Optimization of biomethane production and distribution networks from livestock waste in Northwest Argentina

Ferraro, Santiago[1,2] [0009−0003−5243−0184], Machin Ferrero, Lucas M.[1,2] [0000−0003−1348−6057], Mele, Fernando D.[1,2] [0000−0003−4401−7878]

[1] Facultad de Ciencias Exactas and Tecnología, Universidad Nacional de Tucumán. Av. Independencia 1800, T4000 San Miguel de Tucumán, Tucumán, Argentina.
[2] Consejo Nacional de Investigaciones Científicas and Técnicas, CCT CONICET NOA Sur, Crisóstomo Álvarez 722, T4000 San Miguel de Tucumán, Tucumán, Argentina.
santiagoferraro99@gmail.com
lmachinferrero@herrera.unt.edu.ar
fmele@herrera.unt.edu.ar

Abstract. In the current context of climate change and energy transition, biomethane is emerging as a sustainable biofuel with significant potential for transportation and injection into the natural gas grid. This study proposes a mixed-integer linear programming (MILP) model to design the optimal configuration of the biomethane supply chain over a multi-period horizon. The model integrates two objective functions: an economic one (total cost) and an environmental one (global warming potential), incorporating Life Cycle Assessment as a methodology to evaluate environmental impacts. Key constraints are imposed, including livestock waste availability, product demand, and mass balances, allowing the assessment of two strategic approaches: (i) maximizing the use of available feedstock and (ii) partially satisfying the demand for compressed natural gas. Model results include the optimal location, capacity, and number of biomethane production facilities, as well as the annual flows of raw materials to be processed and the product obtained. A trade-off between objectives is observed, as prioritizing cost reduction leads to a higher environmental impact and *vice versa*. Furthermore, the optimal supply chain configuration varies depending on the strategy adopted and the selected objective function. Finally, in the optimizations performed, the environmental credits outweigh the global warming potential generated by the supply chain, confirming the role of biomethane as a viable solution for climate change mitigation.

Keywords: biogas, sustainable transportation, supply chain management, math programming.

Optimización de redes de producción y distribución de biometano a partir de residuos ganaderos en el Noroeste Argentino

Resumen. En el contexto actual de cambio climático y transición energética, el biometano se posiciona como un biocombustible sostenible con gran potencial para el transporte y la inyección en la red de gas natural. Este estudio propone un modelo matemático MILP (mixto entero lineal) para diseñar la configuración óptima de la cadena de suministros de biometano en un horizonte multiperíodo. El modelo integra dos funciones objetivo: una económica (costos totales) y otra ambiental (potencial de calentamiento global), incorporando el Análisis de Ciclo de Vida como metodología para evaluar los impactos ambientales. Se imponen restricciones clave, como la disponibilidad de residuos ganaderos, la demanda del producto y los balances de materia, permitiendo evaluar dos enfoques estratégicos: (i) maximización del uso de materia prima disponible y (ii) satisfacción parcial de la demanda de gas natural comprimido. Los resultados del modelo determinan la ubicación, capacidad y cantidad óptima de plantas de producción de biometano, así como los flujos anuales de materia prima a tratar y de producto obtenido. Como resultado se observa un compromiso entre los objetivos, ya que priorizar la reducción de costos conlleva un mayor impacto ambiental y viceversa. Además, la configuración óptima de la cadena de suministros varía según la estrategia adoptada y la función objetivo elegida. Finalmente, en las optimizaciones realizadas, los créditos ambientales superan el potencial de calentamiento global generada por la cadena de suministros, reafirmando el papel del biometano como una solución viable para la mitigación del cambio climático.

Palabras claves: biogás, transporte sostenible, gestión de cadenas de suministros, programación matemática.

1 Introduction

Climate change and biodiversity loss have emerged as dominant environmental risks on the global agenda, prompting the 2030 Agenda for Sustainable Development to emphasize the need for urgent and effective mitigation strategies (World Economic Forum, 2024). Key actions include the deployment of renewable energy sources, improvements in energy efficiency, electrification, and a progressive reduction in fossil fuel consumption (International Energy Agency, 2023). In Argentina, more than 80% of primary energy demand is still met by hydrocarbons, with natural gas accounting for 53% and oil for 31% of the energy mix (Carrizo & Jacinto, 2024).

The transportation sector is particularly carbon-intensive, accounting for about 30% of national greenhouse gas emissions (Climate Transparency, 2022). Within this sector, oil accounts for 82% of energy consumption, followed by compressed natural gas (CNG) (12%) and biofuels (5.5%), while electricity remains marginal. These figures underscore the urgent need to diversify the energy matrix with sustainable alternatives, especially in the transportation sector.

