Sustainable Energy & Fuels

ROYAL SOCIETY OF CHEMISTRY

PERSPECTIVE

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Sustainable Energy Fuels*, 2023, 7, 3584

Current state of biogas and biomethane production and its implications for Spain

M. Calero,*[a] V. Godoy,[a] C. García Heras,[b] E. Lozano,[a] S. Arjandas[c] and M. A. Martín-Lara *[a]

Received 29th March 2023
Accepted 3rd June 2023

DOI: 10.1039/d3se00419h

rsc.li/sustainable-energy

In recent years, Europe has tightened legislation to combat climate change. The new targets proposed by the different legal instruments include the European Green Deal, Directives RED I and RED II on renewable energies, 'Clean Energy for all Europeans' package, and the recently approved RepowerEU Plan, where the reduction in greenhouse gas emissions by 2030 and the promotion of renewable gases to be less energy-dependant are the focus of all the measures proposed. The adoption of these legal measures in Spain lags behind other countries and some financial aspects are underdeveloped. However, it is worth highlighting the measures that have been approved promote the development of projects in favour of biomethane and other renewable gases and measures to reduce the emission of greenhouse gases. This study reviews the available information published in literature and discuss the current situation of biogas and biomethane production in Spain. Biomethane is a clean fuel alternative, which allows value addition to waste from numerous sources, such as landfills, agriculture, and sewage sludge. Spain has potential to produce biomass up to 163 TW h per year with important variations between regions. However, currently, it only has 146 biogas plants in operation (2.74 TW h per year) and 6 are producing biomethane, although a great number of projects are underway for the construction of new biomethane plants. The ability to address the obstacles that presently prevent the building of additional facilities will determine how well biomethane development proceeds in our nation.

1. Introduction

It is an undeniable fact that concern about climate change has been increasing in recent years with substantial shifts evidencing this change.[1] In this case, the more developed continents and countries, such as Europe and its member states, consider that it is essential to move towards climate neutrality and the decarbonisation of the economy. To achieve these objectives, biogas and biomethane are presented as technically and economically viable alternatives for the decarbonisation of energy and gas sources.[2] This is because they are generated from waste and are intended for diverse uses (heating, production of renewable electricity, injection into the existing gas network to replace natural gas, *etc.*) in all types of sectors (transport, industry, building, power generation, *etc.*). The major finding is that there are many alternatives for using biogas and biomethane on the road to net zero. They offer adaptable and sustainable systems that are crucial to the circular economy, energy sector, and environmental systems.[3]

[a]Department of Chemical Engineering, Faculty of Sciences, University of Granada, Granada, Spain. E-mail: mcaleroh@ugr.es; vgcalero@ugr.es; emiliolp@ugr.es; marianml@ugr.es
[b]GASNAM, Madrid, Spain. E-mail: c.garcia@gasnam.es
[c]FCC Medio Ambiente, Alhendín, Granada, Spain. E-mail: sunil.arjandas@fcc.es

Biogas can be generated in natural environments or specialised equipment *via* the biodegradation of organic matter by the activity of microorganisms (methanogenic bacteria, *etc.*). The resulting product is a mixture of methane (CH_4) in a proportion ranging from 40–60% and carbon dioxide (CO_2), containing small proportions of other gases, such as hydrogen (H_2), nitrogen (N_2), oxygen (O_2), and hydrogen sulphide (H_2S).[4] The composition of biogas varies significantly depending on the feedstock from which it is generated and the technique employed for upgrading it.[5] In addition, its potential for the generation of electricity and heat varies depending on the amount of waste digested, although high potentials between 300 000–400 000 MW h per year can be obtained with an average input of 1000–2000 tons per day in a digester.[6]

When biogas is properly purified, its methane percentage increases to concentrations of more than 90% in most cases, resulting in the gas known as biomethane. This renewable gas can be used as an alternative fuel for vehicles, replacing other more polluting fuels such as diesel and petrol, and it can also be injected into the natural gas network to supply energy to industries and households.[7] The transformation of biogas to biomethane involves the removal of CO_2 and other trace elements present in it to increase the proportion of methane and obtain a fuel with a higher energy value.[8] Presently, abundant techniques are available to purify biogas and most of them have been widely tested and implemented. However, it is necessary to find a balance among investment costs, operating costs (especially energy consumption) and process efficiency to avoid methane losses as much as possible.[9] In addition, CO_2 can be converted to biomethane to increase the efficiency of the process and the production of biomethane. Some of the most investigated methods include photocatalytic conversion techniques.[10,11] However, it is necessary to develop catalytic systems with high selectivity and efficiency. Other methods include biological removal and the bioconversion of CO_2.[12,13] However, although these methods are promising, there are still several technical and economic barriers that need to be addressed before their widespread application.[13]

Presently, despite the significant economic and environmental advantages of using biogas and biomethane in the energy landscape, these renewable gases still must overcome some challenges and difficulties, which prevent their full development. These challenges include insufficient fiscal incentives, given that a large part of the support schemes for renewables focuses on green electricity, neglecting green gas. Also, the lack of cross-border trade of similar characteristics and the lack of cooperation between member states hamper the internal market for green energy, together with the lack of specific targets for biomethane development in the policies of many member states.[14]

In this case, the developments that are taking place in European legislation and how they are being implemented in the different member states, particularly in Spain are critical. Legislation tools such as the European Green Pact, the 'Fit for 55' package and European RED II (Renewable Energy Directive) pretend to transform the European Union into a modern and decarbonized economy,[15] and also set out a series of policy goals and targets for the whole of Europe for the period 2021–2030. However, new geopolitical and energy market realities are forcing Europe to dramatically accelerate the transition to clean energy and to strengthen its energy independence from unreliable suppliers and volatile fossil fuels. Consequently, the European Commission has launched the REPowerEU plan, which aims to make Europe independent of Russian fossil fuels before 2030, considering Russia's invasion of Ukraine.[16] However, there are already discrepancies in the implementation of all these measures among the different member states, probably because there is a lack of consensus and a clear roadmap that can be adapted in the case of each country.

Spain has great potential to produce biogas and biomethane, mainly from biomass resources (livestock, food waste and agricultural waste).[17] However, the regulations are very relaxed to encourage electricity generation projects due to the significant decrease in the feed-in tariff systems and the abolishment of financial support mechanisms, which resulted in a significant slowdown in the development of renewables after 2015.[18] In addition, although Spain currently has a gas infrastructure of more than 100 000 kilometers of distribution network already prepared for the circulation of biomethane, only 6 facilities currently produce biomethane and inject it into the network, and thus greater effort is needed for implementation installations in the coming years.

Based on the current energy landscape, herein, the aim is to present an exhaustive review of the current state of the production and market of renewable gases, their evolution in recent years and the prospects for this sector in Spain.

2. Legal framework in Spain

2.1. Context in the European Union

The aim of climate neutrality is to achieve a carbon neutral balance, *i.e.*, CO_2 emissions (in tonnes equivalent) equal to the absorption capacity of available natural resources. Since the creation of the EU Treaty in 1992, environmental awareness has spread to all areas of European policy, but it was not until the Lisbon Treaty in 2009 that the concept of climate change was introduced and real concern about global warming began to emerge.

In the Paris Agreement concluded in 2015, all participating states agreed not to produce an increase of more than 2 °C on the Earth's surface and not more than 1.5 °C for industrial emissions. To achieve this, existing emission reduction targets had to be strengthened. The first GHG emission reduction targets were set in the framework of Horizon 20:20:20, which meant reducing GHG emissions by 20% and using 20% of energy from renewable sources, among other measures. Subsequently, in 2015, the Circular Economy Package was published, which included the objective of reducing GHG emissions by 40% by 2020.

However, within the recently published European Green Pact, in September 2020 the Commission proposed to raise the target for reducing greenhouse gas emissions by 2030, including emissions and removals, to at least 55% compared to 1990. The European Green Pact sets out an action plan to boost resource efficiency by moving to a clean and circular economy, and to restore biodiversity and reduce pollution. In this case, a package of draft legislation has recently been published called Fit for 55's.[16]

Other European legislative tools aimed at decarbonising the economy include the Directive 2018/2001 on the promotion of the use of energy from renewable sources (Directive RED II), in which the overall EU target for Renewable Energy Sources consumption by 2030 has been raised to 32%. This has supposed a 12% increase in the set target with regards to the latter version of the legislation, the Directive 2009/28/CE. In the new Directive RED II, a specific target for transport was also included, which set the objective of a minimum of 14% of the energy consumed in road and rail transport from renewable sources by 2030.

Up to 2020, Directive 2009/28/CE confirmed the existing national renewable energy targets for each country, considering the starting point and the overall renewable energy potential (from a renewable energy share of 10% in Malta to 49% in Sweden). Each EU country set out how it intends to meet the individual targets and the overall roadmap for its renewable energy policy in a national renewable energy action plan. Progress towards national targets is measured every two years, when EU countries publish their national renewable energy progress reports.

The latest 2018 progress report showed positive average results for the EU in moving closer to targets for the use of renewable energy sources. However, noticeable differences among individual member states were highlighted. For example, northern and eastern European countries managed to reach and even surpass their share of renewable energy (notably Sweden and Finland), while southern countries (including Spain) had lowered their share from 2017 to 2018. Specifically, it was estimated that the expected share of renewable energy by 2020 would be reached in most member states except for a small group that would not achieve it, including Spain.[19]

The RED II Directive was published in 2018 as part of the "Clean Energy for All Europeans" package, which aimed to maintain the EU's global leadership in renewable energy.

This package included a robust governance system for the energy union, in which each EU country is required to establish integrated 10 year national energy and climate plans (NECPs) for 2021–30. These plans must be based on the legislations included in the package, which is comprised of four Directives and four Regulations, as follows:

- Energy Performance in Buildings Directive (EU) 2018/844.
- Renewable Energy Directive (EU) 2018/2001.
- Energy Efficiency Directive (EU) 2018/2002.
- Governance of the Energy Union Regulation (EU) 2018/1999.
- Electricity Regulation (EU) 2019/943.
- Electricity Directive (EU) 2019/944.
- Risk Preparedness Regulation (EU) 2019/941.
- Agency for the Cooperation of Energy Regulators (ACER) Regulation (EU) 2019/942.

