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Assessment of Biomethane Production Potential in Spain: A Regional Analysis of Agricultural Residues, Municipal Waste, and Wastewater Sludge for 2030 and 2050

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Abstract: This study evaluates Spain's biomethane production potential for 2030 and 2050, focusing on agricultural residues, livestock manure, municipal solid waste (MSW), and wastewater treatment plant (WWTP) sludge. The research aims to provide a regional analysis based on historical data on livestock populations, cultivated land, waste availability, and demographic projections. Using utilization coefficients and technological assumptions derived from existing biogas infrastructure, the study estimates that Spain could generate 9.71 TWh of biomethane by 2030, slightly below the national target of 10.41 TWh. By 2050, agricultural and livestock residues are expected to contribute 30.04 TWh, accounting for nearly 80% of total biomethane production, while the relative share of MSW and WWTP sludge will decrease. Andalusia, Castilla-La Mancha, and Castilla y León emerge as key contributors due to their extensive agricultural and livestock sectors. Catalonia and Madrid maintain significant roles driven by urban waste generation. The findings underscore the need for infrastructure expansion, particularly enhancing biomethane injection facilities into the natural gas grid, alongside financial incentives to support industry growth. This study highlights the role of biomethane in Spain's renewable energy sector, emphasizing its potential to reduce greenhouse gas emissions, optimize organic waste utilization, and contribute to a sustainable energy transition.

Keywords: biomethane; anaerobic digestion; circular economy; regional analysis; agricultural residues; wastewater sludge; municipal solid waste

Academic Editors: Sara Silva, Alessandra Braga Ribeiro, Carlos Miguel Henriques Ferreira and Catarina Silva S. Oliveira

Received: 3 April 2025
Revised: 19 May 2025
Accepted: 20 May 2025
Published: 21 May 2025

Citation: López-Aguilera, A.; Morales-Polo, C.; Victoria-Rodríguez, J.; Cledera-Castro, M.d.M. Assessment of Biomethane Production Potential in Spain: A Regional Analysis of Agricultural Residues, Municipal Waste, and Wastewater Sludge for 2030 and 2050. *Sustainability* **2025**, *17*, 4742. https://doi.org/10.3390/su17104742

1. Introduction

Biomethane, generated through the anaerobic digestion of agricultural and urban waste, is a sustainable alternative to natural gas that aims to reduce emissions, promote efficient waste management, and strengthen energy independence. It also advances and supports the transition toward a circular economy by replacing artificial fertilizers with digestate, aligning these with global environmental and economic sustainability goals. The global potential for biogas and biomethane production is estimated to be 570 Mtoe and 730 Mtoe, respectively. However, annual global production in 2018 reached only 35 Mtoe of biogas and biomethane jointly [1]. While national averages offer a general view of biomethane potential, they often obscure the substantial spatial variability driven by differences in agricultural intensity, livestock distribution, and waste generation patterns. This study provides a regionally disaggregated outlook for 2030 and 2050, offering a novel community-level perspective that is essential for tailoring infrastructure planning, resource allocation, and policy interventions at subnational scales. This disparity between theoretical potential and current production is due to various factors, including technical, economic, and regulatory limitations.

The “upgrading” process is crucial to transform biogas into biomethane, a pure methane gas which can be injected into the natural gas grid after undergoing compression and quality control processes. Biogas obtained through the anaerobic digestion (AD) process is a mixture of methane, carbon dioxide, and other trace gases in varying proportions, depending on the organic materials used and the type of digester [1].

Regarding its use as an energy vector, both biogas and biomethane present several options, including but not limited to direct thermal use, electricity generation through cogeneration, transport fuel after upgrading the biogas to biomethane, and use as fuel in industrial processes that normally utilize natural gas [2].

Globally, there are numerous barriers to the implementation of biogas and biomethane, ranging from technical aspects such as network infrastructure and waste management to economic challenges like high initial investment costs and profitability issues when compared to cheaper fossil fuel alternatives. Additionally, there are regulatory and legislative barriers, such as complex permitting processes and the lack of adequate economic incentives to promote biomethane production and use [3].

In Europe, despite significant advancements and ambitious policies to promote renewable energy, the development of biogas and biomethane varies widely between countries. Germany stands out as the leader in biogas production, followed by Italy and France, each with different approaches and investment levels [4]. The diversity in national strategies reflects the complexity of the socio-economic and environmental challenges surrounding this emerging technology.