In response, Argentina has promoted the development of biofuels since the late 2000s, primarily through mandatory blending policies. More recently, the focus has expanded to include biogas and biomethane as cleaner alternatives. In 2022, biogas production reached 418 GWh, an increase of 10.6% over the previous year. This growth is driven by 27 industrial plants that convert organic waste into energy and fertilizer. A notable example is a biomethane project led by YPF, which will inject 12,000 m³/day of biomethane into the national gas grid, using waste from a meat processing plant (Bioeconomía, 2024).

This growing interest is particularly relevant in Northwest Argentina (NWA), where significant biomass potential remains underutilized. This biomass comes mainly from the agricultural and livestock sectors and includes cattle manure, lignocellulosic residues from crops such as sugarcane and cereals, and agro-industrial effluents. In the province of Tucumán —home to a dense dairy basin— a large volume of cattle manure is generated annually. This manure represents an untapped resource with significant potential for biomethane production, providing both energy and environmental benefits (Quaia et al., 2023).

In this context, this study proposes a mathematical model to design the optimal configuration of a biomethane supply chain (SC) in a multi-period horizon. This SC includes the following steps: (i) biomass collection from dairy farms, (ii) transportation to processing plants, (iii) anaerobic digestion and upgrading to biomethane, and (iv) distribution to demand centers, primarily for transportation use. If demand is exceeded, excess biomethane can be injected into the national gas grid, as allowed by current regulations (ENARGAS, 2019). Biomethane production involves two key technological steps: anaerobic digestion, in which microorganisms convert organic matter into biogas, and biogas upgrading, which cleans the gas to meet quality standards for injection into the natural gas grid. In addition, the resulting by-product, digestate, can be used as a biofertilizer.

2 Problem Statement and Methods

This study aims to optimally design a biomethane SC based on livestock waste in the province of Tucumán, with the objective of deploying an efficient production and distribution system to supply biomethane for transportation purposes, while allowing the surplus to be injected into the existing natural gas network. To achieve this, an optimization model is proposed, that incorporates two alternative objective functions: the first (FO_1) minimizes the total cost (TC) of the SC, while the second (FO_2) minimizes its global warming potential (GWP). The model also includes mass-balance equations and operational constraints, and can be readily applied to different case studies, with some equations varying slightly depending on the specific context considered (see Section 3.1).

A mixed-integer linear programming (MILP) model is formulated. This model identifies the optimal configuration of the chain, including the number, capacities, locations, and installation timing of production facilities, as well as the coverage of regional demand. It also determines the annual flows of feedstock, products, and by-products, along with the associated costs and environmental impact, specifically the GWP of the SC.

The model considers several types of materials, denoted by i, which fall into three subsets: raw materials $IRM(i)$ (e.g., manure), main products $IMP(i)$ (e.g., biomethane), and by-products $IBP(i)$ (e.g., digestate). It also includes a set of candidate plants p, each with discrete processing capacities c. The geographic regions g (e.g., provinces or departments) are divided into three subsets: feedstock supply regions $GRM(g)$, potential plant locations $GP(g)$, and product demand regions $GD(g)$. Temporal planning is represented by t time periods (e.g., months or years), and l denotes the transportation modes. The subset $IL(i, l)$ specifies which material i can be transported by which mode l.

Although the formulation is general enough to accommodate different feedstocks, products, and by-products, the equations are described using bovine manure as the feedstock, biomethane as the product, and digestate as the by-product. The term "plants" refers to integrated biomethane facilities that combine anaerobic digestion and biogas upgrading via water scrubbing. Biomethane can serve multiple uses. The model considers two main pathways: (1) the biomethane is transported for direct consumption at fueling stations within the demand regions, thereby meeting internal demand; and (2) any surplus of biomethane, once local demand is satisfied, is injected into the existing natural gas distribution network.

2.1 Economic Objective Function

The economic objective function (Eq. 1) represents the total discounted cost of the biomethane SC ($TCSP$), calculated as the sum of all t period-specific costs (TC_t) over the planning horizon, discounted by an interest rate (INT).

$$FO_1: \quad TCSP = \sum_t \left[\frac{TC_t}{(1 + \mathrm{INT})^{t-1}} \right] \tag{1}$$

Each period's total cost (Eq. 2) includes the cost of raw material acquisition (RMC_t), its transportation (TC_t^{RM}) from supply regions $g \in GRM(g)$ to production regions $g \in GP(g)$, plant investment and operating costs (PC_t), product transport costs including gas pipeline installation (TC_t^{MP}), and the transport cost of by-products to disposal sites (TC_t^{BP}). Penalties associated with unmet product demand in a region are not considered.

$$TC_t = \ RMC_t + TC_t^{RM} + PC_t + TC_t^{MP} + TC_t^{BP}, \forall\, t \tag{2}$$

The details of calculating each of these terms, which involve continuous and binary variables as well as numerous price and cost parameters, are omitted for space reasons.