Alternatively, the European Methane Strategy sets out measures to reduce methane emissions at the European and international levels through legislative and non-legislative measures in the energy, agriculture, and waste sectors, which account for about 95% of global methane emissions associated with human activity. Specifically, in Europe, this share is divided into 53% for agriculture, 26% for the waste sector and 19% for the energy sector.[20]

One of the priorities of this strategy is to improve the measurement and reporting of methane emissions, given that the level of monitoring currently differs between sectors and member states, as well as within the international community. Accordingly, the International Methane Emissions Observatory (IMEO) was established at the end of 2021. In less than two years, the membership of IMEO's flagship oil and gas reporting and mitigation programme, the Oil and Gas Methane Partnership 2.0 (OGMP 2.0), expanded to more than 80 companies from around the world. In the second report published at the end of 2022,[21] sixty members are on the programme's "Gold Standard" pathway, having committed in their implementation plans to sequentially improve the quality of their reported data, and are showing progress in moving towards measurement-based estimates of methane emissions. Twelve member companies are not on the Gold Standard pathway this year, where two lost it compared to last year, seven did not achieve it either year, and three companies reporting for the first time this year did not achieve it. Furthermore, among the main conclusions reached by the report based on the results provided by the countries is the fact that the greatest potential to achieve rapid methane emissions reductions is in the fossil fuel sector. Emissions from oil, gas, and coal operations are easier and less expensive to control and this sector can reduce methane emissions by 75% by 2030. In the case of Spain, 3 large companies are part of the OGMP 2.0 group and have set methane emission reduction targets, *i.e.*, Bahía de Bizkaia Gas, Enagás and Nedgia.

In response to the difficulties and disruptions in the global energy market caused by the Russian invasion of Ukraine, the European Commission recently presented the RepowerEU Plan, which focuses on energy savings, clean energy production and diversification of energy supplies. This package of measures aims to make Europe independent of Russian fossil fuels by 2030, favoring the ecological transition and boosting the use of alternative sources of gas, oil, and coal in the short term. Specifically, it includes measures aimed at increasing biomethane production to save 17 billion m^3 of imported gas, as well as increasing renewable energy targets from the current 40% to 45% and allocating more than €3 billion to projects linked to industrial decarbonization projects under the Innovation Fund.

A brief mention should be made of Regulation 2020/1294, which is aimed at controlling the financing of renewable energies. The main objective is to help countries achieve their individual and collective renewable energy targets. The financing mechanism links countries that contribute to the funding of projects (contributor countries) with countries that agree to build new projects on their territories (host countries). The Commission provides an implementation framework and means to finance the mechanism, and establishes that Member States, Union funds or private sector contributions can finance actions under the mechanism. It is also important to highlight the recent review of the Trans-European Energy Network (TEN-E), which reflects the changes in the gas landscape, with a greater role for renewable and low-carbon gases and the creation of a new category of infrastructure for smart gas networks. This will support investments at distribution or transmission level to integrate green gases into the grid and help to manage the resulting more complex system based on innovative technologies. Candidate projects will consist of a variety of investments aimed at "making smart" and decarbonising a given gas network.[19]

2.2. Spanish legal instruments

Following the lines proposed by the European Union, within the Spanish legislative measures, the National Integrated Energy and Climate Plan 2021–2030 (PNIEC)[22] reflects Spain's commitment to the international and European effort to overcome the current climate crisis and move towards a low-carbon economy. This tool was developed in response to the Governance of the Energy Union Regulation (EU) 2018/1999 and the Paris Agreement in 2015.

Specifically, within the PNIEC measures related to biogas and biomethane is measure 1.8, which aims at the promotion of renewable gases through the approval of specific plans for the development of renewable gas integration, including biogas, biomethane and renewable hydrogen, mentions the role of biomethane in transport and in the promotion of advanced biofuels, in line with the provisions of the European RED II Directive.

In addition, measures 1.21 and 1.22 of PNIEC 2021–2030, on the reduction of greenhouse gas emissions in the agricultural and livestock sectors and on the reduction of emissions in waste management, respectively, include a series of actions that complement the proper management of methane-generating waste and the energy recovery of the biogas obtained. In general, Spain is among the ten EU countries whose PNIECs meet the targets set for 2030, including an upward estimation of the decarbonization target and the use of renewable energies. However, there are still some shortcomings to be covered that are not explained in the PNIEC, such as the financing mechanisms to be used to achieve the targets or the technical difficulties in transposing these measures into reality.[23]

Spanish Law 7/2021 of 20 May on climate change and energy transition, for its part, establishes that municipalities with more than 50 000 inhabitants must adopt sustainable urban mobility plans by 2023 that introduce specific measures to electrify the public transport network and use other fuels without GHG emissions, such as biomethane. This law is closely related to the Biogas Roadmap, published in March 2022 by the Ministry for Ecological Transition and the Demographic Challenge published in the Biogas Roadmap (2022).[24] This legal tool establishes that priority should be given to the direct use of biogas in locations close to its production, favouring the emergence of synergies with related industries, as well as its use in transport, when this is the most economically and environmentally efficient option.

Recently, Royal Decree 376/2022 has also been published, which regulates the criteria for sustainability and reduction of greenhouse gas emissions from biofuels, bioliquids and biomass fuels, as well as the system of guarantees of origin of renewable gases. It is a legal tool that partially transposes Directive 2018/2001 of the European Parliament. Thanks to the creation of guarantees of origin for renewable gases, each MW h of 100% renewable gas produced will give rise to the issuance of a guarantee of origin with information on where, when, and how the gas was produced, giving it added value when it is marketed. The volume of gas and its quality will be certified and will cover any renewable gas produced and consumed. In addition, a Census of Gas Production Facilities from renewable sources will be created, as well as a Producers' Committee, which will be able to exchange guarantees of origin with marketers in a transparent manner within the system.

This Royal Decree also establishes targets for the penetration of biofuels and biogas for transport purposes, specifically 10.5% in energy content by 2023 and 12% by 2026.

However, although the legislative measures in Spain comply well with European targets and progress is being made, there is criticism of the lack of ambition and confidence in the biogas sector, which has the technological potential and resources to meet higher targets than that proposed. Furthermore, it is felt that there is a lack of impulse in economic incentive plans for concrete actions in this sector.

3. Production and uses of biogas and biomethane

Biogas is obtained in digesters through the process of anaerobic digestion, which is a biochemical process whereby several complex organic compounds from several types of wastes (sludges, manures, agro-industrial wastes, *etc.*) are broken down to simpler ones by the action of bacteria in the absence of oxygen (anaerobic conditions). The result of this process is the production of biogas, solid digestate and an organic liquor, which can be used as fertilizer.[25]

The composition of biogas varies depending on the feedstock used for its generation, as can be seen in Table 1, but it generally consists of methane (CH_4) in the range of 50% to 70% and carbon dioxide (CO_2) in the range of 30% to 50%. In addition, it also contains minor amounts of nitrogen (N_2) in concentrations of 0 to 3%, which can come from the saturated air in the influent, water vapour (H_2O) in concentrations of 5% to 10%, or more at thermophilic temperatures, derived from average evaporation, oxygen (O_2) in concentrations of 0 to 1%, originating from the influent substrate or leaks, hydrogen sulphide (H_2S) in concentrations of 0 to 10.000 ppm, which is produced from the reduction of sulphate contained in some waste streams, ammonia (NH_3) from the hydrolysis of protein materials or urine, hydrocarbons at concentrations of 0 to 200 mg m^{-3} and siloxanes at concentrations of 0 to 41 mg m^{-3}, *e.g.*, from the effluents of the medical and cosmetic industries.[26]

Biogas is a very versatile energy source, and its different applications include heat production, combined heat, and power generation, as well as its injection into natural gas infrastructures or its use as a fuel in vehicles once purified to biomethane.[27,28] In addition, among the various advantages of biogas compared to other renewable sources, it can be stored and transformed into energy on demand, providing an alternative to intermittent generation and climatic influences.[29,30]

Thermal energy is one of the most frequent uses of biogas, being used for heating generation by feeding it into adapted boilers and transferring the heat released to water.[31] This heat is mainly used for heating in urban areas or in agricultural and livestock processes, where the biomass from which the biogas is obtained is generated and used on site (heating of installations and digesters, aquaculture, greenhouses, and industrial applications) and in agricultural drying systems.[30]

Combined heat and power (CHP) systems are another popular application given that they improve the efficiency of the biogas energy conversion process compared to separate CHP generation.[27] Depending on the installation, the thermal energy can cover the plant's own demands by means of a thermal accumulator or be used for heating and external industrial systems in the surrounding area. In the case of electrical energy, this is also self-consumed in the plant or connected directly to the general grid and sold independently on the markets.[32,33] According to Herbes *et al.*,[30] the numbers are variable regarding the proportion of self-consumption of this excess heat, ranging from 8.5% of the heat produced to 57.2% depending on the technology used.

Table 1 Biogas composition according to the raw material used for its generation.[5]

Components	Household waste	Sludge	Agricultural residues	Agri-food industry waste
CH_4, %volume	50–60	60–75	60–75	68
CO_2, %volume	38–34	33–19	33–19	26
N_2, %volume	5–0	1–0	1–0	—
O_2, %volume	1–0	<0.4	<0.5	—
H_2O, %volume	6 (a 40 °C)	6 (a 40 °C)	6 (a 40 °C)	6 (a 40 °C)
Total, %volume	100	100	100	100
H_2S, mg m^{-3}	100–900	1.000–4.000	3.000–10.000	400
NH_3, mg m^{-3}	—	—	50–100	—
Aromatics, mg m^{-3}	0–200	—	—	—

According to the EurObserv'ER barometer,[34] electricity production from biogas remains stable among European countries as a rule. In 2019, there was a significant drop in energy production in Germany, which was largely offset by the increase in energy production in France. The overall energy balance estimated a production of 2561.9 ktoe (kilotonnes of oil equivalent) in 2019, 2.9% higher than in 2018. However, the use of biogas alone to produce energy is being displaced by those installations that combine CHP engines with biomethane purification units.[2] An increasing number of countries are shifting from subsidising biogas to biomethane, and it is easier for the latter installations to become independent from state financial mechanisms, given that end-use applications and market opportunities are wider.[35] According to Lauven *et al.*,[36] the growth of the biogas sector has been slowed down by the growth of other more competitive energies, such as solar photovoltaics, and today, the concept of flexible biogas energy production is not as economically viable as it used to be. Therefore, a good strategy that is gaining increasing momentum is to incorporate biogas-to-biomethane purification units, giving an end use to this biomethane, and combining it with cogeneration engines for energy production. The main advantage that biomethane offers over biogas is that it has enormous flexibility given that it is a gas comparable to natural gas, which allows it to reach more sectors and gives it the power to decarbonize sectors that are difficult to electrify, such as heat-intensive industrial processes, heavy and maritime mobility, and network injection.

