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Research paper

Energy Recovery from Methane Generated at the Los Picachos Landfill in Popayán, Colombia

Valorización energética del metano generado en el Relleno Sanitario Los Picachos en Popayán, Colombia

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Abstract

Context: Methane generation in sanitary landfills poses an environmental risk due to the global warming potential of methane; however, it also presents an opportunity for renewable energy production. While previous studies have provided biogas estimates, few have addressed the comprehensive energy valorization of biogas. This study assesses the energy potential of methane at the Los Picachos Landfill through various recovery pathways: conversion to electrical, thermal, and chemical energy, and the production of hydrogen and syngas.

Method: Historical population data, per capita waste generation rates, and waste disposal records were used to estimate methane generation with the Landfill Gas Emissions Model (LandGEM). The modeling horizon included two periods: an active disposal period from 2014 to 2044, according to the projected closure year of the landfill, and a post-closure methane generation period from 2045 to 2154, during which no additional waste input was assumed. Energy conversion coefficients were then applied to calculate chemical, electrical, and thermal energy outputs. Hydrogen production was estimated through three technological pathways: steam methane reforming (SMR), chemical looping reforming (CLR), and chemical looping reforming in a packed-bed reactor (CL_PB). Syngas production was also estimated using these pathways.

Results: The findings indicate sustained growth in methane generation, peaking at approximately 10 478 673 m^3 in 2045, with an energy potential of 1 473 156 $MJ \cdot d^{-1}$. Annual hydrogen production ranges from 20 000 Nm^3 to 33 000 000 Nm^3, depending on the conversion pathway. A significant quantity of syngas was also estimated, with potential applications in both chemical synthesis and energy production.

Conclusions: The methane generated at the site presents a high potential for energy valorization, particularly between 2020 and 2070. These findings can inform the

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development of waste-to-energy policies and support future research into hybrid conversion routes and integrated energy systems.
Keywords: methane, renewable energy, sanitary landfill, syngas

Resumen

Contexto: La generación de metano en rellenos sanitarios implica un riesgo ambiental por el potencial de calentamiento global del metano, pero también una oportunidad para producir energía renovable. Aunque existen estimaciones previas de biogás, pocos estudios abordan su valorización energética integral. Este trabajo evalúa el potencial energético del metano en el Relleno Sanitario Los Picachos mediante diversas rutas de aprovechamiento: conversión a energía eléctrica, térmica y química, y producción de hidrógeno y gas de síntesis.
Método: Se emplearon datos históricos de población, tasas de generación per cápita de residuos y registros de disposición de residuos para estimar la generación de metano mediante el modelo LandGEM (Landfill Gas Emissions Model). El horizonte de modelación incluyó dos periodos: un periodo de disposición activa entre 2014 y 2044, de acuerdo con el año proyectado de cierre del relleno sanitario, y un periodo posclausura de generación de metano entre 2045 y 2154, durante el cual no se asumió ingreso adicional de residuos. Posteriormente, se aplicaron coeficientes de conversión energética para calcular la energía química, eléctrica y térmica. La producción de hidrógeno se estimó mediante tres rutas tecnológicas: reformado de metano con vapor (SMR, steam methane reforming), reformado por bucle químico (CLR, chemical looping reforming) y reformado por bucle químico en reactor de lecho empacado (CL_PB). La producción de gas de síntesis también se estimó mediante estas rutas.
Resultados: Los resultados muestran un crecimiento sostenido en la generación de metano, con un pico cercano a 10 478 673 m^3 en 2045 y un potencial energético de 1 473 156 $MJ \cdot d^{-1}$. La producción anual de hidrógeno varía entre 20 000 Nm^3 y 33 000 000 Nm^3, según la ruta de conversión. Se estimó además una producción significativa de gas de síntesis, con potencial para aplicaciones tanto en síntesis química como en producción de energía.
Conclusiones: El metano generado en el sitio presenta un alto potencial de valorización energética, especialmente entre 2020 y 2070. Estos hallazgos pueden orientar el desarrollo de políticas de aprovechamiento energético de residuos y apoyar futuras investigaciones en rutas híbridas de conversión y sistemas energéticos integrados.
Palabras clave: energía renovable, gas de síntesis, metano, relleno sanitario

1. Introduction

The growing global concern over climate change has intensified the search for strategies to mitigate greenhouse gas (GHG) emissions, including methane (CH_4) [1], [2], a potent GHG produced in large volumes in sanitary landfills through the decomposition of organic waste. While it constitutes a significant source of emissions, CH_4 also presents an opportunity for energy generation [3], [4]. Energy recovery from landfill gas (LFG) has emerged as a key strategy within waste-to-energy (WtE) systems, helping to reduce the environmental impact of methane while producing useful energy resources [4], [5].

There is growing interest in the use of LFG within the energy sector and in the valorization of biogas for various applications [6]. Previous studies have evaluated the methane recovery potential for electricity and thermal energy generation in different geographic contexts [3]. For instance, in Colombia, the methane recovery potential at the Villavicencio Sanitary Landfill has been analyzed, with estimates indicating electricity production sufficient to power thousands of households, along with thermal energy suitable for industrial processes—highlighting the significant potential to convert these emissions into energy [3]. Other techno-economic assessments conducted in Colombian cities have compared the performance of technologies such as gas turbines and internal combustion engines, evaluating their economic feasibility using indicators such as net present value (NPV) and internal rate of return (IRR), as well as their potential for GHG reduction [7]. Additionally, interest is increasing in producing hydrogen and ammonia from biogas, although their economic competitiveness still depends on the implementation of supportive policy incentives [8].

However, a gap remains in the assessment of LFG valorization in Latin American landfills, particularly in those lacking basic gas capture and utilization infrastructure. In Colombia, solid waste management continues to follow a linear economy model, with limited valorization of the organic fraction and a reduced landfill lifespan, leading to considerable methane emissions [2]. A representative case is the Los Picachos Sanitary Landfill, located in Popayán, which receives waste from the city and fourteen surrounding municipalities in the department of Cauca [9], [10]. Unlike other landfills in the country, Los Picachos lacks any gas capture or valorization system—a situation identified as a critical issue by the Nationally Appropriate Mitigation Action (NAMA) for Municipal Solid Waste [4].

Therefore, this study aims to evaluate the energy valorization potential of methane generated at the Los Picachos Sanitary Landfill. The research examines several energy conversion pathways, including electricity generation, heat production, and conversion of fuels such as hydrogen and syngas. The selection of these pathways is based on the need to identify sustainable and viable options for this site that contribute to GHG mitigation, diversification of the local energy matrix, extension of the landfill lifespan, and reduction of impacts such as odors and gas accumulation hazards [4], [11], [12]. The novelty of this research lies in its focus on a critical site with no active valorization infrastructure, which allows for the

development of targeted recommendations to inform public policies and future projects in similar regional contexts.

2. Methodology

2.1. Study Area

Los Picachos Sanitary Landfill is located in the village of La Yunga, a rural area of the municipality of Popayán, in the department of Cauca, Colombia, approximately 20 km west of the urban center [9], [10]. It is operated by URBASER POPAYÁN S.A. E.S.P. [13] and, according to Decree 1784 of 2017, is classified as a Category II landfill [10], [13], receiving an average of 263 t of waste per day (based on 2019 data) [4].

The total area of the site is 51.5 ha, of which 20.5 ha are designated for operational infrastructure and 31 ha serve as buffer and environmental protection zones [10]. Waste is delivered by 15 municipalities in the department of Cauca: Almaguer, Cajibío, Caldono, El Tambo, La Sierra, La Vega, Patía, Piendamó, Popayán, Puracé, Rosas, Silvia, Sotará, Timbío, and Totoró [9], [10], [13]. The landfill accepts ordinary waste from domestic, urban, commercial, and street-cleaning sources, as well as construction and demolition waste (CDW) for designated uses, while hazardous waste is prohibited [13]. The environmental license was granted by the Regional Autonomous Corporation of Cauca (CRC) through Resolution 05031 on March 28, 2014 [10], [13], with site closure projected for 2044.

The closest official climatological reference for the study area is the station of the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) at Guillermo León Valencia Airport in Popayán. According to the climatological records reported for this station, Popayán has temperate and humid conditions, with a mean temperature close to 19 °C and annual precipitation above 2000 mm. These conditions indicate moisture availability that can favor anaerobic degradation within the disposed waste, but they do not correspond to the high-temperature tropical environments where accelerated methane decay rates are usually assumed. Therefore, from a climatic perspective, Los Picachos was interpreted as a municipal solid waste landfill with intermediate biodegradation conditions [14].

Regarding methane management, a 2019 report indicated that Los Picachos had no gas capture or utilization systems in place [4]. However, the 2020 Operational Regulations mention the construction of flaring chimneys for the controlled combustion of gas at

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individual points, with a view to installing a centralized flaring system and a future energy recovery system [13]. A methane recovery potential of 4.27 Gg of CH_4 by 2030 has been projected, equivalent to 0.83 MW of net power, assuming the implementation of landfill gas recovery systems with flaring and energy utilization [4].

2.2. Methane Production

Methane emissions at the Los Picachos Sanitary Landfill were estimated using the Landfill Gas Emissions Model (LandGEM), an automated tool developed by the United States Environmental Protection Agency (U.S. EPA) [15], [16], [17]. LandGEM is based on a first-order decay model, given by Equation (1) [18], [19], [20]:

$$Q_{\mathrm{CH_4}} = \sum_{i=1}^{n} \sum_{j=0,1}^{1} K.L_0.\left[\frac{M_i}{10}\right].e^{-k.t_{ij}} \quad (1)$$

In this equation, Q_{CH_4} represents the annual methane generation, in $m^3 \cdot year^{-1}$ [8], [18], [19], [21]. The parameter K, expressed in $year^{-1}$, quantifies the rate at which organic matter decomposes and produces methane [18], [19], [21]. The typical range for K recommended by the LandGEM manual is 0.02 $year^{-1}$ to 1.7 $year^{-1}$ [3]. However, other studies have considered a narrower range of 0.04 $year^{-1}$ to 0.06 $year^{-1}$ [19], and the U.S. EPA has proposed values of 0.02, 0.04, 0.05, and 0.07 $year^{-1}$ [22]. The selection of K depends on waste composition, storage conditions, and the regional climate [6], [11]. For instance, in Colombian landfills such as those in Villavicencio and Valledupar, a methane generation rate of 0.05 $year^{-1}$ has been used [3], [24]. In landfills located in warm and humid regions, higher values—such as 0.16 or 0.21 $year^{-1}$—have been applied [23], influenced by high moisture content and the presence of food waste, with elevated temperatures also accelerating microbial activity [25], [26], [27].