2.2 Environmental Objective Function

For the environmental objective function, GWP is used as the primary indicator of environmental impact. This metric quantifies the total greenhouse gas emissions associated with an activity throughout its life cycle. Similar to the cost-based objective, the GWP is calculated for each stage of the SC and subsequently aggregated in a modular approach to obtain the total environmental impact. Thus, the objective function minimizes the total GWP of the biomethane SC ($GWPTSP$), which is defined as the sum of the GWP for each period t ($GWPT_t$) over the entire planning horizon (Eq. 3). The GWP is expressed in kilograms of carbon dioxide equivalent (kg CO_2e).

$$FO_2: \quad GWPTSP = \sum_t GWPT_t \tag{3}$$

Each period's emissions (Eq. 4) are determined by multiplying the reference flow of each SC stage by its corresponding emission factor. Emission parameters are based on the Life Cycle Assessment (LCA) methodology, guided by the principles of ISO 14040 (2006).

The total GWP in period t is composed of several components. GWP_t^{RM} represents the emissions associated with the use of raw materials, while GWP_t^{TRM} accounts for the emissions associated with their transportation. GWP_t^{ProdMP} gives the emissions related to product manufacturing, including infrastructure requirements. GWP_t^{BP} reflects the emissions from the transportation, distribution, and disposal of by-products. $GWP_t^{TranspMP}$ measures the emissions from transporting biomethane to demand points, including infrastructure construction, whereas GWP_t^{EX} only considers the emissions from transporting the excess biomethane. Finally, GWP_t^{UMP} includes emissions related to the distribution of biomethane to fueling stations and its final use in passenger transportation.

In addition, the model incorporates LCA-based environmental credits for the avoided emissions arising from substituting fossil-based products, thereby enabling the optimization framework to internalize these benefits and steer decisions toward lower carbon SC configurations. Specifically, the digestate generated during anaerobic digestion is assumed to replace fossil-based urea fertilizer, and the associated GHG emissions are credited accordingly (Quaia et al., 2023); furthermore—and solely for modelling purposes—biomethane is credited with the emissions it avoids when substituting natural gas. These benefits, for urea and natural gas, are quantified by the variables $GWP_{u,t}^{av}$ and $GWP_{ng,t}^{av}$, respectively, which are subtracted from the total GWP for each period t.

$$\begin{aligned} GWPT_t = {} & GWP_t^{RM} + GWP_t^{TRM} + GWP_t^{ProdMP} + GWP_t^{BP} + GWP_t^{TranspMP} \\ & + GWP_t^{UMP} + GWP_t^{EX} - GWP_{u,t}^{av} - GWP_{ng,t}^{av}, \qquad \forall\, t \end{aligned} \tag{4}$$

Again, space does not permit us to go into the details of calculating each of these terms, which involve numerous environmental parameters that have been estimated prior to running the model.

2.3 Material Balance and Inventory Constraints

The model's constraints are based on material balances, regional manure availability, CNG demand in consumption regions, and capacity limitations in both biomethane production and transportation systems (for manure and biomethane).

Equation 5 defines that the availability ($A_{i,g,t}$) of raw material $i \in IRM(i)$ in supply region $g \in GRM(g)$ must be allocated either to internal consumption ($H_{i,g,t}$) within the region or to the total quantity of raw material transported from supply regions to production regions $g' \in GP(g')$ using transport method l during period t ($Q_{i,l,g,g',t}$).

$$H_{i,g\in(GRM(g)\cap GP(g)),t} + \sum_{g'\in GP(g'),g'\neq g,l\in IL(i,l)} Q_{i,l,g,g',t} = A_{i,g,t} \quad \forall\, i \in IRM(i), g \in GRM(g), t \tag{5}$$

In production regions $g \in GP(g)$, all available raw material $i \in IRM(i)$, whether sourced locally ($H_{i,g,t}$) or transported from other regions ($Q_{i,l,g',g,t}$), is allocated to biomethane production plants (Eq. 6). The amount directed to each plant p of capacity c in region g during period t is represented by $X_{i,p,c,g,t}$.