Biomethane, a renewable and sustainable form of natural gas produced from organic biomass, can be injected into the natural gas grid across Europe as part of ongoing efforts to reduce greenhouse gas emissions and promote the transition to a cleaner economy. Once injected, it blends with existing conventional natural gas in proportions compliant with European regulations and is considered simply natural gas based on Eurostat criteria. This process must comply with strict quality criteria established in standards such as UNE-EN 16723 [5] for biomethane injection into the natural gas grid.

To adequately monitor and record pure biomethane, i.e., that which has not been mixed with other fossil gases, specific tools such as SHARES [6] are used. This is crucial for issuing Guarantees of Origin and Renewable Fuel Certificates, which are fundamental to verifying and ensuring the authenticity and sustainability of the biomethane used in various energy applications [4]. Despite its high potential, Spain has yet to fully harness its biomethane potential, requiring an in-depth assessment of regional waste availability and technological feasibility [7].

The objective of this study is to estimate Spain’s regional biomethane production potential for the years 2030 and 2050, based on available organic waste streams and current technological assumptions. The analysis is guided by two research questions:

1. What is the regional distribution of biomethane potential in Spain, considering agricultural, livestock, municipal, and wastewater residues?
2. To what extent can Spain’s projected biomethane production contribute to national renewable energy targets under current and future waste utilization scenarios?

2. Materials and Methods

To determine the potential for biogas and biomethane production in Spain, various raw materials were considered and categorized into different groups: the livestock sector (housed and non-housed animals), agricultural residues, wastewater treatment plant (WWTP) sludge, and municipal solid waste (MSW).

All datasets used in this study are derived from publicly available sources such as the National Institute of Statistics (INE) and the Ministry of Agriculture, Fisheries, and Food. The computational methodology is available upon request.

The methodology employed was based on the collection and analysis of historical data on livestock census, cultivated land area, and waste availability. The data were then combined with utilization coefficients and technological assumptions derived from existing biogas infrastructure and industry best practices. Waste was classified based on the LER Code (European Waste List) [8] to ensure its proper management in anaerobic digesters, ensuring regulatory compliance and optimizing substrate composition. Biogas production estimates were calculated using empirical equations based on the volatile solids present in each waste type, their degradability, and average methane yield coefficients, documented in previous studies [7].

Open-source data from the National Institute of Statistics (INE), the Ministry of Agriculture, Fisheries, and Food, and the European Environment Agency were also used. Future scenario simulations for 2030 and 2050 were conducted. Conversion coefficients were derived from documented case studies in countries with well-developed infrastructure, such as Germany and France.

The code used for data processing and simulation scripts can be provided upon request.

While this study relies on official national statistics and publicly available datasets, some regional disparities in data completeness may affect the precision of certain estimates. In particular, under-reporting from regions such as País Vasco or Navarra, as well as limited transparency from multinational waste operators, may result in conservative figures for municipal and industrial waste streams. Where data were incomplete, extrapolations were made based on proportional scaling from adjacent regions with similar demographic and sectoral profiles. These assumptions were kept conservative to avoid overestimation and are discussed in the interpretation of results.

3. Results

This study assessed Spain's biomethane production potential for 2030 and 2050, analyzing key organic waste sources, including agricultural residues, livestock manure, municipal solid waste (MSW), and wastewater treatment plant (WWTP) sludge. The findings highlight the role of different waste streams in biomethane generation and their projected contributions over time. A regional analysis further identifies the most significant contributors across Spain, emphasizing the impact of agricultural and urban waste management practices. Additionally, the study evaluates the feasibility of meeting national biogas targets and the necessary infrastructure improvements for the integration of biomethane into the energy system. The following subsections present a detailed breakdown of these results, providing insights into waste stream contributions, regional variations, and future development needs.

3.1. Generation from Animal Waste

3.1.1. Bovine Waste

Bovines were divided into the following categories:

Dairy cows and replacement heifers1: Generate 9.25 m^3/place of slurry and 12.35 t/place per year [9]. Livestock units per stall [10].

Other cows: Produce 4.55 m^3/place per year of slurry and 5.5 t/place per year [9].

Bovine waste contains approximately 11% of total solids, of which 8% are volatile solids. It is estimated that each kilogram of volatile solids generates about 0.2 N m^3 of biogas composed of 65% methane (CH_4), 30% carbon dioxide (CO_2), and 5% other gases [11].

3.1.2. Porcine Waste

Pigs were divided into the following categories:

Breeding sows: Generate 5.13 m^3/place per year of slurry and 2.27 t/place per year of manure [9].

Other pigs: Produce 2 m^3/place per year of slurry and 1 t/place per year of manure [9].

