management*, vol. 198, no. 111810, pp. 111810, 2019, doi: 10.1016/j.enconman.2019.111810.

[31] H. Al-Najjar, C. Pfeifer, R. Al Afif, and H. J. El-Khozondar, "Performance Evaluation of a Hybrid Grid-Connected Photovoltaic Biogas-Generator Power System," *Energies*, vol. 15, no. 9, pp. 3151, 2022, doi: 10.3390/en15093151.

[32] B. K. Das, N. Hoque, S. Mandal, T. K. Pal, and M. A. Raihan, "A techno-economic feasibility of a stand-alone hybrid power generation for remote area application in Bangladesh," *Energy (Oxford, England)*, vol. 134, pp. 775–788, 2017, doi: 10.1016/j.energy.2017.06.024.

[33] M. Mohammed, I. S. Egyir, A. K. Donkor, P. Amoah, S. Nyarko, K. K. Boateng, and C. Ziwu, "Feasibility study for biogas integration into waste treatment plants in Ghana," *Egyptian Journal of Petroleum*, vol. 26, no. 3, pp. 695–703, 2017, doi: 10.1016/j.ejpe.2016.10.004.

[34] J. Li, P. Liu, and Z. Li, "Optimal design and techno-economic analysis of a solar-wind-biomass off-grid hybrid power system for remote rural electrification: A case study of west China," *Energy*, vol. 208, no. 118387, pp. 1-12, 2020, doi: 10.1016/j.energy.2020.118387.

[35] S. O. Sanni, M. Ibrahim, I. Mahmud, T. O. Oyewole, and K. O. Olusuyi, "Potential of Off-grid Solar PV/Biogas power generation system: case study of Ado Ekiti slaughterhouse," *International Journal of Renewable Energy Research*, vol. 9, pp. 1309–1318, 2019, doi: 10.20508/ijrer.v9i3.9559.g7711.

[36] D. T. Ogunwo, "Techno-economic feasibility of electrifying food markets in Nigeria with biogas hybrid mini-grids," M.S. thesis, Cal Poly Humboldt, Arcata, CA, USA, 2022. [Online]. Available: https://digitalcommons.humboldt.edu/etd/577.

[37] M. M. Rahman, M. M. Hasan, J. V. Paatero, and R. Lahdelma, "Hybrid application of biogas and solar resources to fulfill household energy needs: A potentially viable option in rural areas of developing countries," *Renewable Energy*, vol. 68, pp. 35–45, 2014, doi: 10.1016/j.renene.2014.01.030.

[38] E. U. Khan, B. Mainali, A. Martin, and S. Silveira, "Techno-economic analysis of small scale biogas based polygeneration systems: Bangladesh case study," *Sustainable Energy Technologies and Assessments*, vol. **7**, pp. 68–78, 2014, doi: 10.1016/j.seta.2014.03.004.

[39] Polígono, "Conoce cómo se conforma la matriz energética argentina," Accessed: Sep. 26, 2024, [Online]. Available: https://poligono.com.ar/2024/05/30/conoce-como-se-conforma-la-matriz-energetica-argentina/.

[40] CAMMESA, "Annual Report 2023," [Online]. Available: https://cammesaweb.cammesa.com/informe-anual/.

[41] T. Pamulapati, M. Cavus, I. Odigwe, A. Allahham, S. Walker, and D. Giaouris, "A review of microgrid energy management strategies from the energy trilemma perspective," *Energies*, vol. 16, no. 1, pp. 289, 2022, doi: 10.3390/en16010289.

[42] S. Torro, R. Rusdi, D. Manda, S. Saleh, H. Akib, D. Paramitha Darmayanti, and H. Ardin, "Assessing Public Awareness and Stakeholder Influence in Renewable Energy Implementation: A Case Study from Sulawesi, Indonesia," *J. Asian Energy Stud.*, vol. 8, pp. 95-109, 2024. [Online]. Available: https://ejournals.lib.hkbu.edu.hk/index.php/jaes/article/view/2787.

[43] S. Karimzadeh and E. Kašparová, "Socio-individual prerequisites of energy transition in Iran: Investigating public acceptance of solar panel technology in rural areas," *J. Asian Energy Stud.*, vol. 5, no. 1, pp. 42-57, 2021, doi: 10.24112/jaes050004.

[44] J. Lacea, E. Querikiol, and E. Taboada, "Balancing energy trilemma using hybrid distributed rooftop solar PV (DRSP)/battery/diesel microgrid: A case study in Gilutongan Island, Cordova, Cebu, Philippines," *Energies*, vol. 14, no. 21, pp. 7358, 2021, doi: 10.3390/en14217358.

[45] M. Kojima and C. Trimble, "*Making power affordable for Africa and viable for its utilities,"* Washington, DC, USA: World Bank, 2016. [Online]. Available: https://www.worldbank.org/en/topic/energy/publication/making-power-work-for-africa

[46] INDEC, Instituto Nacional de Estadísticas y Censos de la REPÚBLICA ARGENTINA, "Evolución de la distribución del ingreso (EPH) Segundo trimestre de 2024," 2024. [Online]. Available: https://www.google.com/search?q=https://www.indec.gob.