$$\sum_{g'\in GRM(g'),g'\neq g,l\in IL(i,l)} Q_{i,l,g',g,t} + H_{i,g\in(GRM(g)\cap GP(g)),t} = \sum_{p,c} X_{i,p,c,g,t} \quad \forall\, i \in IRM(i), g \in GP(g), t \tag{6}$$

Material input to each plant is subject to capacity constraints (Eq. 7 and 8), defined by the minimum and maximum processing capacities ($\mathrm{pCAPmin}_c$, $\mathrm{pCAPmax}_c$) of plants with capacity c. These flows can only occur if the plant is constructed, which is modeled through a binary decision variable $y_{p,c,g,t}$ that equals 1 if the plant p of capacity c is built in region g and time t. A summation over prior periods $t' < t$ ensures that once constructed, the plant remains operational in subsequent periods.

$$\mathrm{pCAPmin}_c \sum_{t'<t} y_{p,c,g,t'} \leq X_{i,p,c,g,t}\,, \qquad \forall\, i \in IRM(i), g \in GP(g), p, c, t \tag{7}$$

$$X_{i,p,c,g,t} \leq \sum_{t'<t} y_{p,c,g,t'}\, \mathrm{pCAPmax}_c\,, \qquad \forall\, i \in IRM(i), g \in GP(g), p, c, t \tag{8}$$

Biomethane production (Eq. 9) in plant p of capacity c in region g during period t is determined by multiplying the input of each raw material $i' \in IRM(i)$ by its corresponding conversion factor $\rho_{i',i}$, expressed in cubic meters of biomethane per tonne of raw material.

$$X_{i,p,c,g,t} = \sum_{i'\in IRM(i')} \rho_{i',i}\, X_{i',p,c,g,t}\,, \qquad \forall\, i \in IMP(i), p, c, g \in GP(g), t \tag{9}$$

Similar equations are used to model the production of by-products, e.g., digestate.

All biomethane $i \in IMP(i)$ produced in each region $g \in GP(g)$ is transported to demand regions $g \in GD(g)$ in the same period (Eq. 10).

$$\sum_{p,c} X_{i,p,c,g,t} = \sum_{g' \in GD(g'), g' \neq g, l \in IL(i,l)} Q_{i,l,g,g',t} \ , \qquad \forall\, i \in IMP(i), g \in GP(g), t \quad (10)$$

Digestate generated as a by-product $i \in IBP(i)$ is also transported ($QBP_{g,t}$) for its final application as fertilizer (Eq. 11).

$$\sum_{i \in IBP(i),p,c} X_{i,p,c,g,t} = QBP_{g,t} \ , \qquad \forall\, g \in GP(g), t \quad (11)$$

The amount of biomethane transported is constrained by minimum and maximum pipeline capacity limits.

To avoid redundant infrastructure, once a pipeline is constructed between regions g and g' in a given period t, the model prohibits its reinstallation in subsequent periods. Also, only one pipeline can be constructed between any given production region and demand region. These constraints are not presented for space reasons.

The product balance constraint (Eq. 12) for product $i \in IMP(i)$ in demand regions $g \in GD(g)$ states that the total quantity transported must fulfill the demand $\mathrm{Dem}_{i,g,t}$, with any surplus optionally exported ($EX_{i,g,t}$) or, if insufficient, represented as unmet demand ($DEF_{i,g,t}$).

$$\sum_{g' \in GP(g'), g' \neq g, l \in IL(i,l)} Q_{i,l,g',g,t} + DEF_{i,g,t} = \mathrm{Dem}_{i,g,t} + EX_{i,g,t} \qquad \forall\, i \in IMP(i), g \in GD(g), t \quad (12)$$

The optimization problem can be defined as follows: given the availability of raw materials and a specified product demand for each region g and time period t, along with fixed and variable costs, SC stage-specific environmental impact indicators, and the conversion efficiencies of materials i transported via transport modes l, the objective is to determine the optimal material flows per period and the number of biomethane plants p of capacity c to be installed in each region g over time t. The goal is to minimize the total SC cost or the total SC environmental impact. Material flows are activated only when a production plant is installed, a condition governed by binary variables, thereby ensuring a consistent and efficient SC design.

3 Case Studies

This section describes how the proposed model is used to solve the specific case studies considered. The economic and environmental evaluations performed are also presented, along with the assumptions made to estimate the parameters needed to solve the optimization problem.