L_0 is the methane generation potential per unit mass of waste, expressed in $m^3.Mg^{-1}$ [20], [21]. This value quantifies the maximum volume of methane that can be produced per metric ton of deposited waste [28]. Reported values of L_0 in the literature range from 6 $m^3 \cdot Mg^{-1}$ to 270 $m^3.Mg^{-1}$ of waste [16], with LandGEM suggesting typical values between 96 $m^3 \cdot Mg^{-1}$ and 170 $m^3.Mg^{-1}$ [22], and default values of 96, 100, and 170 $m^3.Mg^{-1}$ [21], [29]. The determination of L_0 depends on the concentration of degradable organic carbon in the waste [5], [16]. Other influencing factors include the degree of waste segregation, temperature, and

moisture conditions at the landfill site [16]. For landfills located in warm and humid climates, values such as 130 $m^3.Mg^{-1}$ have been used, as in the case of Valledupar [24].

Finally, M_i represents the mass of waste accepted in year *i*, expressed in megagrams (Mg) [18], [21]. The time increment *i* is considered annually, and $t_{i,j}$ denotes the age of section *j* of the waste mass M_i accepted in year *i* [18], [19]. The value of M_i was determined by multiplying the projected population of the landfill's service area by the per capita solid waste generation rate (PPC, from the Spanish *producción per cápita*) [3]. Population projections were conducted using the arithmetic method, which had previously been shown to provide the best fit for the study area based on census data from 2005 and 2018 of the National Administrative Department of Statistics (DANE) [3]. This method assumes a constant annual population growth rate, allowing for the extrapolation of future demographic trends [20]. The PPC was obtained from secondary data sources and projected annually using the same arithmetic approach [3]. For example, the Valledupar study applied a per capita generation rate of 0.28 $Mg \cdot person^{-1} \cdot year^{-1}$ [24].

All methane volumes reported from LandGEM correspond to m^3 at the model's standard conditions (approximately 20 °C and 1 atm). For hydrogen and syngas calculations, volumes are expressed in Nm^3.

For the Los Picachos case study, the reference values adopted for the LandGEM simulation were selected according to the operational, climatic, and documentary information available for the landfill. The decay rate coefficient K was set at 0.05 $year^{-1}$ because Los Picachos receives ordinary municipal solid waste from Popayán and 14 surrounding municipalities, including domestic, urban, commercial, and street-cleaning waste, while hazardous waste is prohibited. In addition, the closest official climatological reference for Popayán, the IDEAM Guillermo León Valencia Airport station, indicates temperate and humid conditions, with a mean temperature close to 19 °C and annual precipitation above 2000 mm. These conditions suggest moisture availability for anaerobic degradation, but not the high-temperature environment typically associated with the adoption of very high K values. Furthermore, no site-specific methane monitoring series or detailed gravimetric characterization was available to support the adoption of a locally calibrated K value. Therefore, an intermediate coefficient was selected within the range commonly applied in Colombian landfill studies and within the values proposed by the U.S. EPA for LandGEM applications. Higher K values, generally

associated with warm and highly humid landfills with accelerated biodegradation conditions, were not adopted as the reference case because the available climatic, operational, and compositional evidence for Los Picachos does not provide sufficient support for such an assumption.

The methane generation potential L_0 was set at 130 $m^3 \cdot Mg^{-1}$ as an intermediate value within the LandGEM reference range and as a representative value for landfills receiving predominantly municipal solid waste with an expected biodegradable organic fraction. This value was considered appropriate because the available operational information identifies the acceptance of ordinary domestic, urban, commercial, and street-cleaning waste, but does not provide site-specific biochemical methane potential tests, detailed organic fraction data, or local waste composition datasets that would allow direct calibration of L_0. The PPC was obtained from secondary official and documentary sources and projected using the same arithmetic approach applied to the population series, ensuring consistency between demographic growth and waste generation estimates. The modeling horizon included two periods: an active disposal period from 2014 to 2044, in accordance with the environmental licensing and operational information reporting the projected closure of the landfill, and a post-closure methane generation period from 2045 to 2154, during which no additional waste input was assumed. Therefore, after 2044, population and PPC were not projected for waste input calculations; methane generation from 2045 onward corresponds exclusively to the first-order degradation of the waste accumulated during the active disposal period.

2.3. Sensitivity Analysis of LandGEM Parameters

To account for the inherent uncertainty associated with methane generation parameters, a sensitivity analysis was performed using alternative values of K and L_0 within the plausible ranges reported in the literature and in LandGEM applications. Three scenarios were evaluated: (i) a conservative scenario, defined by a lower biodegradation rate and lower methane generation potential ($K = 0.02$ $year^{-1}$, $L_0 = 96$ $m^3 \cdot Mg^{-1}$); (ii) a reference scenario ($K = 0.05$ $year^{-1}$, $L_0 = 130$ $m^3 \cdot Mg^{-1}$), selected as the main case because it represents intermediate biodegradation and methane potential conditions for a municipal landfill without site-specific methane monitoring or detailed waste composition data; and (iii) an optimistic scenario, defined by a higher biodegradation rate and higher methane generation potential (K = 0.07

year^{-1}, L_0 = 170 m^3·Mg^{-1}). The conservative and optimistic scenarios were included not as alternative operational descriptions of Los Picachos, but as boundary conditions to evaluate how uncertainty in K and L_0 affects methane generation and the subsequent estimates of chemical energy, electricity, thermal energy, hydrogen production, and syngas generation. The results are therefore interpreted as parameter-dependent projections rather than deterministic predictions.

2.4. Potential for the Generation of Commercially Valuable Energy Products

Once the methane generation Q_{CH_4} was determined, the energy estimates were calculated as follows.

2.4.1. Chemical Energy Production

Chemical energy (CE) is calculated using the average daily methane flow and its lower heating value (LHV_{CH_4}), as shown in Equation (2) [24]:

$$CE = Q_{CH4} * LHV_{CH_4} \quad (2)$$

where CE represents the chemical energy output of methane, in MJ·d^{-1}; Q_{CH_4} is the methane flow rate, in Nm^3·d^{-1}; and LHV_{CH_4} is the lower heating value of methane, typically estimated at 35 MJ·Nm^{-3} [18], [19] or 37.2 MJ·Nm^{-3} [5], [29]. Another source reports a value of 11 781 $kcal.kg^{-1}$ (equivalent to 35.2 MJ·Nm^{-3}) [17].

For the energy recovery calculations, the lower heating value of methane was adopted as 37.2 MJ·m^{-3}, consistent with reported values for methane energy content.

2.4.2. Electricity Production

Electrical energy is obtained by converting the chemical energy of methane through an engine or generator, as shown in Equation (3) [24]:

$$EE = CE * \eta_e * CC \quad (3)$$

where EE represents the daily electricity production from methane, in kWh·d^{-1}; CE is the chemical energy of methane, in MJ·d^{-1}; CC is the conversion factor from MJ to kWh (0.2778); and η_e is the efficiency of the engine or electricity generator.

For internal combustion engines or gas turbines, a typical efficiency is 45% [3]. Other sources report efficiencies of 26% for biogas generators [5], [15] and 28% for microturbines [17]. A general efficiency for gas engines is around 30% [16], [18], [19].

The electrical conversion efficiency was set at 26%, representing a conservative value for biogas-based electricity generation systems, while the thermal recovery efficiency was assumed to be 50%, consistent with cogeneration applications in which residual heat can be recovered.

2.4.3. Thermal Energy Production

Thermal energy can be recovered from exhaust gases or residual heat from engines in cogeneration systems and is calculated using Equation (4):

$$TE = CE * \eta_t * CC \quad (4)$$

where TE represents the thermal energy produced from methane, in kWh·d^{-1}, and η_t is the efficiency of the thermal energy generation system. For cogeneration systems using methane, thermal efficiency can reach up to 50% [3].

2.4.4. Hydrogen Production (via Reforming)

To estimate the amount of hydrogen produced, a stoichiometric relationship is applied based on the selected reforming technology, as shown in Equation (5) (adapted from [30], [31], [32], [33]):

$$H_2[Nm^3.day^{-1}] = Q_{CH4} * \eta_{CH_4} * R_{H_2.CH_4^{-1}} \quad (5)$$

where Q_{CH_4} is the methane flow rate, in Nm³·d^{-1}; η_{CH_4} is the methane-to-hydrogen conversion efficiency; and $R_{H_2.CH_4^{-1}}$ is the molar yield, which depends on the type of reforming technology applied.

$R_{H_2.CH_4^{-1}}$ is 2.49 $mol\ H_2.mol\ CH_4^{-1}$ for conventional steam methane reforming (SMR), 2.34 $mol\ H_2.mol\ CH_4^{-1}$ for chemical looping reforming (CLR), and 2.52 $mol\ H_2.mol\ CH_4^{-1}$ for chemical looping reforming in a packed-bed reactor (CL_PB) [39]. Methane conversion in CLR systems with packed-bed reactors can exceed 99% under specific conditions [34], while a general methane conversion efficiency of approximately 92% is typically assumed for large-scale hydrogen production [35].

Hydrogen and syngas estimates were calculated using stoichiometric molar yields and methane conversion efficiencies reported for the selected reforming pathways. These values were not intended to represent a specific plant design at Los Picachos, but rather to quantify the theoretical valorization potential of the methane stream under documented conversion routes.

2.4.5. Syngas Production

To estimate the amount of synthesis gas (syngas), a molar ratio between the input methane and the resulting gases is used, as shown in Equation (6) (adapted from [33], [36], [37], [38], [39], [40], [41], [42], [43]):

$$Syngas[Nm^3.day^{-1}] = Q_{CH4} * R_{Syngas.CH_4^{-1}} \quad (6)$$

where Q_{CH_4} represents the methane flow rate fed into the system, in $Nm^3 \cdot d^{-1}$, and $R_{Syngas.CH_4^{-1}}$ is the molar yield of syngas generated per mole of methane input.

The molar yield of syngas depends on the reforming technology employed and on how syngas is defined—whether it includes only H_2 and CO, or also CO_2 [30], [35], [41]. For syngas composed of H_2 + CO, the yields reported in the literature are 3.79 $mol\ Syngas.mol\ CH_4^{-1}$ for the methanol chemical looping process in a packed-bed reactor (MeOH-CL_PB) [36], [38]; 4.40 $mol\ Syngas.mol\ CH_4^{-1}$ for CLR-PB [38], [40]; and 3.38 $mol\ Syngas.mol\ CH_4^{-1}$ for SMR [31], [35]. When CO_2 is included in the definition (H_2 + CO + CO_2), the CLR-PB process can achieve a yield of up to 5.03 $mol\ Syngas.mol\ CH_4^{-1}$ [38], [40].