Porcine waste has approximately 34% of total solids, of which 85.4% are volatile solids. The estimated biogas production is about 50 m^3 per ton of volatile solids, with a composition of 65% methane (CH_4), 30% carbon dioxide (CO_2), and 5% other gases [12–14].

3.1.3. Laying Hen Waste

For laying hens, it is estimated to be 0.037 m^3/place per year of slurry and 0.04 t/place per year of manure. Laying hen waste has a total solids content of 24%, of which 60% are volatile solids. Each ton of volatile solids is estimated to produce around 490 N m^3 of biogas, with a CH_4 proportion of 64.4%, 34% CO_2, and 1.71% of other gases [15–18].

3.1.4. Ovine Waste

There are two main categories of ovine:

Ewes and replacement lambs: Generate 0.38 tons of slurry and 0.72 tons of manure per livestock unit [16,17].

Other sheep: Produce 0.01 tons of slurry and 0.45 tons of manure per livestock unit [19,20].

Ovine manure contains approximately 38.5% total solids, of which 84.57% are volatile solids. Each ton of volatile solids is estimated to generate around 158 m^3 of biogas, composed of 54% CH_4, 41% CO_2, and 5% other gases.

3.1.5. Caprine Waste

Goats are divided into the following categories:

Breeding and replacement goats: Produce 0.38 tons of slurry and 0.72 tons of manure per livestock unit [21,22].

Other goats: Generate 0.19 tons of slurry and 0.36 tons of manure per livestock unit.

Caprine waste contains around 33.65% total solids, of which 82.21% are volatile solids. The estimated biogas production is about 250.7 m^3 per ton of volatile solids, with a composition of 65.02% CH_4, 30% CO_2, and 4.98% other gases [23–25].

3.1.6. Rabbit Waste

For rabbits, it is estimated that they produce 0.0236 tons of slurry and 0.1124 tons of manure per livestock unit. Rabbit waste has a total solids content of approximately 61.39% and 90.26% volatile solids on a dry matter basis. Each ton of volatile solids is estimated to produce around 325.53 m^3 of CH_4 in biogas [26,27].

3.1.7. Broiler Chicken Waste

For broiler chickens, it is estimated that they produce approximately 0.0333 tons of slurry and 0.036 tons of manure per livestock unit. These wastes have a total solids content of 11.20%, of which 8.27% are volatile solids. The estimated biogas production is around 500 m³ of CH_4 per ton of volatile solids, with a composition of 71.42% CH_4, 23.57% CO_2, and 5.01% other gases [28].

3.1.8. Projection and Energy Potential

The study projects the potential for biogas and biomethane for the years 2030 and 2050, based on utilization coefficients obtained from documented cases in Germany. The results indicate a significant increase in biomethane production, which could result in a significant contribution to renewable energy in Spain, as shown in Figure 1.

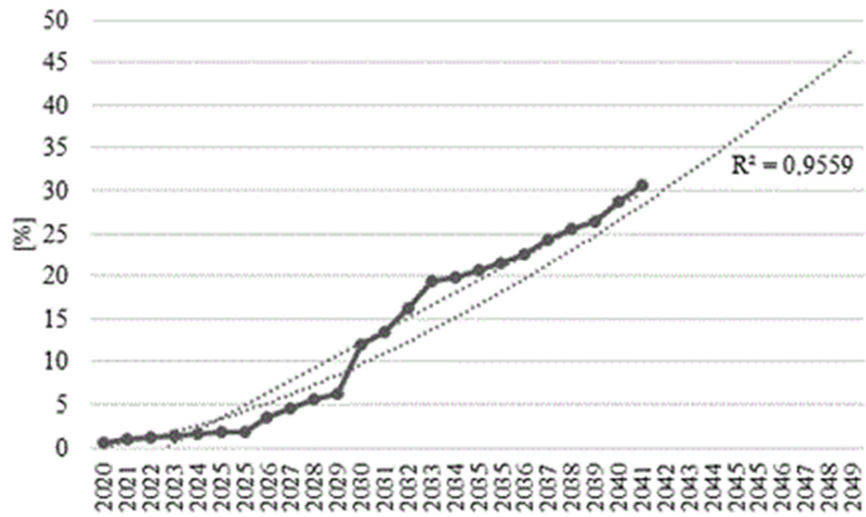


Figure 1. Utilization coefficient in Spain.

This detailed analysis provides a comprehensive perspective on the potential of livestock waste for biogas and biomethane generation, highlighting their relevance in the transition toward more sustainable and cleaner energy in the country, as shown in Figure 2.