3.1 Set Specifications and Description of Proposed Cases

Materials and regions. The set of materials i includes manure, digestate, and biomethane. Manure belongs to the subset of raw materials $IRM(i)$, digestate to the subset of by-products $IBP(i)$, and biomethane to the subset of main products $IMP(i)$. The regional set g comprises 28 geographic locations within the province of Tucumán (Fig. 1). Regions with raw material availability form the subset $GRM(g)$ (Fig. 1a), which are representative of livestock production areas in each department (RIDES, 2016). Departments with less than 500 heads of cattle are excluded from the analysis. The subset $GD(g)$ includes demand regions, defined as departmental capitals with access to the national gas pipeline network (ENARGAS, 2024) (Fig. 1b). All regions within $GRM(g)$ are assumed to be potential production regions $GP(g)$. Table 1 lists all the regions considered. In some cases, departments appear under different codes due to spatial divergence between supply and demand locations within the same department.

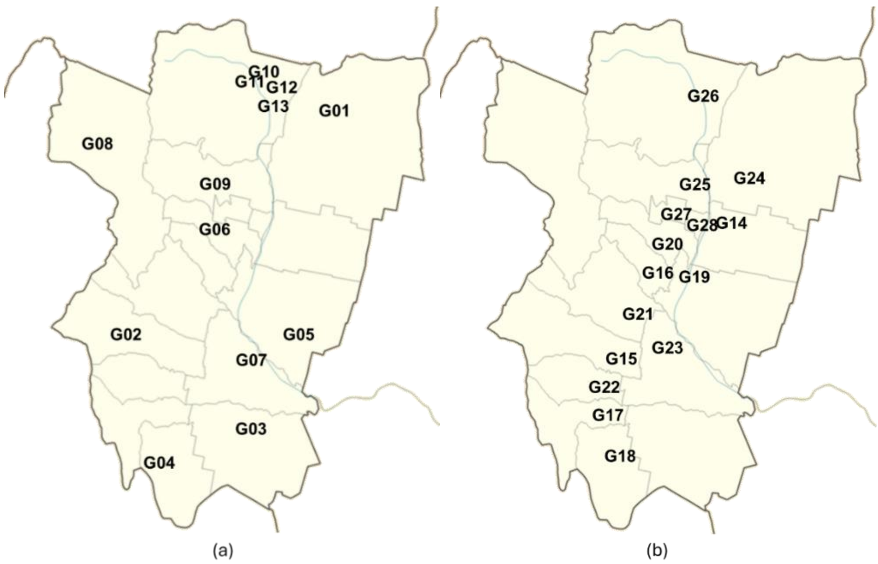

Fig. 1. Geographical distribution of regions considered. (a) Regions with raw material availability and production capacity. (b) Regions with biomethane demand.

Cases considered. Based on the formulation presented in the previous section, the model can be approached from two perspectives: a supply-driven or a demand-driven framework. In the supply-driven approach, the constraints enforce the full utilization of available raw material, whereas in the demand-driven approach, the model is required to satisfy a predefined fraction of the total demand. Accordingly, two case studies are proposed:

Case A: The model is constrained to use all the available manure, considering all regions. In this scenario, the system is driven by feedstock availability using Equations 1-12.

Case B: The model is constrained to meet a specified portion of total demand, assuming that a fraction of CNG demand can be replaced by biomethane. However, due to the infeasibility of meeting the total demand in all demand regions, only the three regions with the highest demand are considered: Cruz Alta (G14), Tafí Viejo (G25), and Capital (G28). These regions account for approximately 60% of the total CNG demand, and the percentage of demand required to be met in them is set at 5%. In this case, the system is demand-driven, using Eq. 1-11, modifying Eq. 5 as an inequality (≤). This allows for the possibility that not all available raw material is consumed.

Additionally, the product balance constraint (Eq. 12) is modified by removing the variables that represent surplus ($EX_{i,g,t}$) and unmet demand ($DEF_{i,g,t}$) and modifying it as an inequality (≥). This ensures that the total transported product is at least equal to the specified demand, resulting in Eq.13, which is considered in this case. The scalar DemFraction represents the required fraction of demand to be met in the demand regions.

$$\sum_{g' \in GP(g'), g' \neq g, l \in IL(i,l)} Q_{i,l,g',g,t} \geq \text{DemFraction } \text{Dem}_{i,g,t} \qquad \forall\, i \in IMP(i), g \in GD(g), t \tag{13}$$

For both case studies, a multi-period optimization is performed using two separate objective functions (FO_1 and FO_2), over a fifteen-year time horizon (2025–2039).

Table 1. GRM and GP regions (G01 – G13), and regions within GD (G14 – G28).