3. Results

3.1. Estimation of Methane (CH_4) Generation

The annual solid waste generation was estimated for the active disposal period based on projected population and per capita production (PPC), using the arithmetic method. Population projections were derived from DANE census data for 2005 and 2018, resulting in a linear growth trend consistent with the demographic evolution of the landfill's service area during operation. The projected PPC ranged from 0.43 $kg \cdot person^{-1} \cdot d^{-1}$ to 0.45 $kg \cdot person^{-1} \cdot d^{-1}$ between 2014 and 2044, reflecting a moderate increase in consumption and disposal patterns. Based on these variables, the annual amount of accepted waste was estimated up to the projected closure year. From 2045 onward, no additional waste input was assumed, and methane generation was calculated only from the degradation of waste accumulated during the active disposal period.

Annual methane generation in the reference scenario was calculated using a methane generation potential (L_0) of 130 $m^3 \cdot Mg^{-1}$ and a decay rate coefficient (K) of 0.05 $year^{-1}$. These values were adopted as intermediate parameters for a municipal solid waste landfill

with temperate and humid climatic conditions, documented ordinary waste disposal, projected closure in 2044, and no available site-specific methane monitoring, detailed gravimetric characterization, or biochemical methane potential data. To evaluate the influence of parameter uncertainty, methane generation was also recalculated under two additional combinations of K and L_0, representing the conservative ($K = 0.02$ year^{-1}, $L_0 = 96$ m^3·Mg^{-1}) and optimistic ($K = 0.07$ year^{-1}, $L_0 = 170$ m^3·Mg^{-1}) scenarios. These results complement the reference scenario and provide an assessment of the sensitivity of methane generation to variations in biodegradation rate and methane generation potential.

Table A1 in the Appendix presents the complete annual dataset used to support the LandGEM-based methane generation estimates, including projected population, per capita solid waste generation, accepted waste during the active disposal period, and estimated methane generation for the complete modeling horizon. From 2045 onward, population and PPC are reported as not applicable because the landfill was assumed to be closed, and accepted waste was set to zero.

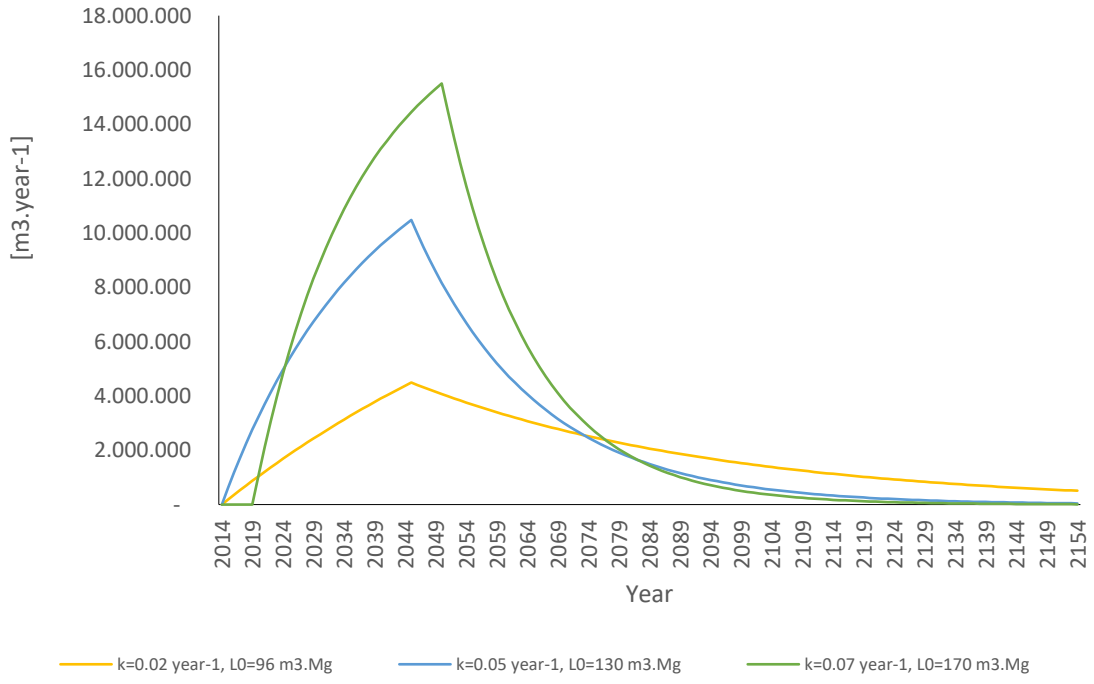


Figure 1 illustrates the temporal evolution of methane generation for the three scenarios.

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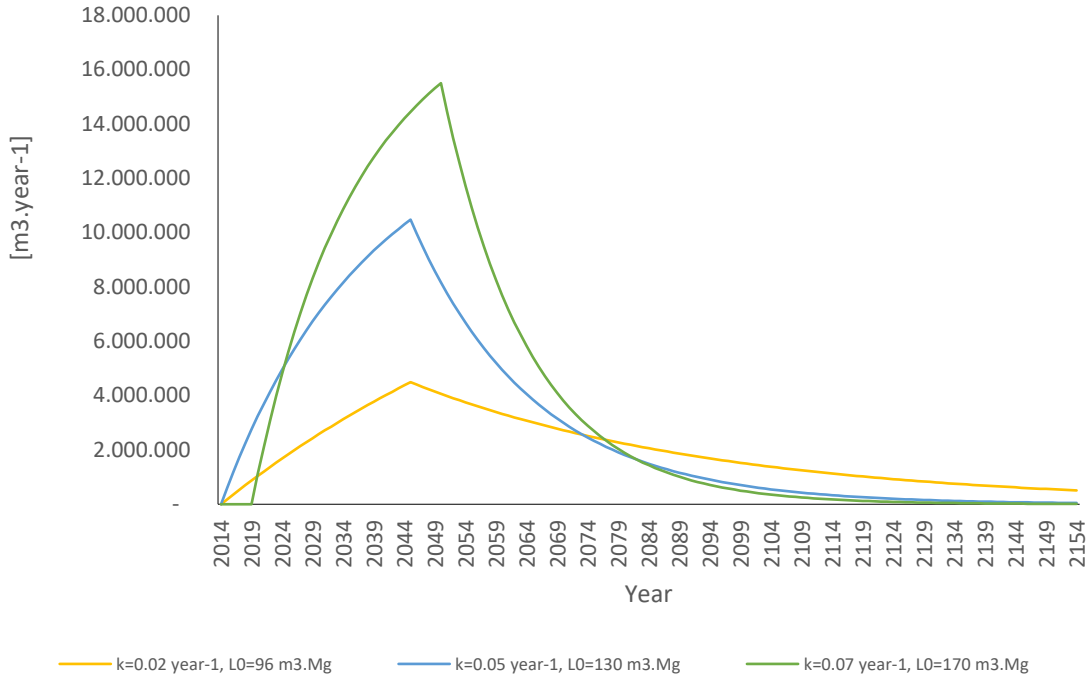


Figure 1. Methane generation estimated under the conservative, reference, and optimistic LandGEM parameter scenarios.

3.2. Energy Valorization of Methane: Chemical, Electrical, and Thermal Energy

Based on the estimated volume of methane, the energy content of the gas was calculated using its lower heating value (LHV), adopting an average value of 37.2 $MJ \cdot m^{-3}$. The potential for electricity generation was estimated assuming an efficiency of 26%, typical of internal combustion engines and gas turbines. Additionally, the recoverable thermal energy in cogeneration systems was evaluated assuming a thermal efficiency of 50%, consistent with biogas-based technologies.

Table A2 in the Appendix presents the complete annual dataset used to support the estimates of available methane energy content, electricity generation, and thermal energy recovery under the evaluated scenarios. Figure 2 illustrates this projected energy valorization, highlighting the increasing energy availability as methane generation rises at the landfill site. The energy projections follow the same trend observed in methane output across the three sensitivity scenarios.

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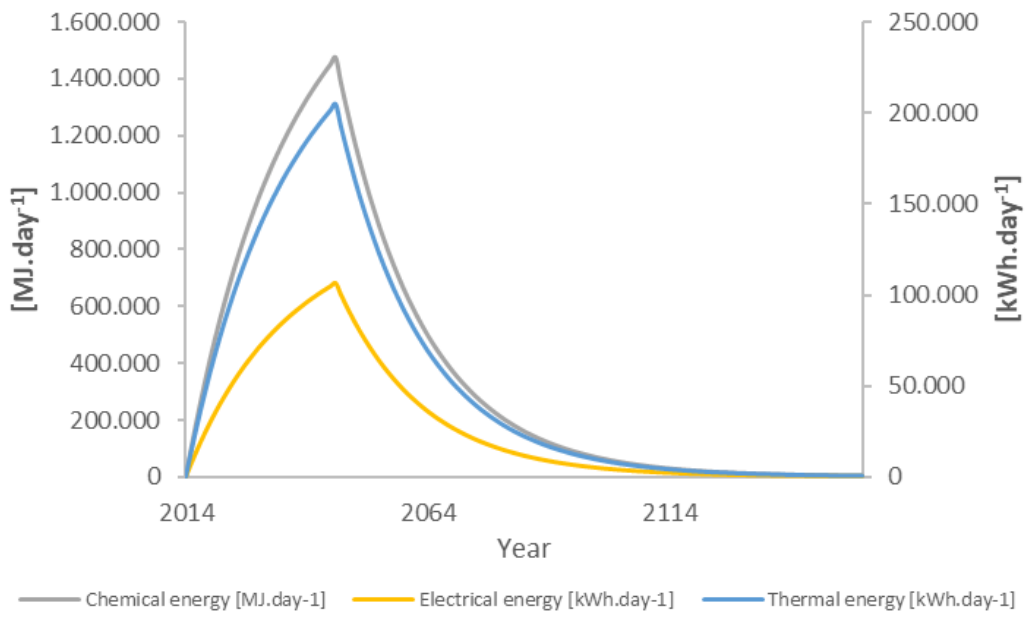
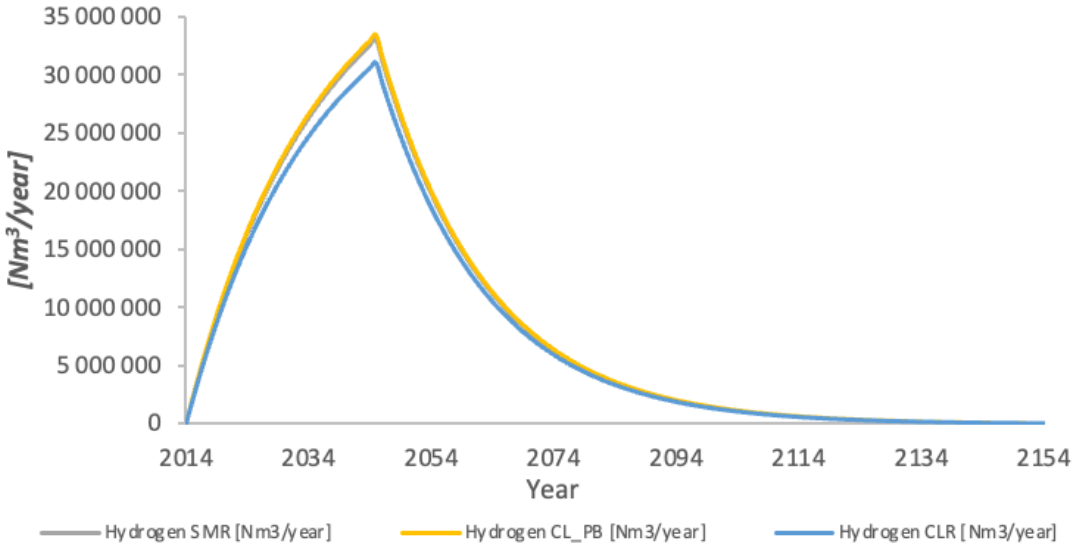


Figure 2. Projected chemical, electrical, and thermal energy recovery from methane generated at the Los Picachos Landfill.