[47] ARUP, "Five minute guide to the Energy Trilemma," 2019. [Online]. Available: https://www.arup.com/insights/five-minute-guide-to-the-energy-trilemma/.

[48] A. K. Karmaker, M. R. Ahmed, M. A. Hossain, and M. M. Sikder, "Feasibility assessment & design of hybrid renewable energy based electric vehicle charging station in Bangladesh," *Sustainable Cities and Society*, vol. 39, pp. 189–202, 2018, doi: 10.1016/j.scs.2018.02.035.

[49] T. A. Boghdady, A. J. Alamer, M. M. Yousef, A. M. Elshafee, M. A. Hassan, and A. M. Seif, "Technical and economic study of powering poultry farm in Egypt using PV-biomass on-grid energy generation system: Case study," *WSEAS Transactions on Power Systems*, vol. 16, pp. 67–77, 2021, doi: 10.37394/232016.2021.16.7.

[50] M. R. Quitoras, P. E. Campana, P. Rowley, and C. Crawford, "Remote community integrated energy system optimization including building enclosure improvements and quantitative energy trilemma metrics," Applied Energy, vol. 267, no. 115017, pp. 115017, 2020, doi: 10.1016/j.apenergy.2020.115017.

[51] R. Jing, Y. Lin, N. Khanna, X. Chen, M. Wang, J. Liu, and J. Lin, "Balancing the Energy Trilemma in energy system planning of coastal cities," *Applied Energy*, vol. 283, no. 116222, pp. 116222, 2021, doi: 10.1016/j.apenergy.2020.116222.

[52] World Energy Council and Oliver Wyman, "*World Energy Trilemma Index 2017: Monitoring the Sustainability of National Energy Systems*." London, UK: World Energy Council, 2017. [Online]. Available: https://www.worldenergy.org/assets/downloads/Energy-Trilemma-Index-2017-Report.pdf

[53] E. Zafeiratou and C. Spataru, "Sustainable Island power system – Scenario analysis for Crete under the energy trilemma index," *Sustain. Cities and Society*, vol. 41, pp. 378–391, 2018, doi: 10.1016/j.scs.2018.05.054.

[54] R. Wu and G. Sansavini, "Energy trilemma in active distribution network design: Balancing affordability, sustainability and security in optimization-based decision-making," *Applied Energy*, vol. 304, pp. 117891, 2021, doi: 10.1016/j.apenergy.2021.117891.

[55] S. Sefiane, M. N. E. Hoda, and H. Ahmed, "Financial or Socio-economic feasibility? Potential assessment of renewable energy investment in Algeria," *J. Asian Energy Stud.*, vol. 6, no. 1, pp. 48–58, 2022, doi: 10.24112/jaes.060004.

Juan Pablo Cecchini holds a Ph.D. in Chemical Engineering from the National University of the Littoral, UNL, Santa Fe, Argentina. He is a researcher at the National Scientific and Technical Research Council (CONICET) and professor at the National University of Rafaela (UNRaf). His research focuses on the renewable energies and environment. His research interests include clean energy, life cycle assessment (LCA) and multidisciplinary projects.

Luis I. Silva received his Electronic Engineering degree (2005) from Universidad Nacional de Rosario, Argentina; his MS degree in Space Sciences (2007) from Lulea Technical University, Sweden and his Doctorate in Engineering Sciences (2012) from Universidad Nacional de Río Cuarto, Argentina. He is also an official researcher at the National Scientific and Technical Research Council (CONICET) of Argentina. His research interest is focused on modelling and simulation of electrical systems and energy efficiency of electrical machines and drives.

Luis E. Venghi received his degree in Electronic Engineering in 2016, from Universidad Nacional de San Luis, San Luis, Argentina. He also received his PhD degree in Engineering Sciences in 2022, at the Universidad Nacional de Río Cuarto, Córdoba, Argentina. He is currently a Postdoctoral Fellow of CONICET and member of the Research and Transfer Center of the Universidad Nacional de Rafaela, Santa Fe, Argentina. His topics of interest are: electric drives, fault diagnosis, fault tolerance and electric vehicles.

Carlos R. Rodríguez received his physical chemistry degree from the National University of Córdoba - UNC (1989). Doctorate in Physics (PhD) - UNC (2000). Postgraduate degree in Finance from the Argentine Business University - UADE (2024).

Senior Associate Consultant at Caldén Consulting (2022). President of the Nova Vektors Foundation (2015). Professor in the Department of Mathematics of the Faculty of Exact, Physical and Natural Sciences - UNC (2009) to the present. Experience and area of interest in research and transfer: Management of the production, storage, transportation, and use of Sustainable Energy and Energy Vectors, and Rational and Efficient Use of Energy.

Ernesto Coutsiers holds a Master's in Business Administration (UTN, FRC), a Master's in Renewable Energy Management (University of Barcelona), and is a Doctoral candidate in Sciences, Renewable Energy Area (UN Salta). He is a specialist in regulation, in the economic evaluation of energy projects, and a founding partner of the consulting firm Calden. He works on projects throughout Latin America, the USA, the EU, and Asia. He is dedicated to the regulatory development of concession contract renewals, the integration of renewable energies into energy systems, and the economic analysis of the green hydrogen value chain. He is strongly committed to the energy transition and the development of new professionals in the sector.