Name	Code	Name	Code	Name	Code	Name	Code
Burruyacú	G01	Tafí del V.	G08	Chicligasta	G15	Río Chico	G22
Chicligasta	G02	Tafí Viejo	G09	Famaillá	G16	Simoca	G23
Graneros	G03	Trancas 01	G10	Juan Alb.	G17	Burruyacú	G24
La Cocha	G04	Trancas 02	G11	La Cocha	G18	Tafí Viejo	G25
Leales	G05	Trancas 03	G12	Leales	G19	Trancas	G26
Lules	G06	Trancas 04	G13	Lules	G20	Yerba B.	G27
Simoca	G07	Cruz Alta	G14	Monteros	G21	Capital	G28

3.2 Model Parameters

The model integrates several key parameters, including productivity and equivalence factors, time allocation factors for infrastructure, maximum and minimum capacity parameters for facilities and transportation and distance parameters. These are derived from process simulations, established databases, and relevant literature, to ensure a consistent representation of material transformations, mobility efficiency, input equivalence, and infrastructure over the model's time horizon.

Manure availability. To estimate the availability of cattle manure as a feedstock for biomethane production, regional data from SENASA (2024) detail the current number of cattle by department and type of production in Tucumán. Manure production rates are taken from EEAOC (Quaia et al., 2023). If the production type is not specified, the higher manure generation rate is assumed. Annual manure quantities per department are projected based on historical cattle trends (2009-2020), assuming linear growth and a fixed distribution across departments (SENASA, 2024).
CNG demand. The CNG demand potentially met by biomethane is estimated using national and international data. It evolves over time due to population growth, fuel substitution, and fleet renewal. Argentina's total natural gas demand is projected using population forecasts (K.C. et al., 2024) and the evolution of the expected CNG vehicle share in Latin America. These projections adjust demand over time, taking into account both population dynamics and changes in CNG vehicle penetration. The projected CNG demand is then allocated to Tucumán using historical ENARGAS (2024) shares. Department-level demand is then distributed proportionally to population based on the projections.
Economic costs. These are obtained from literature sources and updated to 2024 values using M&S cost indices. They include transportation costs for manure by truck (Hoo et al., 2019) and for biomethane by pipelines (Moretto, 2024). Installation costs are disaggregated for each capacity considered for anaerobic digesters and biogas upgrading units, and for pipeline infrastructure (Sun et al., 2015).
Global warming potential. From an environmental perspective, an LCA methodology is applied to estimate and quantify the GWP that defines the environmental parameters of the proposed model. This includes the GWP associated with each stage of the biomethane SC used for passenger mobility —including the GWP of the digestate used as biofertilizer— as well as the GWP of CNG used for the same purpose and of the mineral fertilizer (urea) used in agriculture. The latter two are included to account for the environmental benefits of replacing CNG with biomethane and mineral fertilizer with digestate.

4 Results

The model formulation is implemented in GAMS® v24.0.2 and solved using the MILP solver CPLEX 11.0 on a DELL INSPIRON 15 PC equipped with an AMD Ryzen 5 5500U processor (2.10 GHz) and 8 GB of RAM. The mathematical model contains 25,439 equations, 28,772 continuous and 8,055 binary variables. On average, the CPLEX solver took 9,041 seconds to reach an optimal solution gap of 1%.

The proposed model is run independently for each defined case study and objective function, resulting in four sets of outcomes: two driven by the economic objective function and two driven by the environmental objective function. Accordingly, the resulting subcases are named as follows: Economic Case A (AE) and Environmental Case A (AA), which are driven by feedstock availability, and Economic Case B (BE) and Environmental Case B (BA), driven by demand.

Figures 2 and 3 present the main results regarding the spatial distribution of biomethane production facilities and the corresponding transportation logistics to the regions where demand is partially met.

In Case AE (Fig. 2), a total of nine plants are installed over the entire time horizon, with eight of them commissioned in the first year (2025) and the other in 2036, most of which are large-scale facilities (five in total). Additionally, five pipelines are installed to serve five regions —only one of which produces a biomethane surplus that is injected into the national natural gas grid. Case AA (Fig. 2) involves the installation of thirteen plants —six small-scale and four large-scale— most of which are installed in the first year (nine plants), with the remaining four distributed over the 2026–2031 period. Additionally, eight pipelines are installed to serve seven regions. For Case BE (Fig. 3), nine plants and three pipelines are installed to meet the demand of the three designated regions. Only four plants are installed in the first year, followed by three during 2027–2029, and the remaining two in 2032 and 2033 (one per year). Most of the plants are medium-scale (five in total). Finally, in Case BA (Fig. 3), the solution involves the installation of eleven plants —nine in the initial year and the remaining two in 2027— mostly small and large-scale facilities. In addition, six pipelines are installed to meet the demand of the three target regions.