3.3. Potential Hydrogen (H_2) Production

Table A2 presents the complete annual dataset used to support the projected hydrogen production estimates for the evaluated technological routes: steam methane reforming (SMR), chemical looping reforming (CLR), and chemical looping reforming in a packed-bed reactor (CL_PB). Figure 3 compares the generated volumes of H_2, highlighting the impact of molar yield and conversion efficiency on the final output.



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Figure 3. Hydrogen generation potential according to the applied methane conversion technology.

3.4. Syngas Production

Table A2 provides the complete annual dataset used to support the estimated syngas production under the evaluated reforming scenarios. Figure 4 shows the temporal evolution of syngas generation under the selected conversion routes, allowing comparison of the relative production potential of each technological configuration.

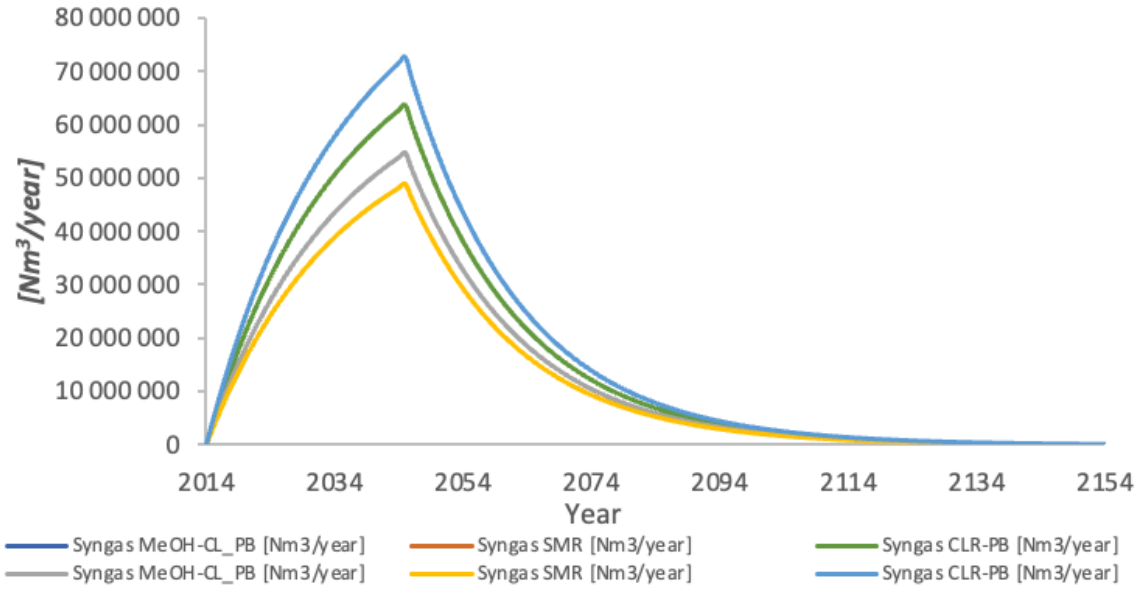


Figure 4. Syngas generation potential according to the applied methane conversion technology.

4. Discussion

4.1. Estimation of Methane (CH_4) Generation

The results indicate sustained growth in methane generation, rising from 603 513 m³ in 2015 to a peak of 10 478 673 m³ in 2045. During the active disposal period, this increase is related to the projected population growth, the per capita waste generation rate, and the corresponding rise in accepted waste, which increased from 94 951 Mg in 2014 to more than 106 000 Mg annually during the final years of operation (Table A1). However, the 2045 peak should not be interpreted as the result of new waste input in that year. Because landfill closure was assumed after 2044, methane generation from 2045 onward corresponds to the delayed anaerobic degradation of waste accumulated during the active disposal period. Figure 1 illustrates this evolution, showing a continuous increase during the operational phase and a gradual decline during the post-closure period.

This behavior is explained by the structure of the first-order decay model. During the active disposal period, the annual input of waste progressively increases the biodegradable mass available for anaerobic conversion, so methane generation rises even though each annual waste fraction begins to degrade at a different time. The maximum value reached around 2045 reflects the cumulative effect of the waste deposited up to 2044 and the delayed response of anaerobic degradation, rather than a new increase in waste disposal after closure. Once no additional waste is accepted, the remaining biodegradable substrate decreases progressively, and methane generation follows a declining trajectory governed by the decay coefficient K. Therefore, the post-closure decrease is not an abrupt interruption of methane production, but the expected reduction of residual methane generation as the accumulated organic matter is depleted.

In addition to the reference trajectory, the conservative and optimistic scenarios reveal the extent to which methane generation depends on the selected values of K and L_0. While the reference scenario reaches its maximum around 2045, the conservative scenario shows a delayed and markedly lower peak, and the optimistic scenario exhibits a higher and earlier maximum. These differences highlight the sensitivity of the LandGEM model to biodegradation kinetics and methane generation potential, reinforcing the need to interpret long-term projections as parameter-dependent outcomes rather than fixed deterministic values.

Methane generation in sanitary landfills shows an almost linear correlation with the mass of waste accepted, driven by the anaerobic decomposition of organic matter [3], [24]. However, degradation kinetics suggest that production may continue to increase during the initial years after waste disposal, owing to the stable methanogenic phase, which typically occurs between 2 and 10 years after disposal before declining [4].

From an environmental standpoint, this dynamic has critical implications, as methane has a global warming potential (GWP) 28 times higher than that of carbon dioxide over a 100-year horizon [4], [43]. Therefore, its capture and valorization are essential strategies to mitigate greenhouse gas emissions and to harness methane as a viable renewable energy source [24]. Comparatively, studies in Latin America report similar patterns [3], [4], with projections of 111.37 Gg of CH_4 for the Doña Juana landfill (Bogotá) by 2030 and 13.14 Gg of CH_4 for El

Carrasco (Bucaramanga) [4]. In contrast, the Los Picachos landfill is projected to generate 4.27 Gg of CH_4 in 2030, placing it in the lower range among regional landfills in Colombia.

4.2. Energy Recovery from Methane: Chemical, Electrical, and Thermal Energy

The available daily chemical energy shows sustained growth from 2015 (91 410 MJ·d^{-1}) to a peak in 2045 (1 473 156 MJ·d^{-1}), as shown in Table A2 and Figure 2. This behavior corresponds to the progressive increase in methane generation discussed above. Based on this energy content, the estimated electricity production exceeded 106 000 kWh·d^{-1} at the peak of the analyzed period—equivalent to the approximate consumption of 35 000 Colombian households, assuming an average residential demand of 3.0 kWh·d^{-1} per household [44]. The projected thermal energy for 2045 exceeds 204 000 kWh·d^{-1}, which is suitable for industrial processes.

The similarity between the methane, chemical energy, electrical energy, and thermal energy curves is expected because these outputs were calculated through linear conversion relationships. Chemical energy depends directly on the methane flow and its lower heating value, while electrical and thermal energy are obtained by applying fixed conversion efficiencies to the available chemical energy. Consequently, the differences among these curves are not associated with independent temporal dynamics, but with the conversion factors used in each case: the LHV determines the chemical energy content, the electrical efficiency controls the recoverable power, and the thermal efficiency defines the fraction of residual heat that can be used in cogeneration. For this reason, the peak in energy recovery occurs in the same period as the maximum methane availability, and the post-closure decline reflects the progressive reduction in methane generation rather than a change in conversion performance.

During the 2024–2045 period, the average chemical energy was 384 000 MJ·d^{-1}, corresponding to an estimated conversion into 27 700 kWh·d^{-1} of electricity and 53 300 kWh·d^{-1} of thermal energy. These values indicate the potential of the landfill to integrate into circular economy schemes through biogas valorization, particularly in regions with high energy demand or limited coverage.

In comparison, however, these results remain modest. For instance, in Colombia, the Villavicencio landfill projects an electricity production of 248 067 kWh·d^{-1} and a thermal energy production of 468 572 kWh·d^{-1} by 2042 [3], and Los Corazones (Valledupar)

estimates 324 798 kWh·d^{-1} of electricity by 2035 [24]. Specifically for the Los Picachos landfill, studies from the Ministry of Housing, City and Territory estimate a net electrical potential of only 0.83 MW (approximately 19 920 kWh·d^{-1}), which is lower than the estimates reported in this study [4], reflecting methodological variability depending on the calculation parameters. Internationally, landfills such as Askar (Bahrain) and Fes (Morocco) have reported 57.4 GWh·year^{-1} [6], [16] and 65.5 GWh·year^{-1} [22], respectively.

The lower energy potential estimated for Los Picachos compared with these larger or more technically developed sites can be attributed to the scale and operational context of the landfill. Los Picachos receives a smaller amount of waste than major metropolitan landfills, and the NAMA assessment reported a limited net power potential for the site under landfill gas recovery assumptions. In addition, the absence of an active gas capture and utilization system during the baseline period implies that the results should be interpreted as a theoretical recovery potential rather than as immediately available energy. Therefore, the energy estimates indicate a technical opportunity, but their materialization would depend on the implementation of gas collection, treatment, and conversion infrastructure.

Given that methane has a global warming potential 28 times greater than that of CO_2, its capture and utilization are essential both to mitigate climate impacts and to generate renewable energy [4].

4.3. Potential Hydrogen (H_2) Production

As shown in Table A2, during the 2015–2154 period, the cumulative hydrogen production at the Los Picachos Sanitary Landfill was 1.22 × 10^9 Nm^3 for the SMR route, 1.14 × 10^9 Nm^3 for CLR, and 1.23 × 10^9 Nm^3 for CL_PB, with average annual productions of 8.63 × 10^6 Nm^3, 8.11 × 10^6 Nm^3, and 8.74 × 10^6 Nm^3, respectively. Figure 3 shows the temporal evolution of these projections, with a progressive increase until 2045, the year in which the maximum production values are reached: 33.1 × 10^6 Nm^3·year^{-1} for SMR, 31.1 × 10^6 Nm^3·year^{-1} for CLR, and 33.5 × 10^6 Nm^3·year^{-1} for CL_PB. From that point onward, a sustained decrease is observed, consistent with the declining trend in methane generation.