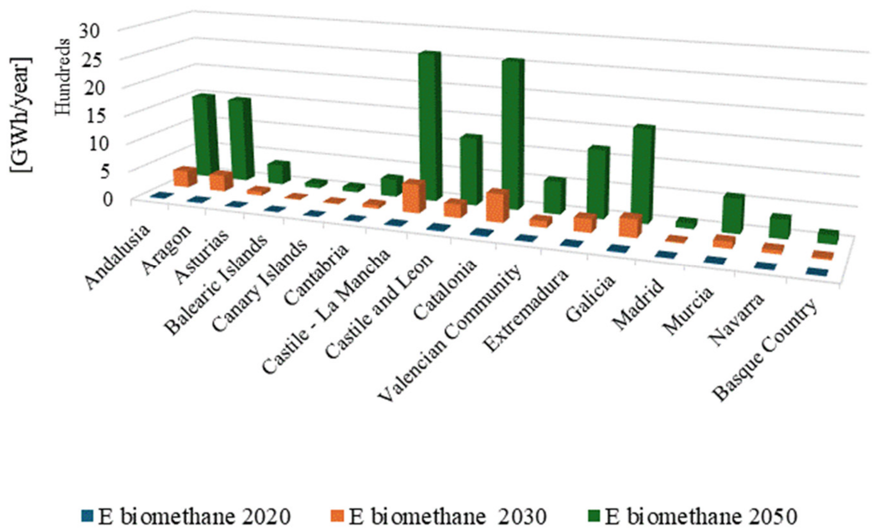


Figure 2. Potential for energy generation from livestock waste.

3.2. Generation from Agricultural Waste

To calculate the biogas generated from agricultural waste, a ratio (tons of straw/hectare) was used to estimate the amount of straw produced based on the arable area. Data on surface area, yield, and production of cereals, olive groves, and vineyards from 2017 to 2021 were used from the annual report of the Ministry of Agriculture, Fisheries, and Food [28]. The crops considered include various types of wheat, barley, rye, oats, corn, rice, sorghum, olive groves, and vineyards. For cereals, the ratio of straw per hectare was calculated and projected into the future. As per olive groves, 70% of the olives are used for olive marc, and 73% are waste, of which 30% was used in the project. In vineyards, marc is 20% of the grape's weight, grape stalks are 4%, and vinification lees are 1.5%. Materials with a high lignin content require pretreatment, resulting in a 10–15% lignin loss and 30% of the raw material [29–32]. Estimates of the straw/hectare ratio for 2030 and 2050 were made considering the Autonomous Communities.

Table 1 presents the total solids (TS) and volatile solids (VS) content of different crop residues, along with their methane production potential per ton of volatile solids (m^3 CH_4/t VS). The biogas composition is also detailed, showing the proportion of methane (CH_4), carbon dioxide (CO_2), and other gases. The data, obtained from previous studies and empirical assessments, highlight the variability in biogas yields depending on the type of crop residue used in the digestion. Among the analyzed residues, olive groves and sorghum exhibit the highest methane production potential, making them promising feedstocks for biomethane generation in Spain.

Table 1. Data for the calculation of AD from agricultural waste.

Crop	TS (%)	VS (%)	Concentration	Biogas Composition	Reference
Wheat	91.6%	87.5%	297 m^3 CH_4/t VS	70.2% CH_4 24.6% CO_2 5.2% other	[33,34]
Barley	90.5%	94.3% (/TS)	229 m^3 CH_4/t VS	54.9% CH_4 40.01% CO_2 5.09% other	[35]
Rye	-	95%	6.16 m^3 biogas/t VS	50.33% CH_4 44.77% CO_2 5% other	[36,37]
Oat	-	87%	242 m^3 CH_4/t VS	65% CH_4 30% CO_2 5% other	[38]
Corn	92.45%	85.24%	275 m^3 biogas/t VS	65% CH_4 30% CO_2 5% other	[34,37]
Rice	88.7%	91.9% (/TS)	195 m^3 CH_4/t VS	46.88% CH_4 48.12% CO_2 5% other	[39]
Sorghum	43%	93% (/TS)	338 m^3 CH_4/t VS	55% CH_4 40% CO_2 5% other	[40,41]
Olive groes	4.6%	97% (/TS)	686 m^3 CH_4/t VS	81.9% CH_4 14.1% CO_2 4% other	[41,42]
Vineyards	-	-	134 m^3 CH_4/t straw	61.7% CH_4 33.3% CO_2 5% other	[43]

Biogas production potential for different crop residues. The table presents total solids (TS) and volatile solids (VS) percentages for each crop, along with their methane or biogas production potential per ton of volatile solids (m^3 CH_4/t VS). The composition of the produced biogas is also detailed, including methane (CH_4), carbon dioxide (CO_2), and other gases. The data presented are based on various references, indicated in the last column.