Biomethane has similar qualities to natural gas, and thus it can be injected into existing natural gas infrastructure or used as a biofuel for transport.[27–29,37] Biomethane for vehicle use can be compressed at high pressures (Bio-CNG) or liquefied (Bio-LNG) to be transported and stored in a liquid state at low temperature (about −160 °C). The latter has significantly greater autonomy, and therefore can be used, for example, in heavy and marine transport.

One of the newest applications in the field of biogas and biomethane is the production of hydrogen and its use in fuel cells to generate clean energy. Technically, hydrogen (H_2) can be released from the BSR (biogas vapour reforming) and SMR (methane vapour reforming) processes.[38] The main difference between BSR and SMR is the presence of carbon dioxide in the raw material. Thus, in addition to the many applications in the chemical industry, hydrogen, combined with oxygen from the air, can be used in fuel cells, which are innovative systems to produce electricity and heat with high efficiency and low emissions.[37]

Biomethane is also one of the cleanest fuels when considering the carbon footprint of vehicles, given that its use reduces GHG emissions, especially CO_2, which will be emitted if natural gas were used. This is due to the feedstock used in the production of biomethane, *i.e.*, biomass instead of fossil fuels. Moreover, the use of biomethane also reduces methane emissions, which would have been emitted in the natural decomposition of raw materials.[39,40] According to Popp *et al.*,[41] about 96% of the global transport energy demand is provided by petroleum products, and thus increasing the use of renewable energies, such as biomethane is necessary to achieve decarbonisation of the transport sector.

The biogas purification process for biomethane production consists of the enrichment of the gas in CH_4 (95–97% purity) by removing unwanted compounds from biogas such as CO_2, which improves the calorific value and density of the gas, and NH_3, H_2S, H_2SO_4, NO_x and SO_2 due to their high corrosive power and environmental pollution problems.[42] In addition, it is necessary to remove moisture, not only because of the corrosion that is accelerated in the presence of H_2S and CO_2, but also because, similar to CO_2, it decreases the calorific value of the gas.[43] There are different biogas purification techniques, which can be differentiated into physical, chemical, and biological methods.[42]

The main differences between purification techniques lie in their cost due to the use of different types of materials and reactants and energy consumption.[26] In this case, the technique chosen to purify biogas must strike a balance between energy consumption and the efficiency of the final biomethane to obtain an economically profitable and environmentally friendly product. To obtain up-to-date information on consumables, investment costs and their relation to process performance, Bauer *et al.*[44] conducted a study in which they interviewed suppliers of various biogas-to-biomethane purification systems for biogas plants. Furthermore, Sun *et al.*[45] compiled calculations on the cost of investment (CAPX) and the cost of operation and maintenance (O&M) of these purification systems. According to the authors, the investment costs (CAPX) are inversely proportional to the size of the plant, *i.e.*, for most scrubbing techniques, the larger the production capacity of the plant, the lower the investment costs. Furthermore, no significant differences in CAPXs between techniques stand out. Alternatively, the operation and maintenance (O&M) costs come mainly from energy, water, and chemical consumption. In general, amine scrubbing, and cryogenic separation have the highest O&M due to the lower overall plant performance, and in the case of amines, due to the degradation and loss of the chemicals used, which leads to higher chemical consumption.

During biogas upgrading, CO_2 is separated from the biogas. Usually, CO_2 is released into the atmosphere without contributing to the net amount of climatic gases due to its biological origin. However, in modern facilities that produce biomethane, a section of CO_2 capture and further utilization or storage is included, contributing to reducing the overall greenhouse gas emissions of the biomethane production process.[46] CO_2 can be used in cooling systems, fire extinguishers, in the production of more methane by using hydrogen to react with CO_2, in the food industry, and in greenhouses, among others.[47–49]

4. Biogas and biomethane production in Spain

4.1. Context in the world and European Union

The development of biogas has been uneven around the world, given that it depends not only on the availability of raw materials, but also on policies that encourage its production and use. In 2019, according to data from the International Renewable Energy Agency,[50] electricity production from biogas worldwide was 91.8 TW h, or 1.3% of the total among renewable energy generation technologies. In 2018, Europe contributed 70% of the global electricity production from biogas, accounting for 61.8 TW h, followed by North America, which generated 14.5 TW h (where the US share was over 90% across North America). Asia produced 6.7 TW h (of which 3.2 TW h was produced in China), followed by Europe with 2 TW h, South America with 1 TW h, and Africa's biogas production accounted for 102 GW h. Thus, Europe, China, and the USA account for almost 90% of the global production.[50,51]

The installed capacity or maximum net generating capacity of power plants in the world that use biogas to produce electricity reached 20.1 GW in 2020 (0.7% of all renewable energy technologies) up from 9.5 GW in 2010, with Germany, the USA and the UK having the largest installed capacity.[50] Deployment in the US and certain European nations has slowed recently, mostly because of the changes in the legislative environment, but growth has emerged in other regions, including China and Turkey. There is significant untapped potential that will increase biogas production in the Asia-Pacific and Latin American regions.[40]

According to WBA,[51] the biogas industry can be analysed in three categories, as follows:

- Small-scale plants and domestic or farm-based microdigesters, which provide energy for cooking, heating, and lighting.
- Medium to large-scale plants that condition biogas to biomethane.
- Large-scale plants that generate electricity.

In 2019, there were already 50 million microdigesters in the world (42 million in China, 4.9 million in India and the rest mainly in Asia and Africa), 132 000 small, medium, and large-scale digesters and almost 700 upgrading plants. Although the exact numbers are unknown, it is known that by 2021, the number of biogas and biomethane plants continued to increase and reached close to 1000 biogas upgrading plants worldwide.[51,52]

Among the 37 member countries of the IEA Bioenergy Task, China has the largest number of biogas plants with more than 100 000 biogas plants, as well as many domestic biogas units. Germany has more than 10 000 plants and the other member countries have no more than 700 biogas plants. Considering the feedstock used in biogas generation, bio-waste and sewage sludge are the most used, followed by organic matter decomposing in landfills.[53]

Regarding the number of biogas-to-biomethane upgrading plants, IEA has a database compiling biogas upgrading plants in various countries, which was updated to 2019 (Fig. 1). For member countries, it is also possible to consult the type of conditioning technology each plant uses and the evolution of the number of plants per country/year/technology used.

Regarding biogas production, in 2018 it was around 35 million tonnes of oil equivalent (Mtoe), equivalent to 407 TW h.[51] Most biogas comes from agricultural crop residues and animal manure, followed by bio-waste, which is widely used in North America in such plants.[51] Sewage sludge is used to a lesser extent in Europe and North America. According to WBA,[51] half of the world's biogas is produced in Europe, followed by China (20.64%) and North America (10.32%).

Thus, the biogas sector experienced an average annual growth of 9% between 2000–2018, as shown in Table 2.

With production at only 6% of the estimated global feedstock potential, these resources are under-exploited, and thus there is huge potential for biogas and biomethane production.[54] Thus, global feedstock resources are currently sufficient to produce around 8472.22 TW h of biomethane, which is equivalent to more than 33% of the global natural gas demand. The availability of sustainable feedstocks for these purposes is

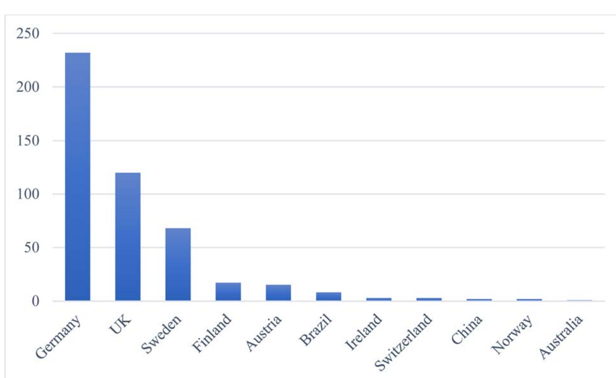

Fig. 1 Number of biogas upgrading plants per IEA Bioenergy member country.[53]

Table 2 Evolution of global biogas production, expressed in Nm^3 and TW h.[51]

Year	Biogas (TW h)	Biogas (M Nm^3)
2000	121.40	12 400
2005	214.93	22 000
2010	362.45	37 100
2015	547.09	56 000
2016	552.95	56 600
2017	563.70	57 700
2018	579.33	59 300

expected to grow by 40% by 2040.[40] In addition, this can lead to a 10% reduction in global GHG emissions per year by 2030.[51] These estimates are also based on a reasonable rate of separate collection of fractions such as bio-waste and a decrease in food waste.

In 2018, almost two thirds of biogas production was used to generate electricity and heat, which was around 18 GW of the installed biogas-fired power generation capacity worldwide, and half of it was in Germany and the USA. About 30% of the global biogas production is consumed in buildings, mainly in the residential sector, while about 8% of the production is upgraded to biomethane. About 60% of the plants are currently online and under development is the injection of biomethane into the gas distribution (grid), with an additional 20% providing fuel for vehicles. The remainder provides methane for a variety of local end uses.[54]

In Sweden, more than half of the biogas produced is upgraded to biomethane and used as vehicle fuel. Germany ranks second in the use of biogas as a transport fuel. Many other countries, such as the USA, France, Netherlands, Denmark, and South Korea, have emerging markets for biomethane as a transport fuel.[53] According to CEDIGAZ,[52] the overall biomethane use in the transport sector reached 1.5 bcm in 2019, which is 40% more than in 2018.

The global production of biomethane (also called renewable natural gas) reached 3.6 Mtoe in 2019, doubling that in 2015. This gas represents around 0.1% of the current demand for natural gas. However, an increasing number of government policies support its injection into natural gas networks and its application in the power sector, given that its use means a reduction in greenhouse gas emissions and dependence on fossil fuels. The market is still dominated by Europe (2.16 Mtoe), but US production is growing at an annual rate of 35%, and in fact, it has become the world's largest single producer (0.99 Mtoe), ahead of Germany.[52] This growth trend is spreading from the pioneer markets of Europe and North America to more countries such as Brazil, China, and India.

The amount of generated biogas that is conditioned differs greatly by regions, where in North America, it is around 15%, whereas in South America, it is over 35%. Around 10% of biogas output is conditioned in Europe, the area that generates the most biogas and biomethane (although the percentages are substantially higher in nations such as Denmark and Sweden), while in Asia, the proportion is 2%.[40] Significant exponential growth is expected in this decade and can reach more than 90 Mtoe in 2030 (all technologies including gasification). This will represent about 3% of the world gas demand and much more in some regions.[52]

Regarding the end-use of the biogas produced, approximately 33% is used for cogeneration, 31% for electricity generation, 27% is used as a fuel to provide heating in buildings, and a minimal part (9%) is used for biogas enrichment to produce biomethane.[40]

In European Union, a study conducted by the Spanish company Engie[14] analyzed the availability of different substrates with the potential to produce biogas, and consequently biomethane, as well as the biomass potential available in the EU countries and 10 other surrounding countries. This is crucial given that, depending on the availability of biomass in each country, the evolution of biogas and biomethane production will have a more positive or slower scenario.