Hydrogen production varies proportionally to methane availability because CH_4 is the base reactant in the reforming routes considered. Therefore, the temporal evolution of H_2 mirrors

the methane generation scenarios: it increases while methane availability rises during the active disposal period and the early post-closure response, reaches its maximum near the methane peak, and then decreases as the residual methane generation declines. The differences among SMR, CLR, and CL_PB are not caused by different landfill dynamics, but by the molar yields and methane conversion efficiencies assigned to each technological pathway. Thus, CL_PB reaches the highest cumulative value because its adopted molar yield is slightly higher, whereas CLR produces a lower estimate under the assumptions used in the calculation.

The three routes exhibit similar yields, although CL_PB shows the highest cumulative production overall [39]. However, the selection among them will depend on technological, energy, and economic considerations according to the specific project context [8], [45].

The projected hydrogen volume could support a substantial fleet of urban fuel cell buses [4], [8]. For instance, assuming an estimated consumption of 25 Nm^3 of H_2 per 100 km traveled and an annual mileage of 60 000 km per bus, the maximum production projected for 2045 would be sufficient to power more than 22 000 buses per year [8]. Alternatively, this hydrogen could be used in industrial applications, such as fuel refining or ammonia synthesis, or blended with natural gas to reduce emissions in distribution networks [4], [6], [8].

However, these results should be interpreted as a theoretical hydrogen potential derived from the estimated methane stream, not as direct evidence of immediate production feasibility. A real implementation would require landfill gas capture; biogas upgrading; the removal of impurities such as CO_2, H_2S, siloxanes, and moisture; methane reforming; hydrogen purification; and compression, storage, and distribution infrastructure. In addition, local demand would be necessary to absorb the hydrogen produced, through industrial uses, transport applications, blending with natural gas, or integration into emerging hydrogen value chains. These requirements explain why hydrogen production represents a higher-value conversion route, but also a more infrastructure-intensive alternative than direct electricity or heat recovery.

Comparatively, studies conducted in Minas Gerais (Brazil) report annual hydrogen production for municipal consortia ranging from approximately 18 332.05 kg $H_2 \cdot year^{-1}$ to 2 470 525.30 kg $H_2 \cdot year^{-1}$ for SMR, and from 15 456.30 kg $H_2 \cdot year^{-1}$ to 2 082 974.32 kg $H_2 \cdot year^{-1}$ for pyrolysis-based reforming. Although the Los Picachos site operates on a smaller

scale, its results stand out due to the long-term stability and continuity projected over more than a century, underscoring its strategic value as a sustained source of clean energy.

4.4. Syngas Production

Synthesis gas (syngas) is a mixture of hydrogen (H_2), carbon monoxide (CO), and methane (CH_4) obtained from biogas through thermochemical and catalytic processes [43]. Its versatility allows its use as a fuel for energy generation, as an industrial feedstock, or as an input for value-added products such as methanol [41], [46], [47]. To evaluate the potential syngas production from methane generated at the Los Picachos Sanitary Landfill, several technological pathways were analyzed: SMR, CLR, and packed-bed chemical looping reforming configurations with carbon capture and methanol production (CLR-PB and MeOH-CL_PB) [41]. The annual syngas production estimates for each route are presented in Table A2, and the temporal evolution of these projections is illustrated in Figure 4.

Syngas production exhibits the same general temporal behavior as methane because it is directly derived from the methane flow available for conversion. As in the hydrogen routes, the increase up to 2045 reflects the accumulation and delayed degradation of waste during the active and early post-closure periods, while the subsequent decrease results from the progressive reduction in residual methane generation. Therefore, Figure 4 should be interpreted primarily as the transformation of methane availability into different syngas-equivalent outputs, rather than as independent production trends.

A steady increase in potential production is observed up to 2045, with a peak exceeding 57 $\times 10^6$ Nm^3 in the CLR-PB scenario. This is followed by a gradual decline associated with the reduction in methane generation as the landfill's organic content is depleted.

The differences among the syngas routes are explained by the definition of syngas and by the molar yield assigned to each conversion pathway. When syngas is defined only as $H_2 + CO$, the estimated volume reflects the production of the main combustible and synthesis components. In contrast, when CO_2 is included in the syngas definition, the total gas volume increases because the carbon dioxide fraction is also counted as part of the product stream. This distinction is important for interpreting the higher values obtained for CLR-PB and related configurations, since a larger volumetric estimate does not necessarily imply a higher fuel quality or higher usable energy content. Instead, it reflects the composition boundary adopted for the calculation and the stoichiometric performance reported for each route.

The CLR-PB and SMR routes show the highest cumulative volumes, exceeding 2.6×10^9 Nm^3 and 1.8×10^9 Nm^3, respectively, highlighting their potential for the energy conversion of captured methane. Syngas can be used for electricity and heat generation in cogeneration systems, as a chemical feedstock, and in industries such as fertilizers, refining, and plastics [41], [46], [47]. However, its implementation requires specialized infrastructure, strict operational control, and economic feasibility assessments [36]. In comparison with international experiences, differences are noted in the types of energy products obtained and the technological approaches adopted.

4.5. Integrated and Prospective Analysis of the Results

The results of this study enable a comprehensive analysis of the energy recovery potential of methane generated at the Los Picachos Sanitary Landfill. Based on annual estimates of solid waste disposal—calculated using population projections and per capita generation rates—the potential production of methane, chemical energy, electrical and thermal energy, hydrogen, and syngas was determined. This approach allowed the modeling of a progressive energy conversion flow and the assessment of resource utilization through multiple technological pathways.

The analysis reveals an increasing trend in methane and derivative production up to 2045, when the maximum modeled methane availability and a daily chemical energy output close to 1 473 000 MJ are reached. This peak does not correspond to continued waste disposal in 2045, but to the cumulative effect of the waste mass accepted up to the projected closure year in 2044 and to the delayed response of the first-order decay model. Subsequently, a gradual decline is observed during the post-closure period, as no additional waste input was assumed and the remaining biodegradable fraction progressively decreased.

The potential for electricity and thermal energy generation is proportional to methane production, with maximum values close to 106 000 $kWh \cdot d^{-1}$ and 205 000 $kWh \cdot d^{-1}$, respectively. These routes represent the most immediate forms of energy recovery because they rely on the direct conversion of captured methane into power and useful heat. In this sense, on-site cogeneration could be considered a first-stage utilization alternative for Los Picachos, particularly to meet operational energy needs or to supply surplus energy where grid connection and gas treatment conditions are technically feasible.

With regard to hydrogen, projected outputs reach up to approximately 33×10^6 Nm^3 per year through the SMR, CLR, and CL_PB routes. These results indicate that captured methane could also serve as a feedstock for higher-value energy vectors. However, unlike direct electricity or thermal recovery, hydrogen production would require biogas upgrading, reforming units, gas purification, compression, storage systems, safety protocols, and local or regional demand capable of absorbing the product. Therefore, hydrogen represents a technologically more advanced valorization route, but one with greater infrastructure and market requirements.

Likewise, the estimated production of synthesis gas through alternative and advanced reforming routes, including MeOH-CL_PB, CLR-PB, and SMR, expands the prospects for using landfill methane as a precursor for value-added chemical products such as methanol or ammonia, or in hybrid energy generation systems. Nevertheless, the syngas results should be interpreted according to the composition boundary used in each route, since the estimated volume changes depending on whether only $H_2 + CO$ or $H_2 + CO + CO_2$ is considered. This makes syngas a flexible but technically demanding route whose application would require composition control, downstream processing, and economic feasibility assessment.

From a forward-looking perspective, the results suggest that methane utilization at Los Picachos can be optimized through a multi-stage strategy that combines electricity generation, thermal cogeneration, and hydrogen or syngas production, depending on availability levels and local demand. This synergistic approach would allow the maximization of resource use, the reduction of greenhouse gas emissions, and the advancement of regional energy transition efforts.

Beyond the energy projections, the practical feasibility of advanced routes such as hydrogen and syngas production depends on non-technical factors that shape their implementation in medium-sized urban contexts such as Popayán [31], [41], [42], [48]. The deployment of reforming technologies requires specialized infrastructure for purification, compression, and storage, as well as local markets capable of absorbing the hydrogen produced [8], [31], [38]. In Colombia, green hydrogen demand remains incipient and is largely concentrated in the petrochemical and steel industries, which limits its territorial deployment in medium-sized cities without consolidated industrial hubs [49]. Likewise, syngas commercialization faces regulatory and energy-standardization barriers, along with the need for policy incentives to

support investment in transitional energy infrastructure [31], [40]. These considerations suggest that, although technically viable, hydrogen- and syngas-based routes require institutional frameworks, value chains, and market strategies that are still under development to fully materialize their potential in Popayán.

5. Conclusions

The projections developed for the Los Picachos Sanitary Landfill demonstrate a significant potential for methane valorization, both for energy generation and for chemical transformation. Based on population data from the 2005 and 2018 DANE censuses and per capita waste generation rates, a cumulative waste disposal exceeding 3.1×10^6 Mg was estimated for the active disposal period from 2014 to 2044, resulting in over 531 000 Mg of cumulative methane generation over the complete modeling horizon from 2014 to 2154. This baseline enabled a quantitative estimation of the different forms of recoverable energy.

The results indicate that most methane generation is concentrated around the final years of operation and the early post-closure period. During the active disposal phase, this behavior is driven by population-based waste input; after closure, methane generation reflects the delayed degradation of the waste accumulated up to 2044. The estimates include more than 5.41×10^7 MJ·d^{-1} of chemical energy, 3.91×10^6 kWh·d^{-1} of electricity, and 7.52×10^6 kWh·d^{-1} of thermal energy. Hydrogen production through different technological routes (SMR, CLR, and CL_PB) was also assessed, with projected outputs of 1.14×10^9 Nm^3 to 1.23×10^9 Nm^3 of H_2, and syngas production reached up to 2.67×10^9 Nm^3.

The integrated analysis confirms that the methane generated at Los Picachos is not only a viable alternative for the transition toward cleaner and more sustainable energy sources, but also a strategic opportunity for industrial decarbonization, particularly in sectors that can incorporate hydrogen or syngas. The projected values are consistent with experimental data reported in the literature, validating the technical approach used.

The sensitivity analysis confirmed that the energy recovery estimates depend on the selected values of K and L_0. Although the reference scenario represents the most plausible trajectory, the conservative and optimistic scenarios indicate that both the magnitude and the timing of methane availability may vary. Nonetheless, the overall conclusions regarding the feasibility

and strategic relevance of methane valorization at Los Picachos remain consistent across all scenarios.

This study provides a rigorous quantitative framework for assessing biogas utilization in Latin American landfills and offers a replicable methodological reference for other regions with similar demographic and operational characteristics. Future research should focus on the pilot-scale implementation of methane reforming technologies, integrating life cycle assessment, economic feasibility, and carbon footprint analysis as complementary tools for decision-making in waste management policies and energy transition planning.