Figure 3 illustrates the estimated energy generation potential from agricultural waste in Spain. The projection considers various crop residues and their respective methane production yields, as detailed in Table 1. The results highlight the significant contribution of wheat, barley, and olive groves to biogas generation, with regional variation based on agricultural activity and land availability. These findings emphasize the role of agricultural residues in enhancing biomethane production and supporting Spain's renewable energy transition.

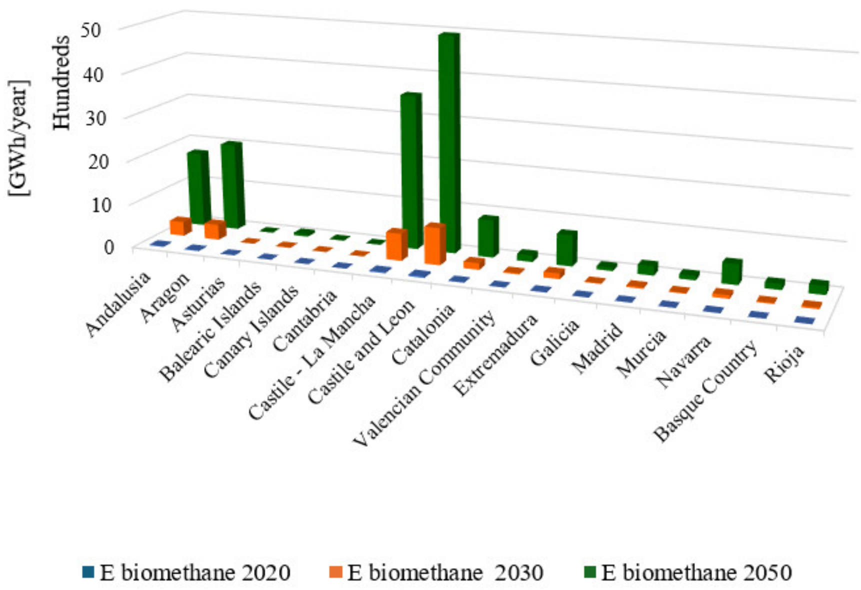


Figure 3. Potential for energy generation from agricultural waste.

3.3. Generation from WWTP Waste

Wastewater treatment plants (WWTPs) treat urban and industrial wastewater, generating biogas through anaerobic digestion. This biogas can be converted into biomethane, primarily composed of CH_4. To estimate the volume of biomethane, the population of each Autonomous Community and a specific equation were used. A 1:1 ratio between actual and equivalent inhabitants was assumed, although the equivalent inhabitants would be higher due to the presence of various industries which have a higher conversion ratio. Additionally, it was considered that between 60% and 80% of the available material was used in biogas generation. Based on projections for future population, it is concluded that Andalusia, Catalonia, and Madrid have the greatest potential for anaerobic digestion [44–48].

Figure 4 illustrates the estimated energy generation potential from WWTP sludge across different regions in Spain. The analysis considers the population size and wastewater treatment capacity of each Autonomous Community, as well as the biogas yield from sludge anaerobic digestion. The results indicate that regions with the largest urban populations, such as Andalusia, Catalonia, and Madrid, have the highest potential for biomethane production from WWTP sludge. These findings highlight the role of wastewater treatment facilities in contributing to Spain's renewable gas supply and emphasize the need for further infrastructure development to optimize biomethane recovery and grid injection.

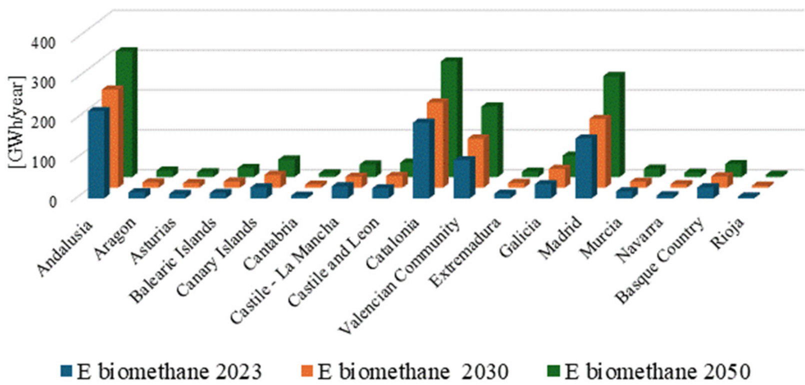


Figure 4. Potential for energy generation from WWTP.