A summary of the mono-objective optimization results such as total cost and total GWP of the SC, pipeline length constructed, total demand coverage and total raw material utilization for all proposed cases, is provided in Table 2.

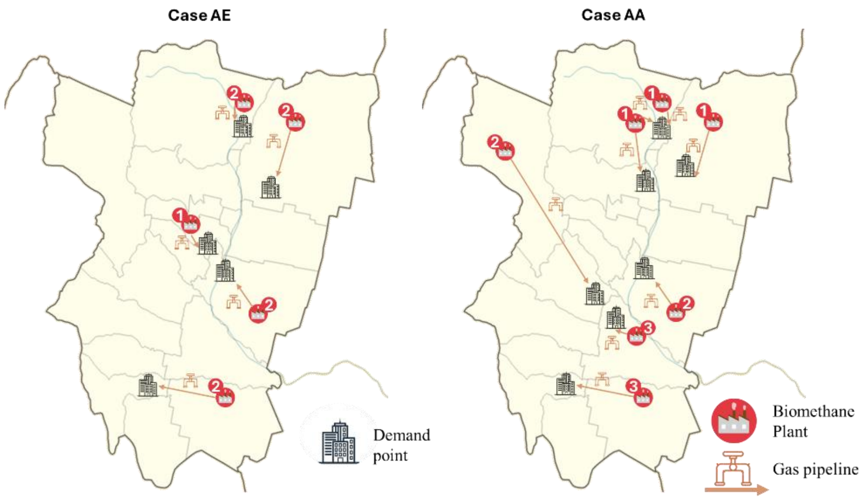

Figure 2. Total number of biomethane plants installed over the 15-year planning horizon for Case A, under the economic objective (left) and the environmental objective (right).

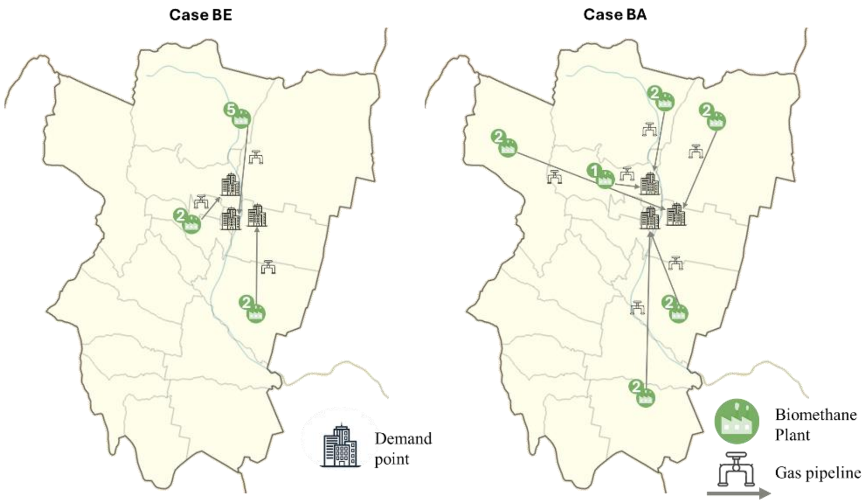

Figure 3. Total number of biomethane plants installed over the 15-year planning horizon for Case B, under the economic objective (left) and the environmental objective (right).

Table 2. Summary of the results for the proposed cases.

	CASE AE	CASE AA	CASE BE	CASE BA
Total plants installed	9	13	9	11
Gas pipeline built (km)	157.9	364	167.1	508.3
Total SC Cost (10^8 USD)	2.83	3.66	2.01	4.69
Total SC GWP (10^9 kg CO_2e)	-2.21	-2.35	-1.29	-2.33
Range of product demand coverage over all periods and regions (%)	4.5-8.4	4.5-8.4	5.0-5.7	7.4-14.4
Range of raw material utilization over all periods and regions (%)	100	100	39.9-65.1	98-100

5 Conclusions

This proposed study presents a mathematical optimization model consisting of 51 equations, including two independently optimized objective functions: economic and environmental. The model supports the strategic planning of a biomethane SC over a 15-year horizon, with the goal of either fully utilizing the available bovine manure or meeting a specified portion of the CNG demand for transportation in selected regions.

The economic optimization (cases AE and BE) results in fewer biomethane plants and shorter pipeline networks compared to the environmental optimization (cases AA and BA). Notably, in case AE, where full manure utilization is enforced, most plants are installed in the first year, resulting in a decentralized infrastructure. In contrast, case BE, which focuses on meeting demand targets, shows a more temporally distributed and centralized configuration. The environmental optimization favors a decentralized deployment of plants and infrastructure due to the lower carbon intensity of biomethane transportation compared to manure logistics. Consequently, longer pipeline distances are observed in these cases.