This study estimated the biogas potential present in each EU country based on three parameters, as follows:

- Geographical analysis of land use in each country and the industrial waste produced.

- Existing regulations in each country for the use of waste, especially regarding waste from agriculture and livestock farming.

- Biogas production potential of each type of biomass source.

The main conclusions of the study were that the total EU biomethane potential was estimated to be more than 1700 TW h, with a clear predominance of energy crops as the reference biomass source, as well as plant residues from pruning and forest residues (mainly wood). Between these two sources, they can account for around 50% of the estimated biomethane generation potential for the EU. Regarding the biomethane potential by country, 70% is in less than a third of all EU countries, with France and Germany being the two countries with the greatest potential, concentrated in the presence of forestry waste. This is followed by Turkey and Spain, with a higher representation of energy crops.[14] The specific situation in Spain will be analyzed in later sections.

According to the EurObserv'ER,[34] the production of primary energy from biogas in EU countries has increased only slightly since 2017. In 2019, the production reached 193 TW h, which is slightly higher than in 2018, but almost at the same level as in 2017. This is explained by the lower incentive payments for energy supplied through biogas, fewer tenders, and incentives for plant construction. In addition, 26 TW h of biomethane was produced in 2019. The share of energy from renewable sources used in transport activities in the EU-27 reached 8.9% in 2019, reflecting the need to promote the use of biogas as an energy tool for the transition to a low-emission economy.

There is a strong consensus that by 2030, the biogas and biomethane sectors combined can almost double their production, and by 2050, production can increase by up to four times. The EU estimates that it has a potential of between 1000 and 2500 TW h to produce biogas in 2050.[34] As indicated above, in 2016, the EU produced 193 TW h, and thus the potential for biogas production would be multiplied by 7–12 times.

France is at the forefront of development with more than 1000 ongoing projects. It has been one of the fastest growing member states in this sector in the last year (11%). It is also the only country to have increased its primary energy production with biogas, among the top five countries including Germany, the United Kingdom, Italy, and the Czech Republic. Spain has remained in ninth place in the European ranking.[34]

By the end of 2019, there were 18 943 biogas plants in Europe. The use of biogas for electricity generation is incentivised in most of the European countries, which means less energy consumption from fossil fuels as well as recycling of waste products.

Currently, in Europe, the number of biomethane plants is 729, which has increased by 51% since 2018, when there were 483.[34] There are currently 18 countries producing biomethane in Europe. Germany has the highest proportion of biomethane plants (232), followed by France (131) and the UK (80).

With regards to the distribution of plants by type of feedstock, the majority use energy crops, agricultural or factory waste, sewage sludge or municipal waste, with 88% of all biomethane plants in the EU using this type of feedstock.[55] Furthermore, the most used biogas purification techniques in the European Union are water scrubbing, which is the most cost-effective. To a lesser extent, purification with chemical solvents, membrane separation and pressure adsorption are also used.[55]

In terms of refuelling station data, of the 4120 CNG and LNG refuelling stations currently operating in Europe, more than 25% supply biomethane. According to estimations by the European Biogas Association, 40% of natural gas consumption in road transport will be biomethane by 2030, resulting in a GHG emission reduction of 55%, equivalent to avoiding 15 million tonnes of CO_2 emissions.[24]

4.2. Biomethane production potential by type of waste in Spain

The importance and relevance of the primary sector in the Spanish economy are evident in the amount of waste generated at the national level, which is likely to be useable to produce biomethane. A study carried out by SEDIGAS reported that the potential available in Spain to produce biomethane is 163 TW h, which will cover around 45% of the national demand for natural gas. The information in the SEDIGAS report is summarized based on the type of waste in Table 3.[56] By autonomous community, Castille and Leon leads the ranking with 37.78 TW h, which represents 23.2% of the total. This is followed by Andalusia, with 23.62 TW h (14.5%) and Castilla-La Mancha, with 20.37 TW h (12.5%). Therefore, these three account for half (50.2%) of the total national potential.

4.2.1. Agricultural waste. An important part of the waste used for biomethane production comes from agricultural residues generated by agricultural activities. These residues mainly include the materials left in the fields, following the harvesting of the main crop (*i.e.*, grain or seed). The potential obtained varies significantly depending on the number of farms and their size, because depending on the Autonomous Community, the size of the farms varies considerably. The Autonomous Community with the largest number of farms is Andalusia, with more than 260 000 farms, which is almost 30% of the total in Spain, while that with the largest area is Castile and Leon, with more than 5 million hectares dedicated to this activity, 22.1% of entirely agricultural land in Spain.

4.2.2. Livestock waste. Another sector with great potential for biomethane generation is the livestock sector. Livestock substrates do not have great energy potential given that the main content of these excrements is water. However, the large amount of waste from this sector at the national level means that they have a high relative weight in the total potential for the generation of biomethane.

In Spain, there is a total of 237 207 livestock farms spread throughout its territory. These farms are classified into different categories according to the type of livestock, where the main ones are as follows: (i) bovines (cows, buffaloes, and other bovines such as males and heifers), (ii) sheep, (iii) goats, (iv) pigs, (v) poultry (laying hens, broilers, turkeys, ducks, geese, and other birds), and (vi) mother rabbits.

Although Galicia is the community with the largest number of farms, these farms are small and the Autonomous Communities with the greatest potential for biomethane production from animal manure are Andalusia, Aragon, and Asturias.

4.2.3. Organic fraction of MSW. Regarding the use of MSW, according to MITECO,[57] in 2019 more than 22 Mton of MSW was

Table 3 Biomethane production potential by type of waste in Spain (TW h)

	Total (Spain)	Average	Main autonomous communities		
Agricultural waste	24.77	1.46	Andalusia (24.8%)	Castile and Leon (24.7%)	Castile-La Mancha (20.1%)
Animal manure	25.48	1.50	Andalusia (19.5%)	Aragon (14.8%)	Asturias (10.6%)
Organic fraction of municipal solid waste	7.92	0.47	Andalusia (19.8%)	Catalonia (16.8%)	Madrid (11.8%)
Sewage sludge	2.99	0.18	Com. Valencian (16.9%)	Andalusia (15.6%)	Catalonia (13.9%)
Agri-food industry residues	6.42	0.38	Catalonia (17.2%)	Andalusia (15.5%)	Castile and Leon (10.9%)
Sequential cropping	58.80	3.46	Castile and Leon (32.4%)	Castile-La Mancha (16.4%)	Aragon (14.6%)
Residual forest biomass	27.66	1.63	Andalusia (24.6%)	Aragon (14.4%)	Asturias (11.3%)
Landfills	8.81	0.52	Andalusia (22.3%)	Madrid (13.6%)	Catalonia (11.7%)
Total	**162.82**	—	**Castile and Leon (23.2%)**	**Andalusia (14.5%)**	**Castile-La Mancha (12.5%)**

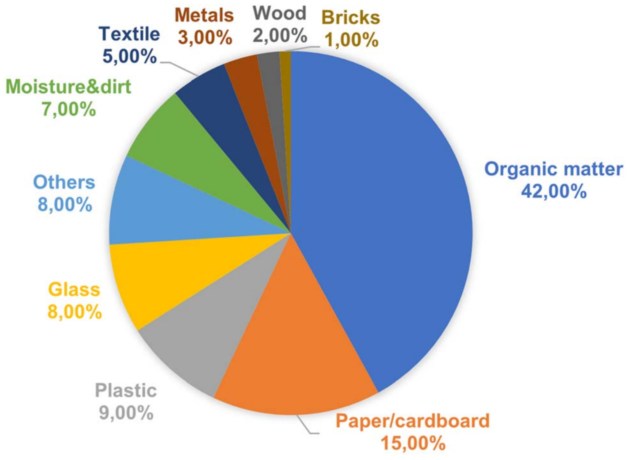

Fig. 2 Average composition of the rest fraction of MSW in Spain. Source: PEMAR 2016–2022.[58]

generated, with an average generation of more than 400 kg per inhabitant per year. It is worth noting that approximately 40% of MSW in Spain is organic matter or bio-waste, according to the PEMAR (Waste Management Framework State Plan) 2016-2022 (Fig. 2).[58] This waste, when clean and separated from the rest of the fractions, has good potential for biogas generation. In addition, the new Law on Waste and Contaminated Land has recently been published, which requires the implementation of selective collection of this fraction by the end of 2023 in all Spanish municipalities.

Many of the waste treatment plants are not yet ready to take on the entry of clean biowaste and carry out adequate classification and composting, and thus a large amount of biomass with good energy potential will be available in the near future, which can be perfectly exploited in biogas and biomethane production facilities.

4.2.4. Sewage sludge. The biomethane production potential obtained from sewage sludge is strongly impacted by the population and its distribution in the Autonomous Communities. The Autonomous Communities with more population and larger urban centers have a greater number of water purification plants. In Spain, these Autonomous Communities are Com. Valencian, Andalusia, and Catalonia.

4.2.5. Agri-food industry residues. The agri-food industry has had a predominant development in communities such as Andalusia, which is the world's leading producer of olive oil. The national average is 0.38 TW h per Autonomous Communities.

4.2.6. Sequential cropping. Intermediate or sequential crops are, without any doubt, the type of waste with the greatest potential to produce biomethane. It refers to the cultivation of a second crop before or after the harvest of the main food or feed crop on the same agricultural country during a still otherwise fallow period. The communities of Andalusia, Aragon, Castile and Leon, Castile-La Mancha and Extremadura are the Autonomous Communities with the greatest potential. These crops alone represent 36.1% of the total Spanish potential with 58.80 technically useable annual TW h.

4.2.7. Residual forest biomass. Residues from forest biomass also have great potential to produce biomethane at the national level. The national potential is clearly related to the territories with the highest forest density.

4.2.8. Landfills. Similar to the organic fraction of municipal solid waste, the Autonomous Communities with the greatest potential for biomethane production from landfill waste are Andalusia, Madrid, and Catalonia.