3.4. Generation from OFMSW Waste

To evaluate organic waste in Spain between 2011 and 2021, the following categories obtained from the INE were considered: domestic and similar waste, animal and vegetable waste, and common sludge (the latter negligible after 2012). The organic fraction of urban waste in cities, like Barcelona, can generate 382 N m^3/kg of volatile solids (VS) of biomethane, with a 98% CH_4 content. It is recommended to differentiate between large cities and rural areas for greater accuracy. The total organic waste and the biomethane produced in each Autonomous Community were calculated by projecting data to 2030 and 2050. It was also assumed that 24.5% of WWTP sludge is correctly classified and that the utilization of organic waste for anaerobic digestion increases from 55% in 2021 to 80% in 2050. The 24.5% classification rate corresponds to national-level figures for OFMSW separation, based on municipal waste reports. It was selected as a conservative yet representative estimate of current sorting efficiency across Spain's urban areas. While regional variability exists, internal consistency checks confirmed that a ±5 percentage point deviation in this parameter would not significantly alter total national projections or change the regional distribution trends presented in this study. Biomethane values are estimated in GWh/year utilizing a calorific value of 9.945 kWh/N m^3 [11].

Figure 5 presents the estimated energy generation potential from the organic fraction of municipal solid waste (OFMSW) in Spain. The analysis considers waste generation patterns, organic matter content, and biogas yield from anaerobic digestion. The results indicate that highly urbanized regions, such as Madrid, Catalonia, and Andalusia, exhibit the greatest potential due to their high population density and waste production rates. The findings emphasize the importance of effective waste separation and collection systems to maximize biomethane recovery. Additionally, the increasing role of OFMSW in Spain's biomethane strategy highlights the need for improved waste treatment infrastructure and policy support to enhance its contribution to the renewable energy mix.

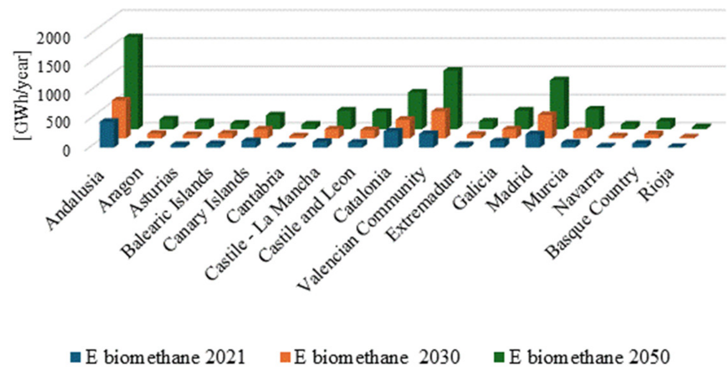
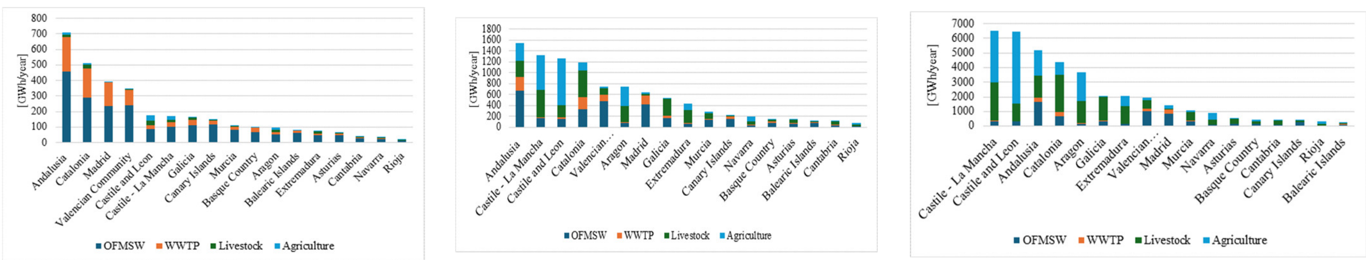


Figure 5. Potential for energy generation from OFMSW.

4. Discussion

The results presented in Figure 6 provide a comprehensive assessment of Spain's biomethane production potential for 2023, 2030, and 2050, highlighting the evolution of different waste streams and their contributions to the country's renewable energy transition. The findings indicate that, while municipal solid waste (MSW) and WWTP sludge are currently the primary sources of biomethane production (2023), a shift toward agricultural and livestock residues is expected by 2030 and 2050. This transition aligns with previous studies in Germany and France, where agricultural biogas has played a crucial role in expanding renewable gas production.