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7. Author Contributions

Luisa F. Ramírez-Ríos: Conceptualization, Data curation, Writing – original draft. Dorance Becerra-Moreno: Data curation, Writing – review & editing, Supervision. Judith Y. Ortega-Contreras: Data curation, Writing – original draft.

8. Access to Research Data

All data used in this research were obtained from public sources. Population projections were taken from the official DANE website; per capita waste generation data were obtained from the Superintendency of Residential Public Services (Superservicios); the LandGEM model was accessed through the U.S. EPA website; and the equations and mathematical models were derived from the scientific literature cited in this article.

9. Conflict of Interest

The authors declare that there is no conflict of interest regarding the conduct or publication of this study.

10. Statement on Artificial Intelligence

The authors declare that they did not use generative AI or AI-assisted technologies during the preparation of this work.

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11. Appendices

Table A1. Complete annual dataset supporting population, waste input, and methane generation estimates at the Los Picachos Landfill.

Year	Population (inhabitants)	Per capita production (kg·person^{-1}·d^{-1})	Waste Accepted [Mg·year^{-1}]	Methane [m^3·year^{-1}] K = 0.02 year^{-1}, L_0 = 96 m^3·Mg^{-1}	Methane [m^3·year^{-1}] K = 0.05 year^{-1}, L_0 = 130 m^3·Mg^{-1}	Methane [m^3·year^{-1}] K = 0.07 year^{-1}, L_0 = 170 m^3·Mg^{-1}
2014	607 371	0.43	94 951	0	0	0
2015	608 292	0.43	95 328	180 676	603 513	0
2016	609 214	0.43	95 706	358 492	1 179 990	0
2017	610 136	0.43	96 083	533 504	1 730 749	0
2018	611 058	0.43	96 460	705 769	2 257 045	0
2019	611 980	0.43	96 837	875 340	2 760 070	0
2020	612 902	0.43	97 214	1 042 272	3 240 959	1 095 103
2021	613 824	0.44	97 591	1 206 615	3 700 792	2 120 520
2022	614 745	0.44	97 968	1 368 422	4 140 597	3 080 962
2023	615 667	0.44	98 346	1 527 743	4 561 348	3 980 822
2024	616 589	0.44	98 723	1 684 626	4 963 977	4 824 196
2025	617 511	0.44	99 100	1 839 121	5 349 367	5 614 903
2026	618 433	0.44	99 477	1 991 274	5 718 358	6 356 503
2027	619 355	0.44	99 854	2 141 132	6 071 751	7 052 316
2028	620 276	0.44	100 231	2 288 740	6 410 305	7 705 437
2029	621 198	0.44	100 609	2 434 144	6 734 745	8 318 754
2030	622 120	0.44	100 986	2 577 385	7 045 760	8 894 956
2031	623 042	0.45	101 363	2 718 508	7 344 003	9 436 553
2032	623 964	0.45	101 740	2 857 554	7 630 098	9 945 885
2033	624 886	0.45	102 117	2 994 565	7 904 637	10 425 133
2034	625 808	0.45	102 494	3 129 580	8 168 184	10 876 331
2035	626 729	0.45	102 871	3 262 639	8 421 275	11 301 374
2036	627 651	0.45	103 249	3 393 781	8 664 420	11 702 032
2037	628 573	0.45	103 626	3 523 044	8 898 103	12 079 953
2038	630 266	0.45	104 007	3 650 466	9 122 787	12 436 674
2039	632 215	0.45	104 389	3 776 089	9 338 935	12 773 629
2040	634 164	0.45	104 772	3 899 952	9 546 972	13 092 153
2041	636 113	0.45	105 154	4 022 090	9 747 293	13 393 492
2042	638 063	0.45	105 536	4 142 537	9 940 274	13 678 810
2043	640 012	0.45	105 919	4 261 327	10 126 273	13 949 187
2044	641 961	0.45	106 301	4 378 492	10 305 632	14 205 681
2045	N/A	N/A	N/A	4 494 065	10 478 673	14 449 243
2046	N/A	N/A	N/A	4 405 076	9 967 622	14 680 749
2047	N/A	N/A	N/A	4 317 850	9 481 496	14 901 014
2048	N/A	N/A	N/A	4 232 351	9 019 078	15 110 797
2049	N/A	N/A	N/A	4 148 545	8 579 212	15 310 807

2050	N/A	N/A	N/A	4 066 398	8 160 799	15 501 706
2051	N/A	N/A	N/A	3 985 878	7 762 792	14 453 694
2052	N/A	N/A	N/A	3 906 952	7 384 196	13 476 535
2053	N/A	N/A	N/A	3 829 589	7 024 065	12 565 438
2054	N/A	N/A	N/A	3 753 758	6 681 497	11 715 937
2055	N/A	N/A	N/A	3 679 429	6 355 637	10 923 867
2056	N/A	N/A	N/A	3 606 571	6 045 669	10 185 346
2057	N/A	N/A	N/A	3 535 157	5 750 818	9 496 754
2058	N/A	N/A	N/A	3 465 156	5 470 347	8 854 715
2059	N/A	N/A	N/A	3 396 541	5 203 555	8 256 081
2060	N/A	N/A	N/A	3 329 285	4 949 775	7 697 919
2061	N/A	N/A	N/A	3 263 361	4 708 371	7 177 492
2062	N/A	N/A	N/A	3 198 742	4 478 741	6 692 249
2063	N/A	N/A	N/A	3 135 403	4 260 311	6 239 812
2064	N/A	N/A	N/A	3 073 317	4 052 533	5 817 962
2065	N/A	N/A	N/A	3 012 462	3 854 889	5 424 632
2066	N/A	N/A	N/A	2 952 811	3 666 883	5 057 893
2067	N/A	N/A	N/A	2 894 341	3 488 047	4 715 948
2068	N/A	N/A	N/A	2 837 030	3 317 933	4 397 121
2069	N/A	N/A	N/A	2 780 853	3 156 116	4 099 849
2070	N/A	N/A	N/A	2 725 788	3 002 190	3 822 674
2071	N/A	N/A	N/A	2 671 814	2 855 772	3 564 237
2072	N/A	N/A	N/A	2 618 908	2 716 494	3 323 273
2073	N/A	N/A	N/A	2 567 051	2 584 009	3 098 599
2074	N/A	N/A	N/A	2 516 220	2 457 985	2 889 114
2075	N/A	N/A	N/A	2 466 395	2 338 108	2 693 792
2076	N/A	N/A	N/A	2 417 557	2 224 077	2 511 675
2077	N/A	N/A	N/A	2 369 686	2 115 608	2 341 871
2078	N/A	N/A	N/A	2 322 763	2 012 428	2 183 546
2079	N/A	N/A	N/A	2 276 770	1 914 281	2 035 925
2080	N/A	N/A	N/A	2 231 687	1 820 920	1 898 283
2081	N/A	N/A	N/A	2 187 496	1 732 113	1 769 948
2082	N/A	N/A	N/A	2 144 181	1 647 637	1 650 288
2083	N/A	N/A	N/A	2 101 723	1 567 281	1 538 719
2084	N/A	N/A	N/A	2 060 106	1 490 844	1 434 692
2085	N/A	N/A	N/A	2 019 313	1 418 134	1 337 698
2086	N/A	N/A	N/A	1 979 328	1 348 971	1 247 261
2087	N/A	N/A	N/A	1 940 135	1 283 181	1 162 939
2088	N/A	N/A	N/A	1 901 718	1 220 599	1 084 317
2089	N/A	N/A	N/A	1 864 061	1 161 070	1 011 010
2090	N/A	N/A	N/A	1 827 150	1 104 444	942 660
2091	N/A	N/A	N/A	1 790 970	1 050 580	878 930
2092	N/A	N/A	N/A	1 755 507	999 342	819 509
2093	N/A	N/A	N/A	1 720 745	950 604	764 105

2094	N/A	N/A	N/A	1 686 672	904 242	712 447
2095	N/A	N/A	N/A	1 653 274	860 142	664 281
2096	N/A	N/A	N/A	1 620 537	818 192	619 372
2097	N/A	N/A	N/A	1 588 448	778 289	577 498
2098	N/A	N/A	N/A	1 556 995	740 331	538 456
2099	N/A	N/A	N/A	1 526 164	704 225	502 053
2100	N/A	N/A	N/A	1 495 944	669 879	468 111
2101	N/A	N/A	N/A	1 466 323	637 209	436 464
2102	N/A	N/A	N/A	1 437 287	606 132	406 956
2103	N/A	N/A	N/A	1 408 827	576 570	379 443
2104	N/A	N/A	N/A	1 380 931	548 451	353 791
2105	N/A	N/A	N/A	1 353 586	521 702	329 872
2106	N/A	N/A	N/A	1 326 783	496 259	307 571
2107	N/A	N/A	N/A	1 300 511	472 056	286 777
2108	N/A	N/A	N/A	1 274 760	449 033	267 389
2109	N/A	N/A	N/A	1 249 518	427 134	249 312
2110	N/A	N/A	N/A	1 224 776	406 302	232 457
2111	N/A	N/A	N/A	1 200 523	386 487	216 741
2112	N/A	N/A	N/A	1 176 751	367 637	202 088
2113	N/A	N/A	N/A	1 153 450	349 708	188 426
2114	N/A	N/A	N/A	1 130 610	332 652	175 687
2115	N/A	N/A	N/A	1 108 223	316 429	163 810
2116	N/A	N/A	N/A	1 086 278	300 996	152 735
2117	N/A	N/A	N/A	1 064 769	286 316	142 409
2118	N/A	N/A	N/A	1 043 685	272 353	132 782
2119	N/A	N/A	N/A	1 023 019	259 070	123 805
2120	N/A	N/A	N/A	1 002 761	246 435	115 435
2121	N/A	N/A	N/A	982 905	234 416	107 631
2122	N/A	N/A	N/A	963 443	222 983	100 354
2123	N/A	N/A	N/A	944 365	212 108	93 570
2124	N/A	N/A	N/A	925 665	201 764	87 244
2125	N/A	N/A	N/A	907 336	191 924	81 345
2126	N/A	N/A	N/A	889 370	182 563	75 846
2127	N/A	N/A	N/A	871 759	173 660	70 718
2128	N/A	N/A	N/A	854 497	165 190	65 937
2129	N/A	N/A	N/A	837 577	157 134	61 480
2130	N/A	N/A	N/A	820 992	149 470	57 323
2131	N/A	N/A	N/A	804 735	142 180	53 448
2132	N/A	N/A	N/A	788 800	135 246	49 834
2133	N/A	N/A	N/A	773 181	128 650	46 465
2134	N/A	N/A	N/A	757 871	122 376	43 324
2135	N/A	N/A	N/A	742 864	116 408	40 395
2136	N/A	N/A	N/A	728 154	110 730	37 664
2137	N/A	N/A	N/A	713 736	105 330	35 118