4.2.9. Reflections about Spain's potential in the biomethane sector. To date, in addition to the SEDIGAS report, there are other European studies that report estimations about the potential of biomethane production in Spain.[59–61] Most of them refer to Spain as one of the countries with the greatest production potential in the European Union, a situation that clashes with the current development of this technology in our country. At the international level, the European Commission, in its report published in April 2020 "Impact of the use of the biomethane and hydrogen potential on trans-European infrastructure" predicted the biomethane development potential for Spain in the year 2050 of around 122 TW h per year, which places Spain as the third country in the Union in terms of potential after France and Germany.[62] Also, the estimations published by the European Biogas Association in its latest sectorial report[60] place the biomethane production potential in Spain above 100 TW h. Similarly, the last report published in July 2022 by Gas for Climate (Biomethane production potentials in the EU) places Spain as the third country in the UE in terms of biomethane production potential from anaerobic digestion, with a potential of around 13.5 bcm, which is equivalent to about 130 TW h. These estimations can be increased if the production of biomethane by thermal gasification is included (additional 6.5 bcm), making a total of 190 TW h. At the Spanish level, another study that reports estimations about the potential of biomethane production in Spain is the study prepared by PwC Spain, in accordance with the request made by the Naturgy Foundation. This study estimated that the potential of biomethane production in Spain is 137 TW h.[63]

Taking advantage of the wide potential identified will allow Spain to position itself as one of the leading European countries in the development of biomethane and achieve the objectives established at the European level for the production and integration of this renewable gas to achieve the energy transition. However, the complexity related to obtaining permits and the delay in the procedures to obtain them reduce the growth that can be achieved in the development of biomethane projects. From the analysis of certain European countries that are leading the development of the biomethane sector, it becomes clear that support mechanisms are essential to achieve the necessary momentum and position biomethane as an economically viable alternative to achieve a sustainable energy transition. To maximize the number of biomethane production plants and achieve the development of biomethane in Spain, the support and coordination between all administrations and reduction of the complexity of administrative procedures must be overcome. A specific regulation to properly control the activity of the biomethane sector has not yet been developed.

The success of the deployment of biomethane in our country depends on whether we can overcome certain barriers that are currently slowing down the construction of new plants. It is necessary to facilitate and speed up the procedures for investments and requests for connection to the grid, consistent with the expansion of renewable gases, creating a single procedure for the entire national territory. In this sense, presently, thanks to the implementation of measures such as those proposed in the Biogas Roadmap or Royal Decree 376/2022, a major boost is expected from new projects that will help to exploit the available potential. However, the Biogas Roadmap sets only a biogas production of 10.4 TW h the 2030 and 1% of gas consumption of biomethane, which is an unambitious goal compared to that established in other European countries.

Nevertheless, the promotion of biomethane will mean the start-up of 2326 specialized plants, which will mobilize an investment of almost 40 500 million euros, the equivalent of 3.6% of GDP and generate close to 62 000 jobs, both direct and indirect, associated with its operation and maintenance.[58]

The report also differentiates these 2326 plants according to their type as follows:

• Agro-industrial waste plants + WWTP (waste, normally in the form of sludge, from the activity carried out in the wastewater treatment plants) + RSU (waste, garbage, waste or waste generated in urban centers or in their areas of influence): with a total of 1566 plants, each with an estimated annual production of 40 gigawatt hour (GW h), an estimated investment of 12 million euros, eight direct jobs and ten indirect jobs generated per plant.

• Sequential cropping plants: they will use the so-called intermediate crops as raw materials for the generation of biomethane with a total of 609 plants, each with an estimated annual production of 100 GW h, an estimated investment of 24 million, 12 direct jobs and 35 jobs. Indirectly generated by plants.

• Residual forest biomass plants: planned thermal gasification plants that will use residual forest biomass as raw material for the generation of biomethane with a total of 151 plants. Excessively, the location and the available forest biomass have differentiated 3 plant sizes, as follows: (i) 75 GW h per year biomethane production plants, estimated investment of 20 million, eight direct jobs and 15 indirect jobs generated per plant, (ii) 100 GW h per year biomethane production plants, estimated investment of 27 million, eight indirect jobs and 15 indirect jobs generated per plant, and (iii) 200 GW h per year biomethane production plants, 50 million investment per plant, 12 direct jobs and 20 indirect jobs generated per plant.

The recent communication from the European Commission REPowerUE precisely indicated a joint production target of 35 bcm of biomethane by 2030, and where Spain, due to its potential, will play a relevant role in achieving it. If the EU's energy diversification and resilience strategy involves covering around 8.5% of its demand with biomethane, our country cannot miss out on the enormous potential of this vector for decarbonization. Moreover, at this point, it should be noted that the Spanish gas system is essential for the security of the European supply in the medium and long term due to its high storage and regasification capacity and its solid distribution infrastructure, which, although must continue to be improved, is equipped to transport renewable gases such as biomethane (and in the future green hydrogen). Finally, it is also important to focus on the fact that the development of the biomethane industry has a positive impact in the fight against the depopulation of Spanish rural areas, helping to establish employment in these areas.

Therefore, the introduction of biomethane into the Spain energy mix is essential to meet decarbonization objectives, facilitate greater energy independence from abroad and help reduce the problems derived from poor waste management, also attracting investment in certain primary sectors and helping to establish employment in rural areas.

4.3. Description of important biogas and biomethane Spanish plants and projects

In Spain, according to the Spanish Biogas Association (AEBIG) and the European Biogas Association (EBA), there are currently 210 active biogas plants in Spain with a capacity total production of 836 MW, of which plants based on sewage sludge are the most (80 plants), followed by those with an agricultural base (53 plants), the landfill (40 plants) and "others" (40 plants). In 2020, biogas production was 8079 GW h, most of which was consumed in electricity generation plants (cogeneration and non-cogeneration). These data are very modest compared to the rest of Europe, where there are about 19 000 plants, of which 725 inject biomethane into the natural gas grid.

Regarding biomethane, currently Spain has six biomethane production plants including Valdemingómez (Madrid), Torre Santamaría (Lleida), Unue (Burgos), Vilanant (Girona), Elena (Barcelona) and Bens (A Coruña). Furthermore, other projects are still under construction. The main characteristics of all these biomethane production plants are listed in Table 4. The data shows that it is necessary to promote biomethane at the national level in a more forceful way, given that although steps have been taken, Spain is at the tail of Europe in the development of this vector. Thus, it is necessary to facilitate and speed up the procedures for investments and requests for connection to the grid, consistent with the expansion of renewable gases, creating a single procedure for the entire national territory.

In the area of Madrid, Valdemingómez Technology Park brings together all the urban waste treatment facilities in the capital. It has three treatment centres including Las Dehesas, La Paloma, and Las Lomas. At Valdemingómez, biogas is produced, and then part of it is transformed into biomethane. It was the first biogas plant in Spain to inject biomethane into the conventional gas grid. Moreover, now, it is the largest biomethane plant in Spain.

The Torre Santamaría plant is the result of an investment of almost four million euros and turns the Balaguer company into a practical example of the circular economy by converting its livestock waste into biomethane, which is injected directly into the Nedgia network.

Unue was the first biomethane generation facility from agro-industrial waste put into operation by private initiative,

Table 4 Location and production capacity of the main biomethane plants in Spain.[64–67]

Installation	Location	Feedstock	Application of biomethane	Biomethane production capacity (Nm^3 h^{-1})	Biomethane production capacity (GW h per year)	Year of operation
Valdemingómez	Madrid	Organic fraction of MSW	Natural gas grid	2093	180	2012
Torre Santamaría	Vallfogona de Balaguer, Lleida	Organic-livestock waste	Natural gas grid	350	30	2022
Unue	Burgos	Agri-food industry residues	Natural gas grid	300	26	2021
Vilanant	Vilanant, Girona	Agri-food industry residues – bovine	Vehicular use	200	12	2021
Elena plant	Cerdanyola del Vallès, Barcelona	Landfill	Natural gas grid	140	12	2021
Bens	Bens, A Coruña	Sewage sludge	Natural gas grid	100	8	2018
Serós	Seròs, Lleida	Agri-food industry residues	Natural gas grid	3500	300	June, 2023
Sologas	As Somozas, A Coruña	Organic residues, sewage sludge		2571	220	2023
Lugo	Lugo	Biowaste			100	2024
Valencia	Valencia	Biowaste			100	2024
Huesca	Vencillón, Huesca	Organic residues (mainly manure)		1117	96	2024
Madrid	Madrid			996	83	September, 2023
Albacete	Albacete	Organic residues			80	2024
Luchete	Luchete, Valencia	Organic residues		861	74	September, 2023
Can Mata	Els Hostalets de Pierola, Barcelona	Sewage sludge	Natural gas grid	815	70	June, 2023
Antequera	Antequera, Málaga			756	65	September, 2023
Medina Sidonia	Medina-Sidonia, Cádiz	Landfill		550	54	September, 2023
Los Santos de Maimona	Los Santos de Maimona, Badajoz			593	51	September, 2023
Godall	Godall, Tarragona	Agri-food industry residues		580	50	June, 2023
La Galera	La Galera, Tarragona	Organic fraction of MSW, agri-food industry residues	Vehicular use	500	43	2023
Valles Oriental	Granollers	Organic fraction of MSW-sewage sludge	Natural gas grid	500	43	July, 2023
Villanueva de la Serena	Villanueva de la Serena, Badajoz			447	41	September, 2023
Zurgena	Zurgena, Almería			465	40	September, 2023
Galivi solar	Lorca, Murcia	Livestock waste, agri-food industry residues, sewage sludge		400	40	March, 2023
Ólvega	Ólvega, Soria	Livestock waste, agri-food industry residues, residual oils		407	38	2023

Table 4 (*Contd.*)

Installation	Location	Feedstock	Application of biomethane	Biomethane production capacity (Nm^3 h^{-1})	Biomethane production capacity (GW h per year)	Year of operation
Alcalá de Guadaíra	Alcalá de Guadaira, Sevilla			372	32	June, 2023
Vall de Uxó	Vall de Uxó, Castellón			267	23	September, 2023
Campillos	Campillos, Málaga			232	20	September, 2023
Alcarràs	Alcarràs, Lleida			197	17	September, 2023
Vila-sana	Vila-sana, Lleida	Livestock waste	Natural gas grid	137	12	Summer, 2023
Vilademuls	Vilademuls, Girona			104	9	September, 2023
Peñarroya	Peñarroya, Teruel	Livestock waste		15	1	September, 2023

injecting it into the gas network. It is located in the town of Burgos, next to the existing Biogasnalia biogas production facility. The plant is in operation, injecting the biomethane produced into the distribution network owned by Nedgia.