Germany's biomethane expansion has been driven by targeted subsidies and a well-developed injection infrastructure. A similar approach could be adapted in Spain to accelerate biomethane deployment.



(**a**) (**b**) (**c**)

Figure 6. Energy in the years (**a**) 2023, (**b**) 2030, and (**c**) 2050. Source: Own elaboration.

4.1. Analysis by Waste Type or Raw Material Source

The results indicate that OFMSW has been the primary source of biomethane production in Spain during the 2020–2023 period, contributing 2079.39 GWh/year. However, while absolute production is projected to increase to 3127 GWh/year in 2030 and 6632.7 GWh/year in 2050, its relative share of total biomethane production is expected to decline significantly, from 64.39% in 2023 to only 17.43% in 2050. This shift reflects a transition toward greater reliance on agricultural and livestock residues, as these waste streams gain importance in Spain's biomethane strategy.

Similarly, biomethane production from WWTPs is estimated to increase from 0.88 TWh/year in 2020–2023 to 1.35 TWh/year in 2050, yet its percentage contribution will drop from 27.24% to just 3.55%. This decline in relative share, despite the absolute increase in production, highlights the growing dominance of agricultural and livestock waste as a biomethane feedstock.

The agricultural and livestock sector is projected to experience the most significant growth in biomethane production. Starting with just 0.15 TWh/year from livestock waste and 0.12 TWh/year from crop residues in 2023, these values are estimated to rise to 2.88 TWh/year and 2.69 TWh/year, respectively, by 2030. By 2050, these contributions are projected to surge to 14.83 TWh/year for livestock waste and 15.21 TWh/year for crop residues, collectively accounting for 79.01% of Spain's total biomethane production.

4.2. Analysis by Region and Year

At the regional level, the findings reveal significant geographical variations in biomethane production potential. From 2020 to 2023, Andalusia will emerge as the leading region, followed by Catalonia and Madrid, largely due to their high levels of urban waste generation.

By 2030, Andalusia maintains its leadership, while Castilla-La Mancha and Castilla y León rise to second and third positions, respectively. This shift is attributed to the expansion of agricultural biomethane production, as these regions have vast agricultural land and livestock resources, making them key contributors to Spain's renewable gas sector.

By 2050, Castilla-La Mancha is projected to surpass Andalusia as the top biomethane-producing region, with Castilla y León trailing closely. Andalusia drops to third place, though it remains a major producer with a more diversified waste-to-biomethane strategy. Meanwhile, Catalonia ranks fourth, driven primarily by its strong livestock waste contribution.

The regional analysis shows that Andalusia, Castilla-La Mancha, and Castilla y León will become the leading contributors to Spain's biomethane sector due to their extensive agricultural and livestock activities. Meanwhile, Catalonia and Madrid maintain significant contributions, driven by high urban waste generation. These results emphasize the importance of regional waste management strategies, as the availability of raw materials varies significantly across Spain.

Compared to national targets, the study estimates that Spain could produce 9.71 TWh of biomethane by 2030, slightly below the 10.41 TWh goal outlined in the National Biogas Roadmap. Achieving this target will require policy support, financial incentives, and infrastructure expansion, particularly in biomethane injection facilities for integration into the national gas grid.

In a broader context, the shift toward agricultural and livestock residues reflects a global trend in biomethane production, where waste valorization and circular economy principles are increasingly prioritized. The findings support the need for investments in anaerobic digestion plants, as well as regulatory frameworks that incentivize biogas production and its use in transport, heating, and industry.

4.3. Environmental and Energy Impact

The shift toward agricultural and livestock biomethane production has significant implications for emissions reduction and energy sustainability. The estimated methane emission savings during the first period of study amount to 4,658,609.27 tons of CH_4 [48]. Additionally, the availability of digestate from animal and vegetable sources, a key by-product of anaerobic digestion, was 1,036,380.8 tons in 2020 [49], highlighting the potential for nutrient recovery and circular economy integration.

From an energy perspective, biomethane could play a critical role in covering Spain's thermal demand, assuming a 90% efficiency rate. However, to fully realize this potential, investments in infrastructure, regulatory incentives, and integration into the national gas grid will be essential.

Table 2 presents the estimated contribution of biomethane to thermal energy demand in different regions of Spain, assuming a 90% efficiency rate. The table details the total percentage of thermal demand covered, as well as specific contributions to the residential, tertiary (commercial and services), and industrial sectors. The results highlight regional variations, with the Canary Islands, the Balearic Islands, and Andalusia showing the highest contributions, reflecting differences in biomethane production potential and energy demand across sectors.