In all scenarios, the environmental benefits —due to the substitution of fossil fuels and mineral fertilizers— exceed the emissions generated by the SC. Thus, the system shows strong potential as a carbon offset strategy. Finally, a clear trade-off between cost and environmental performance is observed: economic optimization leads to higher emissions, while environmental optimization incurs higher costs, highlighting the need for balanced decision-making in low-carbon energy planning.

The projections of the present work include the assessment of various feedstocks and the expansion of the study's geographical scope. Additionally, further developments will explore multiple potential applications across different sectors, aiming to enhance the versatility and impact of the proposed approach. Future work will also advance towards a multi-objective analysis that jointly considers the different objective functions, providing a more integrated and robust decision-making framework.

References

Bioeconomía (2024). YPF inyectará biometano en la red de gas natural: El potencial del biometano, una nueva vía para la bioeconomía argentina. https://www.bioeconomia.info/2024/11/07/ypf-inyectara-biometano-en-la-red-de-gas-natural/#el-potencial-del-biometano-una-nueva-v%C3%ADa-para-la-bioeconom%C3%ADa-argentina

Carrizo, S. C., Jacinto, G. P. (2024) Caleidoscopio energético argentino: Redes y territorios en transición. https://www.ign.gob.ar/odc-13-carrizo, last accessed 2025/03/10

Climate Transparency (2022). Climate Transparency Report: Argentina 2022. https://www.climate-transparency.org/wpcontent/uploads/2022/10/CT2022-Argentina-Web.pdf

ENARGAS (2019). Ente Nacional Regulador del Gas. Norma Argentina del Gas NAG602. https://www.enargas.gob.ar/secciones/normativa/pdf/normas-tecnicas/NAG-602.pdf

ENARGAS (2024). Sistema de Transporte y Distribución de Gas Natural de la Provincia de Tucumán. https://www.enargas.gob.ar/secciones/informacion-geografica/Mapas/Atlas/tucuman.pdf

Hoo, P. Y., Hashim, H., Ho, W. S., Yunus, N. A. (2019). Spatial-economic optimisation of biomethane injection into natural gas grid: The case at southern Malaysia. *Journal of Environmental Management, 241*, 603–611. https://doi.org/10.1016/j.jenvman.2018.11.092.

International Energy Agency (2023). World Energy Outlook 2023: Executive summary. https://www.iea.org/reports/world-energy-outlook-2023/executive-summary?language=es,

ISO 14040 (2006). Environmental management - Life cycle assessment - Principles and framework.

K. C., S., Dhakad, M., Potančoková, M., Adhikari, S., Yildiz, D., Mamolo, M., Sobotka, T., Zeman, K., Abel, G., Lutz, W., Goujon, A. (2024). *Updating the Shared Socioeconomic Pathways (SSPs) global population and human capital projections* (IIASA Working Paper No. WP-24-003). International Institute for Applied Systems Analysis.

Moretto, D. (2024). Tesis de Maestría. Cost-optimal investment decision for the natural gas infrastructure of Piedmont with biomethane distributed sources. Politecnico di Torino, Italy.

Quaia, E. A., Machado, W. D., Molina, C. F., Acuña, M. F., Muñoz, L. A. C., Núñez, G.M. (2023). Estado de situación y potencial de producción de biogás en la provincia de Tucumán. Estación Experimental Agroindustrial "Obispo Colombres" (EEAOC).

RIDES (2016). Área de Ganadería, Forrajeras, Legumbres, Hortalizas y Frutales. Provincia de Tucumán. https://rides.producciontucuman.gob.ar/wp-content/uploads/2017/02/Area_Ganadera.pdf

SENASA (2024). Bovinos y bubalinos - Sector primario. Gobierno de Argentina. https://www.argentina.gob.ar/senasa/mercados-y-estadisticas/estadisticas/animal-estadisticas/bovinos/bovinos-y-bubalinos-sector-primario, last accessed 2025/03/10

Sun, Q., Li, H., Yan, J., Liu, L., Yu, Z., Yu, X. (2015). Selection of appropriate biogas upgrading technology-a review of biogas cleaning, upgrading and utilization. *Renewable and Sustainable Energy Reviews, 51*, 521–532. http://dx.doi.org/10.1016/j.rser.2015.06.029

World Economic Forum (2024). The Global Risks Report 2024. https://www3.weforum.org/docs/WEF_The_Global_Risks_Report_2024.pdf