The first 100% vehicular biomethane project in Spain was the Vilanant plant. The project is based on the biogas generated in an anaerobic co-digestion plant of waste from the agri-food industry and a cattle farm, located at the Mas Jonquer Farm in Vilanant, Girona. The biogas plant is owned by Apergas, a company dedicated to the engineering, development, and operation of biogas plants.

At the beginning of June 2021, Naturgy became the first company to inject renewable gas from landfill into the Spanish gas distribution network by the operation of the Elena Plant. Previously, the Elena de Cerdanyola del Vallès landfill was in the decommissioning phase, and the gas generated in the decomposition of the waste was captured through a degassing network and burned in torches. The new renewable gas project in the Elena landfill makes energy use of the recovered biogas to contribute to the environmental improvement of the landfill with respect to the current situation, avoiding the combustion of the generated gas, being used as an energy resource for injection to the network and subsequent consumption.

One of the plants already in operation is the Bens plant in A Coruña, which uses sludge from a wastewater treatment plant (WWTP) to obtain biogas and its subsequent transformation into biomethane. In addition to producing biomethane for injection into the grid, there is already a bus and three vans from the WWTP running on biomethane.

Some projects under construction in 2023 include the Vila-sana plant, which will operate with livestock waste. The Vila-sana biomethane plant will be the third that Naturgy puts into commercial operation in Spain and the second for the company located in Catalonia. Starting next summer, this facility will inject 11.8 GW h per year of biomethane into the gas distribution network. Another example is the Galivi Solar plant in Lorca (Murcia), which will obtain biomethane from a mixture of livestock and agro-industrial waste, and the Godall Plant, which includes the world's first bioenergy tech facilities with zero waste, hybridised with photovoltaics in self-consumption mode, with biomethane storage and production, making it possible to diversify income in sectors as diverse as waste management, renewable biofuels (biomethane PPAs), photovoltaic energy, organic fertilisers and the "Guarantees of Origin" (GoO) and certificates that will accredit their origin. It is planned to inject biomethane production into the gas grid, with more than 98% purity in the biomethane injected.

Enagás Renovable and Genia Bioenergy have just announced the creation of a joint venture to create the Green Vector (TGV), a platform to promote the development of biomethane from organic waste in Spain. The initiative integrates all the players in the waste recovery chain, from the production and distribution to the final consumption of biomethane. Through a collaborative platform model, TGV plans to implement by 2030 at least 10 biomethane production plants with the capacity to produce up to one terawatt hour of renewable energy each year.

In November 2021, two companies announced a project for the first time, *i.e.*, the construction of a biomethane plant in Vencillón (Huesca). This facility, whose construction is scheduled to start in 2024 and in which an investment of more than 15 million euros is estimated, will be capable of digesting more than 140 000 tons of organic waste (mainly manure) and converting it into biomethane with an energy capacity of nearly one hundred gigawatt hour (100 GW h) each year. In November 2022, the construction of a biomethane plant in Lugo was announced, with an energy capacity of more than 100 GW h per year, which will allow the conversion of around 150 000 tons of biowaste into renewable energy per year.

Regarding the other plants, two are in Valencia, one with a recovery of up to 180 000 tons of organic waste to produce about 75–80 GW h of energy per year, and the other with an expected energy production of 100 GW h from 130 000 tons of biowaste per year. The fifth planned plant is in Albacete, with a value of 100 000 tons of organic waste to also produce more than 80 GW h per year.

4.4. Biomethane perspectives in transport sector in Spain

Greenhouse gas emissions in the transport sector in Spain have a higher relative weight than the EU average (27.5% compared to 22.9%), according to the Transport and Logistics Observatory in Spain.[69] Furthermore, in Spain, the transport sector produces the most GHG emissions, ahead of industry and the energy sector, which has not been the case in any EU country to date. The share of transport emissions has increased by 3.5% between 2015 and 2017, and by more than 1% between 2017 and 2018. Fig. 3 shows the emissions from the main sectors in Spain compared to the EU.

Within the transport sector, road transport is the sector that produces most GHG emissions and pollutants. Spain has a much higher rate of road freight transport than the European average, which is due to geographical factors such as its size and the dispersion of its population, as well as the structure of Spanish economic activity. Table 5 shows the GHG emissions and pollutants in the different areas of transport (rail, air, maritime and road), with data for road transport being much higher for all pollutants measured, and especially for non-urban roads (motorways and dual carriageways).

Among the pollutants, GHGs have been the least reduced, given that the types of fuels used for transport have not changed significantly over the last decade and emission factors are constant, and thus to achieve a significant reduction in GHGs, the fuel landscape needs to change and fossil fuels need to be replaced by other alternatives, including CNG and biomethane. The OTLE report also analyses the relationship between GHG emissions and transport unit-kilometres for each transport typology, showing that road is the second highest GHG emitter per km, behind only air transport.

In December 2019, the twenty-fifth Conference of the Parties (COP25) to the United Nations Framework Convention on Climate Change took place in Madrid, where the foundations were laid for the countries involved to present more ambitious

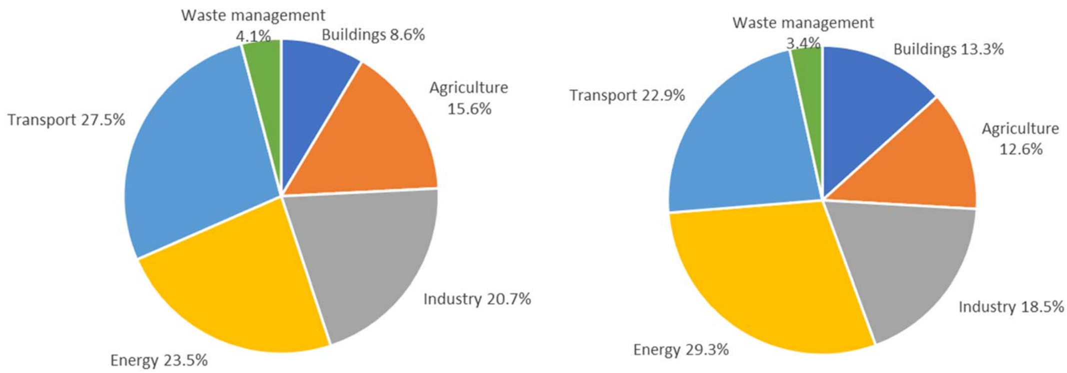

Fig. 3 Contribution of different economic sectors to GHG emissions in Spain (left) and Europe (right).[69]

Table 5 GHG and other pollutant emissions associated with transport in Spain.[68]

Means of transport	GHG emissions (kt CO_2 eq.)	Acidifying substances (acid eq.·10^6)	Ozone precursors (t eq. VOCNM)	Particulate material (t)
Railway	253	91	5496	120
Air	3045	239	18 323	132
Maritime	3160	1811	75 876	3400
Total road	83 659	5356	331 550	20 122
Urban road	28 249	1683	119 695	17 152
Non-urban road	55 410	3673	211 856	2970
Passengers	30 940	2084	120 424	1977
Goods	24 469	1589	91 432	994
Total national transport	**90 116**	**7586**	**431 246**	**23 774**

emission reduction commitments to respond to the climate emergency and accelerate the decarbonisation of the economy. Given that transport is currently the sector with the greatest weight in Spain's global GHG emissions, new regulations and targets for the reduction and substitution of fuels used are increasingly being imposed, within the framework of tools already described such as the PNIEC or the Law on Climate Change and Energy Transition.

In the area of conventional fuels in road mode, a shift towards a preference for petrol and electric vehicles over diesel vehicles is happening. In the period 2016–2018, there was an average year-on-year growth of 3.2% in petrol consumption compared to 0.8% for diesel.

Regarding fossil fuels, Directive 2014/94/EU establishes measures for the implementation of an alternative fuel infrastructure in the European Union to minimise the dependence of transport on oil and mitigate the environmental impact of transport. This legislation requires each member state to adopt a National Action Framework for the development and implementation of the provisions set out in the Directive. The National Action Framework for Alternative Energies in Transport published in 2016 adapts the guidelines of the European regulation to the Spanish context, establishing an action plan focused mainly on the transport market and infrastructure for alternative energy sources. In the National Action Framework, estimates are made of the evolution of the vehicle fleet in terms of alternative energy sources, obtaining very positive results for them. Directive 2018/2001 sets targets for the integration of renewable energy in the transport sector, which should be at least 14% by 2030.

Therefore, a slow but progressive change is taking place in Spain regarding the use of fuels, mainly in the automotive sector, which is causing some well-known vehicle manufacturers to expand their sales catalogue in our country with vehicles that run on CNG. This is the case for SEAT and FIAT, which are marketing cars prepared to run on CNG. In light commercial vehicles and heavy-duty vehicles, IVECO and SCANIA are the pioneers in our country, marketing vans of 3.5 tonnes MMA (Maximum Authorised Mass), as well as EUROCARGO trucks of greater tonnage. VOLVO also offers a gas/diesel hybrid truck.