Table 2. Percentage of thermal demand covered for the year 2023. Source: Own elaboration.

	Total (%)	Residential (%)	Thirds (%)	Industry (%)
Andalucía	1.95	9.08	15.96	2.95
Aragón	0.81	2.88	4.56	1.50
Asturias	0.43	4.60	4.27	0.53
Islas Baleares	2.93	7.38	7.06	15.69
Canarias	12.24	-	-	12.24
Cantabria	0.88	17.35	8.68	1.03
Castilla-La Mancha	0.89	2.27	7.01	1.87
Castilla y León	0.72	1.81	3.68	1.79
Cataluña	1.17	4.80	7.10	1.97
Comunidad Valenciana	1.75	9.37	10.72	2.69
Extremadura	1.38	3.51	8.33	3.13
Galicia	0.74	4.34	4.85	1.09
C. de Madrid	1.47	3.58	3.98	6.71
R. de Murcia	2.18	9.00	12.82	3.72
C. F. de Navarra	0.44	2.14	4.62	0.63
País Vasco	0.59	3.92	3.65	0.87
La Rioja	0.11	0.73	0.68	0.16

5. Conclusions

This study provides a comprehensive assessment of Spain's biomethane production potential, highlighting the evolution of key waste streams and their role in achieving renewable energy targets for 2030 and 2050. The findings reveal that agricultural and livestock residues will become the dominant sources of biomethane, increasing from 0.27 TWh in 2023 to 30.04 TWh in 2050, accounting for nearly 80% of total production. Meanwhile, the contribution of municipal solid waste (MSW) and wastewater treatment plant (WWTP) sludge will decline in relative terms, despite their absolute growth.

These results offer valuable guidance for policymakers in developing targeted incentives and infrastructure strategies to accelerate biomethane deployment within Spain's energy transition.

At the regional level, Castilla-La Mancha, Castilla y León, and Andalusia emerge as the key contributors by 2050, benefiting from extensive agricultural and livestock resources. Catalonia and Madrid will also remain important, largely driven by their urban waste streams and existing biogas infrastructure. The study estimates that Spain's biomethane production could reach 9.71 TWh by 2030, slightly below the 10.41 TWh target set in the National Biogas Roadmap, emphasizing the need for investment and policy support to bridge this gap.

From a broader perspective, the transition toward biomethane as a renewable energy source aligns with European sustainability goals and a circular economy model, offering multiple environmental and economic benefits. Biomethane reduces greenhouse gas emissions, enhances organic waste valorization, and strengthens energy independence by substituting fossil fuels with renewable alternatives. However, unlocking its full potential requires the following:

- Infrastructure expansion, particularly for biomethane injection into the national gas grid.
- Regulatory and financial incentives to promote investment in anaerobic digestion plants.
- Advancements in waste management to optimize substrate availability and efficiency.
- Research and technological innovation to enhance biomethane production and integration with other renewable energy vectors, such as hydrogen production and carbon capture technologies.

With the right policy framework and strategic investments, biomethane has the potential to become a key pillar of Spain's decarbonization strategy, contributing to a more sustainable and resilient energy system. Future research should focus on techno-economic feasibility, process optimization, and policy impact assessments to ensure the long-term viability of biomethane as a cornerstone of Spain's renewable energy transition.

Realizing the biomethane potential identified in this study will require targeted policy support, grid infrastructure upgrades, and coordinated action from regional authorities, waste management agencies, and agricultural stakeholders. Feed-in incentives, streamlined permitting, and guarantees of origin could play a crucial role in accelerating biomethane deployment. Further investment in research, including pilot-scale projects and process optimization, will be key to unlocking this opportunity for Spain's sustainable energy future.

Author Contributions: A.L.-A.: conceptualization, methodology, software, investigation, writing—original draft preparation; C.M.-P.: conceptualization, methodology, formal analysis, investigation, writing—review and editing, visualization, supervision; J.V.-R.: conceptualization, methodology, investigation, supervision, validation; M.d.M.C.-C.: conceptualization, methodology, formal analysis, investigation, writing—review and editing, visualization, supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AD	Anaerobic Digestion
CH_4	Methane
CO_2	Carbon Dioxide
INE	National Institute of Statistics (from Spanish: Instituto Nacional de Estadística)
LER	European Waste List (from Spanish: Lista Europea de Residuos)
MSW	Municipal Solid Waste
OFMSW	Organic Fraction of Municipal Solid Waste
SHARES	Statistical tool for renewable energy data (European Commission)
TS	Total Solids
VS	Volatile Solids
WWTP	Wastewater Treatment Plant

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