2138	N/A	N/A	N/A	699 603	100 193	32 744
2139	N/A	N/A	N/A	685 750	95 306	30 530
2140	N/A	N/A	N/A	672 171	90 658	28 466
2141	N/A	N/A	N/A	658 861	86 237	26 541
2142	N/A	N/A	N/A	645 815	82 031	24 747
2143	N/A	N/A	N/A	633 027	78 030	23 074
2144	N/A	N/A	N/A	620 492	74 225	21 514
2145	N/A	N/A	N/A	608 206	70 605	20 060
2146	N/A	N/A	N/A	596 162	67 161	18 703
2147	N/A	N/A	N/A	584 357	63 886	17 439
2148	N/A	N/A	N/A	572 786	60 770	16 260
2149	N/A	N/A	N/A	561 444	57 806	15 161
2150	N/A	N/A	N/A	550 327	54 987	14 136
2151	N/A	N/A	N/A	539 430	52 305	13 180
2152	N/A	N/A	N/A	528 748	49 754	12 289
2153	N/A	N/A	N/A	518 279	47 328	11 458
2154	N/A	N/A	N/A	508 016	45 020	10 684
Total			3.12E+06	2.75E+08	4.06E+08	5.32E+08
Average			1.01E+05	1.95E+06	2.88E+06	3.77E+06

Note. From 2045 onward, population and PPC were not projected because the landfill was assumed to be closed after the active disposal period ending in 2044. Accepted waste was therefore set to zero from 2045 onward. Methane generation after 2045 corresponds to the first-order degradation of waste accumulated during the active disposal period.

Table A1 provides the complete annual dataset used to construct Figure 1 and to support the LandGEM-based methane generation estimates. It is included to ensure transparency and reproducibility of the calculations and should not be interpreted as an additional result beyond the graphical and analytical summaries discussed in the main text. N.A. means not applicable. From 2045 onward, population and PPC were not projected because the landfill was assumed to be closed after the active disposal period ending in 2044. Accepted waste was therefore set to zero from 2045 onward, while methane generation corresponds to the first-order degradation of waste accumulated during the active disposal period.

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Table A2 Complete annual dataset supporting energy, hydrogen, and syngas production estimates from methane recovery at the Los Picachos Landfill.

Year	Chemical energy [MJ·d⁻¹]	Electrical energy [kWh·d⁻¹]	Thermal energy [kWh·d⁻¹]	Hydrogen SMR [Nm³·year⁻¹]	Hydrogen CLR [Nm³·year⁻¹]	Hydrogen CL_PB [Nm³·year⁻¹]	Syngas MeOH-CL_PB [Nm³·year⁻¹]	Syngas CLR-PB [Nm³·year⁻¹]	Syngas SMR [Nm³·year⁻¹]	Syngas CLR-PB [Nm³·year⁻¹]
2014	0	0	0	0	0	0	0	0	0	0
2015	91 410	6 602	12 697	2 054 612	1 930 841	2 079 367	3 399 241	3 946 348	3 031 513	4 511 394
2016	178 118	12 865	24 741	4 003 548	3 762 371	4 051 784	6 623 646	7 689 721	5 907 104	8 790 749
2017	260 385	18 807	36 168	5 852 663	5 500 093	5 923 177	9 682 902	11 241 363	8 635 411	12 850 922
2018	338 457	24 446	47 012	7 607 486	7 149 204	7 699 143	12 586 159	14 611 900	11 224 596	16 704 058
2019	412 567	29 799	57 306	9 273 243	8 714 614	9 384 969	15 342 061	17 811 363	13 682 365	20 361 627
2020	482 934	34 881	67 079	10 854 869	10 200 961	10 985 650	17 958 771	20 849 233	16 016 002	23 834 464
2021	549 765	39 708	76 362	12 357 024	11 612 625	12 505 904	20 444 003	23 734 462	18 232 382	27 132 806
2022	613 256	44 294	85 181	13 784 112	12 953 744	13 950 186	22 805 040	26 475 508	20 338 004	30 266 319
2023	673 592	48 652	93 562	15 140 292	14 228 226	15 322 705	25 048 764	29 080 359	22 339 003	33 244 137
2024	730 949	52 795	101 529	16 429 493	15 439 765	16 627 439	27 181 674	31 556 561	24 241 176	36 074 887
2025	785 491	56 734	109 105	17 655 426	16 591 846	17 868 142	29 209 911	33 911 242	26 050 000	38 766 715
2026	837 374	60 482	116 311	18 821 596	17 687 765	19 048 362	31 139 273	36 151 135	27 770 645	41 327 321
2027	886 745	64 048	123 169	19 931 314	18 730 632	20 171 450	32 975 240	38 282 600	29 407 998	43 763 973
2028	933 744	67 442	129 697	20 987 708	19 723 389	21 240 572	34 722 985	40 311 645	30 966 673	46 083 540
2029	978 502	70 675	135 914	21 993 733	20 668 810	22 258 718	36 387 397	42 243 944	32 451 030	48 292 509
2030	1 021 144	73 755	141 837	22 952 180	21 569 519	23 228 712	37 973 093	44 084 858	33 865 186	50 397 008
2031	1 061 785	76 691	147 482	23 865 684	22 427 992	24 153 222	39 484 434	45 839 449	35 213 031	52 402 825
2032	1 100 539	79 490	152 865	24 736 736	23 246 571	25 034 769	40 925 541	47 512 501	36 498 239	54 315 427
2033	1 137 508	82 160	158 000	25 567 687	24 027 465	25 875 732	42 300 303	49 108 531	37 724 281	56 139 980
2034	1 172 792	84 708	162 901	26 360 760	24 772 762	26 678 360	43 612 398	50 631 807	38 894 434	57 881 361
2035	1 206 484	87 142	167 581	27 118 053	25 484 435	27 444 777	44 865 297	52 086 360	40 011 795	59 544 180
2036	1 238 672	89 467	172 052	27 841 549	26 164 347	28 176 989	46 062 280	53 475 998	41 079 289	61 132 788
2037	1 269 440	91 689	176 325	28 533 120	26 814 257	28 876 892	47 206 445	54 804 316	42 099 679	62 651 298
2038	1 298 866	93 815	180 413	29 194 535	27 435 828	29 546 276	48 300 719	56 074 713	43 075 575	64 103 593
2039	1 327 029	95 849	184 324	29 827 549	28 030 709	30 186 917	49 348 005	57 290 560	44 009 567	65 493 527

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2040	1 354 000	97 797	188 071	30 433 764	28 600 405	30 800 436	50 350 954	58 454 933	44 904 017	66 824 617
2041	1 379 844	99 663	191 660	31 014 665	29 146 311	31 388 335	51 312 021	59 570 684	45 761 117	68 100 123
2042	1 404 624	101 453	195 102	31 571 653	29 669 746	31 952 035	52 233 528	60 640 508	46 582 935	69 323 126
2043	1 428 400	103 170	198 405	32 106 055	30 171 955	32 492 875	53 117 666	61 666 947	47 371 428	70 496 533
2044	1 451 226	104 819	201 575	32 619 121	30 654 114	33 012 123	53 966 505	62 652 407	48 128 440	71 623 093
2045	1 473 156	106 403	204 621	33 112 034	31 117 333	33 510 975	54 782 002	63 599 158	48 855 717	72 705 401
2046	1 391 535	100 508	193 284	31 277 431	29 393 249	31 654 268	51 746 754	60 075 387	46 148 820	68 677 091
2047	1 314 435	94 939	182 575	29 544 476	27 764 688	29 900 434	48 879 677	56 746 855	43 591 902	64 871 973
2048	1 241 608	89 679	172 459	27 907 537	26 226 360	28 243 772	46 171 453	53 602 742	41 176 652	61 277 681
2049	1 172 815	84 710	162 904	26 361 294	24 773 264	26 678 900	43 613 281	50 632 833	38 895 221	57 882 534
2050	1 107 834	80 017	153 878	24 900 722	23 400 678	25 200 731	41 196 846	47 827 473	36 740 195	54 675 498
2051	1 046 454	75 583	145 352	23 521 074	22 104 142	23 804 461	38 914 297	45 177 548	34 704 571	51 646 151
2052	988 474	71 396	137 299	22 217 867	20 879 441	22 485 552	36 758 214	42 674 444	32 781 732	48 784 648
2053	933 707	67 440	129 692	20 986 866	19 722 597	21 239 719	34 721 591	40 310 026	30 965 429	46 081 689
2054	881 974	63 703	122 506	19 824 069	18 629 848	20 062 913	32 797 809	38 076 612	29 249 761	43 528 490
2055	833 107	60 174	115 719	18 725 698	17 597 644	18 951 309	30 980 616	35 966 942	27 629 151	41 116 754
2056	786 948	56 840	109 307	17 688 183	16 622 630	17 901 294	29 264 106	33 974 160	26 098 332	38 838 642
2057	743 347	53 690	103 251	16 708 153	15 701 638	16 909 456	27 642 701	32 091 790	24 652 330	36 686 751
2058	702 161	50 716	97 530	15 782 422	14 831 674	15 972 572	26 111 131	30 313 714	23 286 444	34 654 087
2059	663 257	47 906	92 126	14 907 982	14 009 911	15 087 597	24 664 420	28 634 155	21 996 237	32 734 045
2060	626 509	45 251	87 022	14 081 992	13 233 679	14 251 654	23 297 865	27 047 653	20 777 515	30 920 385
2061	591 796	42 744	82 200	13 301 766	12 500 455	13 462 028	22 007 025	25 549 052	19 626 318	29 207 212
2062	559 007	40 376	77 646	12 564 769	11 807 855	12 716 152	20 787 705	24 133 483	18 538 903	27 588 960
2063	528 035	38 139	73 344	11 868 606	11 153 630	12 011 602	19 635 943	22 796 345	17 511 738	26 060 368
2064	498 779	36 026	69 280	11 211 015	10 535 653	11 346 088	18 547 995	21 533 293	16 541 484	24 616 469
2065	471 143	34 030	65 442	10 589 858	9 951 915	10 717 447	17 520 326	20 340 221	15 624 988	23 252 570
2066	445 039	32 144	61 816	10 003 117	9 400 520	10 123 637	16 549 596	19 213 252	14 759 271	21 964 240
2067	420 381	30 363	58 391	9 448 885	8 879 675	9 562 727	15 632 651	18 148 724	13 941 519	20 747 291
2068	397 090	28 681	55 156	8 925 361	8 387 689	9 032 896	14 766 509	17 143 177	13 169 077	19 597 768
2069	375 089	27 092	52 100	8 430 843	7 922 961	8 532 420	13 948 357	16 193 343	12 439 432	18 511 935