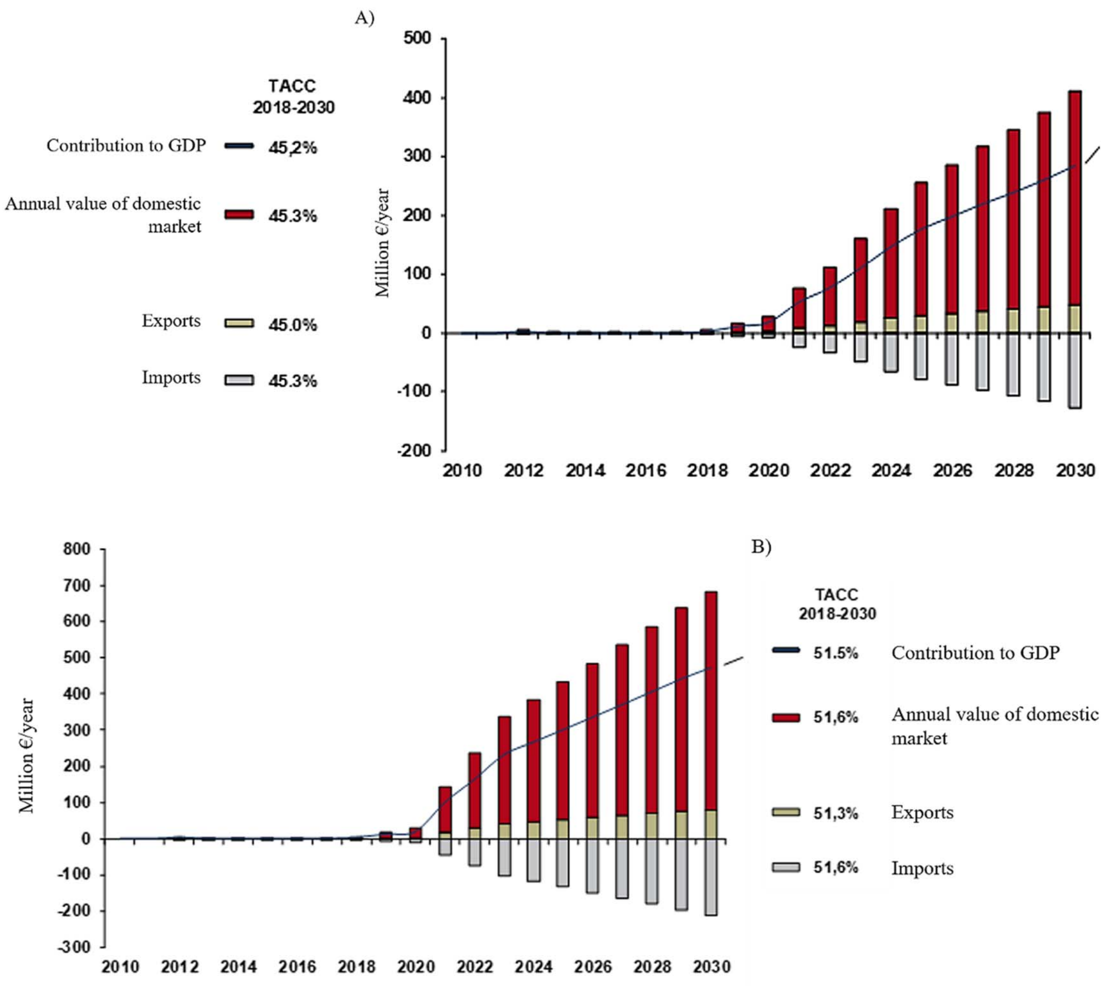

Fig. 4 Expected development of economic activity generated by biomethane production in (A) lower range and (B) upper range of the production target to 2030.[71]

As mentioned before, Spain currently accounts for 235 refuelling gas stations, of which 140 supply CNG and 95 supply LNG. In addition, another 41 stations are under development for opening soon.[70] The report Smart CO_2 standards for negative emission mobility[55] makes three key recommendations to ensure the deployment of biomethane in transport, as follows:

(1) Harmonisation of the approach to CO_2 emissions in all EU transport policies, considering the WtW approach and LCA.

(2) Recognition of CO_2 emission reductions in emission regulations for new vehicle fleets.

(3) Replace fossil fuels with advanced biofuels.

5. Expected growth and economic perspectives for biogas and biomethane and Spain

SEDIGAS[71] mentions in its annual report the economic activity of the biomethane technology sector based on biogas data. According to their study, the market value of biomethane is 1% of the biogas market. Given that most biogas installations to be implemented will be biomethane production, this value is expected to grow by more than 150% compared to the current rate by 2030. This report also calculated the contribution of this sector to GDP in two ranges, *i.e.*, lower and higher.

On the one hand, in the lower production range, the sector's contribution to GDP amounts to 284 million euros in 2030 with a growth rate of 45.2 (Fig. 4a). On the other hand, in the upper range of production, the sector is expected to contribute 472 million euros to GDP for the same timeframe. Therefore, the difference between the contribution to GDP in 2030 between the upper and lower range amounts to 188 million euros (Fig. 4b). The analysis of economic activity for both ranges of the 2030 biomethane production target reveals that Spain has high potential for biomethane production.

5.1. Economic support mechanisms for the Spanish biogas and biomethane sector

The Biogas Roadmap sets out the main funding instruments for the biogas sector at both the national and European levels.

Table 6 Main financial instruments to support renewable energies and alternative fuels in Spain.[24]

Financial instrument	Name	Characteristics
National	CIEN projects	Subsidy for projects developed by business consortia, with budgets between 5 and 20 M€
	Science and innovation missions	Grants for R&D initiatives carried out by clusters of companies and research organisations. The 2021 call for proposals had a budget of €141 million
	Renewable, thermal and electricity investment aid lines	Subsidies aimed at promoting renewable energy installations to produce thermal and electrical energy. The subsidies to be applied for are based on € per MW or kW of installed power. Financial endowment of 316 M€
	PIMA and circular economy programmes	Tools to promote measures to improve the environment. Of particular note are the PIMAs in the waste sector
	Recovery, transformation and resilience plan (RTRP)	It has a "Plan to support the implementation of waste legislation" with a planned budget of €850 million. Among its objectives is the improvement of waste treatment facilities. Financial envelope of €416 million in 2021
	SGIPYME programmes	Financial support programmes for investment projects that improve industrial competitiveness or contribute to the reindustrialisation of an area
	Carbon fund for a sustainable economy (FES-CO_2)	Climate finance instrument targeting low-carbon activities and clean technologies that contribute to climate change mitigation through the purchase of credits in the form of emission reductions
European	Innovation fund	European funding programme for innovative low-carbon technologies, with an envelope of €10 billion for the period 2020–2030. It includes innovative low-carbon processes, carbon capture and storage projects, and renewable energy generation projects
	European Green Deal Call	Call for grants, in the framework of the European Green Pact, for pilot projects for the green and digital transition following the Covid-19 crisis. Financial envelope of €1 billion
	Horizon Europe	Research and innovation investment programme with an envelope of €75.9 billion over the period 2021–2027, of which 35% will go to low-carbon economy and environmental protection projects
	InnovFin energy Demonstration Projects	Financing through loans for renewable energy projects, energy storage, CO_2 capture and storage, *etc.* They finance between €7.5–75 million
	Connecting Europe Facility (CEF)	Financing of infrastructure projects in the energy, transport, and digital services sectors. Financial envelope for the period 2021–2027 of €28 396 million, of which 60% is earmarked for the sectors described above
	InvestEU	Public and private funding to support investment projects in sustainable infrastructure, research and digitisation, SMEs and social investment. More than €650 billion is foreseen between 2021 and 2027
	NextGenerationEU	Recovery instrument after the Covid-19 crisis, which will finance projects towards a climate-neutral economy, including biogas. 750 billion in direct support and loans are foreseen for the period 2021–2024

Table 6 shows a summary of the main tools and calls planned for the development of this sector in our country.

6. Conclusions

Global and especially European policies on the environment and climate change have been tightened in recent years. Ambitious greenhouse gas emission reduction targets have been proposed to achieve a low-carbon economy by 2050. However, despite the progress made by some countries such as Germany, the United Kingdom and the USA, others continue to face technical or economic difficulties in meeting these targets.

Herein, the final objective was to shed light on the current situation of biogas and biomethane production in Spain, highlighting the positive but slow progress in the substitution of fossil fuels. For this purpose, a literature review of the most relevant and updated publications in the sector was carried out, with special emphasis on associations such as WBA, EBA, IEA Bioenergy or IRENA. This review shows for the first time a holistic analysis of biogas and biomethane legal instruments, the Spanish biomass availability to produce biogas, as well as the main challenges faced.

The situation in Spain was considered of special importance, given that in 2018, only 1 biomethane production plant was operating, but currently there are already 6 plants in operation and a great number under construction.

Finally, the positive and progressive growth of biogas and biomethane as alternative energy sources in Spain can be observed, a situation that is likely to grow faster in these turbulent times to curb the energy dependence of Spain and other countries.

Author contributions

M. Calero: conceptualization, project administration, supervision; V. Godoy: investigation, data curation, writing – review and editing; C. García-Heras: investigation, data curation; E. Lozano: methodology; writing – original draft; S. Arjandas: project administration, funding acquisition; M. A. Martín-Lara: conceptualization, validation, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors are grateful to the European Project LIFE LANDFILL BIOFUEL (LIFE18 ENV/ES/000256).

References

1 NASA, *Evidence, How Do We Know Climate Change Is Real? Global Climate Change*, 2021, **https://climate.nasa.gov/evidence/**.
2 U. Brémond, A. Bertrandias, J. Steyer, N. Bernet and H. Carrere, A vision of European biogas sector development towards 2030: Trends and challenges, *J. Clean. Prod.*, 2021, **125065**, 287, DOI: **10.1016/j.jclepro.2020.125065**.
3 IEA Bioenergy, *Task 37: The role of biogas and biomethane in pathway to net zero*, 2022, p. 10, **https://www.ieabioenergy.com/wp-content/uploads/2022/12/2022_12_12-IEA_Bioenergy_position-paper_Final2.pdf**, accessed May 2023.
4 Y. Li, P. Alaimo, M. Kim, N. Y. Kado, Y. Peppers, J. Xue, C. Wan, P. G. Green, R. Zhang, B. M. Jenkins, C. Vogel, S. Wuertz, T. M. Young and M. J. Kleeman, Composition and toxicity of biogas produced from different feedstocks in California, *Environ. Sci. Technol.*, 2019, **53**, 11569–11579, DOI: **10.1021/acs.est.9b03003**.
5 R. A. Terrones Ramirez and Y. Cruz Balcazar, *Pre-feasibility Study for the Installation of a Hydrogen Production Plant from Biogas*, Doctoral thesis, Pedro Ruiz Gallo National University, 2019, p. 115.
6 L. M. Gutiérrez-Castro, P. Quinto-Diez, J. G. Barbosa-Saldaña, L. R. Tovar-Galvez and A. Reyes-Leon, Comparison between a fixed and a tracking solar heating system for a thermophilic anaerobic digester, *Energy Proc.*, 2014, **57**, 2927–2945, DOI: **10.1016/j.egypro.2014.10.329**.
7 F. Calise, F. Liberato, L. Cimmino, M. Dentice and M. Vicidomini, A review of the state of the art of biomethane production: recent advancements and integration of renewable energies, *Energies*, 2021, **4895**, 14, DOI: **10.3390/en14164895**.
8 X. He, T. Wallington, J. Anderson, G. Keoleian, W. Shen, R. De Kleine, H. Kim and S. Winkler, Life-cycle greenhouse gas emission benefits of natural gas vehicles, *ACS Sustainable Chem. Eng.*, 2021, **9**(23), 7813–7823, DOI: **10.1021/acssuschemeng.1c01324**.
9 D. Hidalgo-Barrio, J. M. Martín-Marroquín and F. Corona-Encinas, Transformation of biogas into biomethane: A review of available technologies, *DYNA Energy Sustainability*, 2017, 12.
10 W.-K. Jo, S. Kumar and S. Tonda, N-doped C dot/CoAl-layered double hydroxide/g-C_3N_4 hybrid composites for efficient and selective solar-driven conversion of CO_2 into CH_4, *Composites, Part B*, 2019, **107212**, 176, DOI: **10.1016/j.compositesb.2019.107212**.
11 Q. Niu, Z. Cheng, Q. Chen, G. Huang, J. Lin, J. Bi and L. Wu, Constructing nitrogen self-doped covalent triazine-based frameworks for visible-light-driven photocatalytic conversion of CO_2 into CH_4, *ACS Sustainable Chem. Eng.*, 2021, **9**, 1333–1340, DOI: **10.1021/acssuschemeng.0c07930**.
12 L. Wu, W. Wie, L. Song, M. Wozniak-Karczewska, L. Chrzanowski and B.-J. Ni, Upgrading biogas produced in anaerobic digestion: Biological removal and bioconversion of CO_2 in biogas, *Renew. Sustain. Energy Rev.*, 2021, **111448**, 150, DOI: **10.1016/j.rser.2021.111448**.
13 S. Fu, I. Angelidaki and Y. Zhang, In situ biogas upgrading by CO_2-to-CH_4 bioconversion, *Trends Biotechnol.*, 2021, **39**, 336–347, DOI: **10.1016/j.tibtech.2020.08.006**.