2070	354 307	25 591	49 213	7 963 724	7 483 982	8 059 673	13 175 535	15 296 136	11 750 213	17 486 264
2071	334 676	24 173	46 486	7 522 487	7 069 325	7 613 119	12 445 532	14 448 639	11 099 182	16 517 422
2072	316 133	22 834	43 911	7 105 697	6 677 643	7 191 307	11 755 976	13 648 099	10 484 221	15 602 258
2073	298 617	21 569	41 478	6 711 999	6 307 662	6 792 866	11 104 625	12 891 913	9 903 333	14 737 801
2074	282 072	20 373	39 180	6 340 114	5 958 180	6 416 501	10 489 363	12 177 625	9 354 630	13 921 239
2075	266 444	19 245	37 009	5 988 834	5 628 061	6 060 989	9 908 190	11 502 912	8 836 328	13 149 920
2076	251 681	18 178	34 958	5 657 017	5 316 233	5 725 174	9 359 218	10 865 583	8 346 743	12 421 336
2077	237 736	17 171	33 022	5 343 585	5 021 682	5 407 966	8 840 662	10 263 565	7 884 284	11 733 121
2078	224 564	16 220	31 192	5 047 519	4 743 451	5 108 332	8 350 836	9 694 902	7 447 448	11 083 036
2079	212 122	15 321	29 464	4 767 856	4 480 636	4 825 300	7 888 151	9 157 747	7 034 815	10 468 970
2080	200 369	14 472	27 831	4 503 689	4 232 382	4 557 950	7 451 100	8 650 354	6 645 045	9 888 927
2081	189 268	13 670	26 289	4 254 158	3 997 883	4 305 413	7 038 265	8 171 073	6 276 870	9 341 022
2082	178 781	12 913	24 833	4 018 452	3 776 377	4 066 867	6 648 304	7 718 347	5 929 094	8 823 474
2083	168 876	12 198	23 457	3 795 806	3 567 143	3 841 539	6 279 948	7 290 705	5 600 587	8 334 601
2084	159 519	11 522	22 157	3 585 496	3 369 502	3 628 695	5 932 002	6 886 757	5 290 281	7 872 815
2085	150 681	10 883	20 930	3 386 838	3 182 812	3 427 643	5 603 334	6 505 189	4 997 168	7 436 614
2086	142 332	10 280	19 770	3 199 187	3 006 465	3 237 732	5 292 876	6 144 763	4 720 295	7 024 582
2087	134 446	9 711	18 675	3 021 933	2 839 889	3 058 342	4 999 619	5 804 307	4 458 763	6 635 378
2088	126 997	9 173	17 640	2 854 500	2 682 542	2 888 892	4 722 610	5 482 714	4 211 721	6 267 739
2089	119 960	8 665	16 663	2 696 344	2 533 914	2 728 830	4 460 950	5 178 939	3 978 367	5 920 469
2090	113 314	8 184	15 739	2 546 951	2 393 520	2 577 637	4 213 787	4 891 995	3 757 942	5 592 440
2091	107 036	7 731	14 867	2 405 834	2 260 905	2 434 820	3 980 318	4 620 950	3 549 729	5 282 586
2092	101 105	7 303	14 044	2 272 537	2 135 637	2 299 917	3 759 785	4 364 922	3 353 053	4 989 899
2093	95 503	6 898	13 265	2 146 625	2 017 310	2 172 488	3 551 470	4 123 079	3 167 274	4 713 429
2094	90 212	6 516	12 530	2 027 689	1 905 539	2 052 119	3 354 698	3 894 636	2 991 789	4 452 277
2095	85 214	6 155	11 836	1 915 343	1 799 961	1 938 420	3 168 828	3 678 850	2 826 026	4 205 595
2096	80 492	5 814	11 180	1 809 222	1 700 233	1 831 020	2 993 256	3 475 020	2 669 447	3 972 580
2097	76 033	5 492	10 561	1 708 980	1 606 030	1 729 570	2 827 412	3 282 483	2 521 544	3 752 475
2098	71 820	5 187	9 976	1 614 293	1 517 046	1 633 742	2 670 756	3 100 614	2 381 835	3 544 566
2099	67 841	4 900	9 423	1 524 851	1 432 993	1 543 223	2 522 781	2 928 822	2 249 868	3 348 176

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2100	64 082	4 629	8 901	1 440 365	1 353 596	1 457 719	2 383 004	2 766 548	2 125 212	3 162 667
2101	60 531	4 372	8 408	1 360 561	1 278 599	1 376 953	2 250 971	2 613 265	2 007 462	2 987 437
2102	57 178	4 130	7 942	1 285 177	1 207 757	1 300 662	2 126 254	2 468 474	1 896 237	2 821 915
2103	54 010	3 901	7 502	1 213 971	1 140 840	1 228 597	2 008 447	2 331 706	1 791 174	2 665 564
2104	51 017	3 685	7 086	1 146 710	1 077 631	1 160 526	1 897 167	2 202 516	1 691 933	2 517 876
2105	48 191	3 481	6 694	1 083 175	1 017 924	1 096 226	1 792 053	2 080 483	1 598 189	2 378 371
2106	45 520	3 288	6 323	1 023 161	961 525	1 035 488	1 692 762	1 965 212	1 509 640	2 246 595
2107	42 998	3 106	5 972	966 472	908 251	978 116	1 598 973	1 856 328	1 425 997	2 122 120
2108	40 616	2 934	5 642	912 923	857 928	923 923	1 510 381	1 753 476	1 346 989	2 004 542
2109	38 366	2 771	5 329	862 342	810 394	872 732	1 426 697	1 656 323	1 272 357	1 893 479
2110	36 240	2 618	5 034	814 563	765 493	824 377	1 347 649	1 564 553	1 201 861	1 788 569
2111	34 232	2 473	4 755	769 432	723 080	778 702	1 272 981	1 477 868	1 135 271	1 689 471
2112	32 335	2 336	4 491	726 801	683 017	735 557	1 202 451	1 395 985	1 072 370	1 595 865
2113	30 544	2 206	4 243	686 531	645 174	694 803	1 135 828	1 318 639	1 012 955	1 507 444
2114	28 852	2 084	4 007	648 494	609 428	656 307	1 072 896	1 245 579	956 831	1 423 923
2115	27 253	1 968	3 785	612 563	575 662	619 943	1 013 451	1 176 566	903 817	1 345 029
2116	25 743	1 859	3 576	578 624	543 767	585 595	957 300	1 111 377	853 740	1 270 507
2117	24 317	1 756	3 378	546 564	513 639	553 149	904 260	1 049 801	806 438	1 200 113
2118	22 969	1 659	3 190	516 281	485 180	522 502	854 159	991 635	761 756	1 133 620
2119	21 697	1 567	3 014	487 676	458 298	493 552	806 833	936 693	719 550	1 070 810
2120	20 495	1 480	2 847	460 656	432 906	466 206	762 130	884 795	679 683	1 011 481
2121	19 359	1 398	2 689	435 133	408 920	440 376	719 903	835 772	642 025	955 439
2122	18 286	1 321	2 540	411 024	386 264	415 976	680 016	789 465	606 453	902 502
2123	17 273	1 248	2 399	388 251	364 862	392 929	642 340	745 724	572 852	852 498
2124	16 316	1 178	2 266	366 740	344 647	371 158	606 750	704 406	541 112	805 265
2125	15 412	1 113	2 141	346 420	325 551	350 594	573 133	665 378	511 131	760 648
2126	14 558	1 052	2 022	327 226	307 514	331 169	541 378	628 512	482 812	718 504
2127	13 752	993	1 910	309 096	290 476	312 820	511 382	593 689	456 061	678 694
2128	12 990	938	1 804	291 970	274 382	295 488	483 048	560 795	430 793	641 091
2129	12 270	886	1 704	275 793	259 179	279 116	456 285	529 724	406 924	605 570
2130	11 590	837	1 610	260 513	244 819	263 652	431 004	500 374	384 378	572 018
2131	10 948	791	1 521	246 079	231 255	249 044	407 124	472 650	363 081	540 325
2132	10 341	747	1 436	232 445	218 442	235 245	384 567	446 463	342 964	510 388
2133	9 768	706	1 357	219 566	206 339	222 211	363 259	421 726	323 962	482 109

2134	9 227	666	1 282	207 401	194 907	209 899	343 133	398 360	306 013	455 398
2135	8 716	630	1 211	195 909	184 108	198 270	324 121	376 288	289 058	430 166
2136	8 233	595	1 144	185 055	173 907	187 284	306 163	355 440	273 042	406 332
2137	7 777	562	1 080	174 802	164 271	176 908	289 200	335 746	257 914	383 819
2138	7 346	531	1 020	165 117	155 170	167 106	273 176	317 144	243 624	362 553
2139	6 939	501	964	155 968	146 573	157 847	258 041	299 572	230 126	342 466
2140	6 555	473	910	147 327	138 452	149 102	243 744	282 974	217 376	323 491
2141	6 191	447	860	139 164	130 780	140 841	230 239	267 296	205 332	305 568
2142	5 848	422	812	131 453	123 534	133 037	217 482	252 486	193 955	288 637
2143	5 524	399	767	124 170	116 690	125 666	205 432	238 497	183 209	272 645
2144	5 218	377	725	117 290	110 225	118 703	194 050	225 283	173 058	257 539
2145	4 929	356	685	110 792	104 118	112 127	183 299	212 801	163 470	243 270
2146	4 656	336	647	104 653	98 349	105 914	173 143	201 010	154 412	229 791
2147	4 398	318	611	98 855	92 900	100 046	163 550	189 873	145 857	217 059
2148	4 154	300	577	93 378	87 752	94 503	154 488	179 353	137 776	205 033
2149	3 924	283	545	88 204	82 890	89 267	145 929	169 416	130 142	193 673
2150	3 707	268	515	83 317	78 298	84 321	137 843	160 029	122 931	182 942
2151	3 501	253	486	78 701	73 960	79 649	130 206	151 163	116 120	172 806
2152	3 307	239	459	74 340	69 862	75 236	122 992	142 787	109 687	163 232
2153	3 124	226	434	70 221	65 991	71 067	116 177	134 876	103 609	154 188
2154	2 951	213	410	66 331	62 335	67 130	109 740	127 403	97 869	145 645
Total	5.41E+07	3.91E+06	7.52E+06	1.22E+09	1.14E+09	1.23E+09	2.01E+09	2.34E+09	1.80E+09	2.67E+09
Average	3.84E+05	2.77E+04	5.33E+04	8.63E+06	8.11E+06	8.74E+06	1.43E+07	1.66E+07	1.27E+07	1.90E+07

Note. Table A2 provides the complete annual dataset used to construct Figures 2, 3, and 4 and to support the estimates of chemical energy, electrical energy, thermal energy, hydrogen production, and syngas generation. It is included to ensure transparency and reproducibility of the calculations and should not be interpreted as an additional result beyond the graphical and analytical summaries discussed in the main text.