14 J. Birman, J. Burdloff, H. de Peufeilhoux, G. Erbs, M. Feniou and P. Lucille, *Geographical analysis of biomethane potential and costs in Europe in 2050*, Study conducted for ENGIE company, 2021, p. 43.

15 European Commission, *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions*, The European Green Deal, Brussels, 2019, 11.12.2019, COM (2019) 640 final.

16 European Commission, *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. 'Fit for 55': Delivering the EU's 2030 Climate Target on the Way to Climate Neutrality*, Brussels, 2021, 14.7.2021, COM (2021) 550 final.

17 C. Morales-Polo, M. Cledera-Castro, M. Revuelta-Aramburu and K. Hueso-Kortekaas, Bioconversion process of barley crop residues into biogas – Energetic-environmental potential in Spain, *Agronomy*, 2021, **640**, 11, DOI: 10.3390/agronomy11040640.

18 M. Pablo-Romero, A. Sánchez-Braza, J. Salvador-Ponce and N. Sánchez-Labrador, An overview of feed-in tariffs, premiums, and tenders to promote electricity from biogas in the EU-28, *Renew. Sustain. Energy Rev.*, 2017, **73**, 1366–1379, DOI: 10.1016/j.rser.2017.01.132.

19 European Commission, *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Renewable Energy Progress Report*, Brussels, 2020, 14.10.2020, COM (2020) 952 final.

20 European Commission, *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, on the EU Strategy to Reduce Methane Emissions*, Brussels, 2020, 14.10.2020, COM (2020) 663 final.

21 United Nations Environment Programme (UNEP), *An Eye on Methane: International Methane Emissions Observatory 2022*, Nairobi, 2022, p. 69, https://www.unep.org/resources/report/eye-methane-international-methane-emissions-observatory-2022-report, accessed May 2023.

22 MITECO, *National Integrated Energy and Climate Plan 2021-2030*, 2021, p. 427, https://www.miteco.gob.es/es/ministerio/planes-estrategias/plan-nacional-integrado-energia-clima/plannacionalintegradodeenergiayclima2021-2030_tcm30-546623.pdf, accessed May 2023.

23 M. Pascual-Núñez, *The Evaluation of the Final NECPs: Climate and Energy Planning as the Basis of Economic Recovery. Actualidad Jurídica Ambiental, 106, Section "Comments"*, 2020, ISSN: 1989-5666, NIPO: 832-20-001-3.

24 MITECO, *Biogas roadmap, Published in the Strategic Framework for Energy and Climate, within the Recovery, Transformation and Resilience Plan*, 2022, p. 72, https://energia.gob.es/es-es/Novedades/Documents/00HR_Biogas_V6.pdf, accessed May 2023.

25 E. U. Kiran, K. Stamatelatou, G. Antonopoulou and G. Lyberatos, Production of biogas via anaerobic digestion, in *Handbook of Biofuels Production*, ed. Luque R., Lin C., Wilson, K. and Clark J., 2nd edn, 2016, pp. 259–301, DOI: 10.1016/B978-0-08-100455-5.00010-2.

26 I. Angelidaki, L. Treua, P. Tsapekosa, G. Luoc, S. Campanarob, H. Wenzeld and P. Kougiasa, Biogas upgrading and utilization: current status and perspectives, *Biotechnol. Adv.*, 2018, **36**(2), 452–466, DOI: 10.1016/j.biotechadv.2018.01.011.

27 M. T. Varnero, *Biogas Manual, Project CHI/00/G32 Chile: Removal of Barriers for Rural Electrification with Renewable Energy*, 2011, p. 119, ISBN 978-95-306892-0.

28 R. Iglesias, R. Muñoz, M. Polanco, I. Díaz, A. Susmozas, A. D. Moreno, M. Guirado, N. Carreras and M. Ballesteros, Biogas from anaerobic digestion as an energy vector: current upgrading development, *Energies*, 2021, **2742**(10), 14, DOI: 10.3390/en14102742.

29 H. Hahn, B. Krautkremer, K. Hartmann and M. Wachendorf, Review of concepts for a demand-driven biogas supply for flexible power generation, *Renew. Sustain. Energy Rev.*, 2014, **29**, 383–393, DOI: 10.1016/j.rser.2013.08.085.

30 C. Herbes, V. Halbherr and L. Braun, Factors influencing prices for heat from biogas plants, *Appl. Energy*, 2018, **221**, 308–318, DOI: 10.1016/j.apenergy.2018.03.188.

31 N. Abatzoglou and S. Boivin, A review of biogas purification processes, *Biofuels Bioprod. Biorefining*, 2009, **3**, 42–71, DOI: 10.1002/bbb.117.

32 T. Muche, C. Höge, O. Renner and R. Pohl, Profitability of participation in control reserve market for biomass-fueled combined heat and power plants, *Renewable Energy*, 2016, **90**, 62–76, DOI: 10.1016/j.renene.2015.12.051.

33 M. Pirouti, J. Wu, A. Bagdanavicius, J. Ekanayake and N. Jenkins, Optimal operation of biomass combined heat and power in a spot market, *IEEE Trondheim PowerTech*, 2011, pp. 1–7, DOI: 10.1109/PTC.2011.6019322.

34 EurObserv'ER, *Biogas Barometer*, December 2020, https://www.eurobserv-er.org/biogas-barometer-2020/, last access on 2 june 2022.

35 REGATRACE, *D6.1. Mapping the State of Play of Renewable Gases in Europe*, This project receives funding from the European Union's Horizon 2020 Framework. Programme for Research and Innovation under Grant Agreement no. 857796, 2020, p. 60.

36 L.-P. Lauven, J. Geldermann and U. Desideri, Estimating the revenue potential of flexible biogas plants in the power sector, *Energy Pol.*, 2019, **128**, 402–410, DOI: 10.1016/j.enpol.2019.01.007.

37 IEA Bioenergy, *Task 24: Energy from biological conversion of organic waste. Biogas upgrading technologies–developments and innovations*, 2009, p. 20, https://www.ieabioenergy.com/wp-content/uploads/2009/10/upgrading_rz_low_final.pdf, accessed May 2023.

38 A. M. Abdalla, S. Hossain, O. B. Nisfindy, A. T. Azad, M. Dawood and A. K. Azad, Hydrogen production, storage, transportation and key challenges with applications: A review, *Energy Convers. Manage.*, 2018, **165**, 602–627, DOI: 10.1016/j.enconman.2018.03.088.

39 A. De Vita, P. Capros, L. Paroussos, *et al*, *European Commission, Directorate-General for Climate Action, Directorate-General for Energy, Directorate-General for Mobility and Transport. EU Reference Scenario 2020: Energy, Transport and GHG Emissions: Trends to 2050*, Publications Office, 2020, **https://data.europa.eu/doi/10.2833/35750**.
40 IEA Bioenergy, *Outlook for Biogas and Biomethane. Prospects for Organic Growth*, 2020, p. 93, **https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth**, accessed May 2023.
41 J. Popp, S. Kovács, J. Oláh, Z. Divéki and E. Balázs, Bioeconomy: biomass and biomass-based energy supply and demand, *Bio Technol.*, 2021, **60**, 76–84, DOI: **10.1016/j.nbt.2020.10.004**.
42 O. W. Awe, Y. Zhao, A. Nzihou, D. P. Minh and N. Lyczko, A review of biogas utilisation, purification and upgrading technologies, *Waste Biomass Valorization*, 2017, **8**(2), 267–283, DOI: **10.1007/s12649-016-9826-4**.
43 H. G. Katariya and H. P. Patolia, Advances in biogas cleaning, enrichment, and utilization technologies: a way forward, *Biomass Convers. Biorefin.*, 2021, DOI: **10.1007/s13399-021-01750-0**.
44 F. Bauer, C. Hulteberg, T. Persson and D. Tamm, *Biogas Upgrading – Review of Commercial Technologies. SGC Rapport*, 2013, vol. 270, p. 83.
45 Q. Sun, H. Li, J. Yan, L. Liu, Z. Yu and X. Yu, Selection of appropriate biogás upgrading technology – A review of biogás cleaning, upgrading and utilisation, *Renew. Sustain. Energy Rev.*, 2015, **51**, 521–532, DOI: **10.1016/j.rser.2015.06.029**.
46 S. S. Cordova, M. Gustafsson, M. Eklund and N. Svensson, Potential for the valorization of carbon dioxide from biogas production in Sweden, *J. Clean. Prod.*, 2022, **370**, 133498, DOI: **10.1016/j.jclepro.2022.133498**.
47 E. Esposito, L. Dellamuzia, U. Moretti, A. Fuoco, L. Giorno and J. C. Jansen, Simultaneous production of biomethane and food grade CO_2 from biogas: an industrial case study, *Energy Environ. Sci.*, 2019, **12**, 281–289, DOI: **10.1039/C8EE02897D**.
48 Z. Zhang, S.-Y. Pan, H. Li, J. Cai, A. G. Olabi, E. J. Anthony and V. Manovic, Recent advances in carbon dioxide utilization, *Renew. Sustain. Energy Rev.*, 2020, **109799**, 125, DOI: **10.1016/j.rser.2020.109799**.
49 B. Castellani, S. Rinaldi, E. Bonamente, A. Nicolini, F. Rossi and F. Cotana, Carbon and energy footprint of the hydrate-based biogas upgrading process integrated with CO_2 valorization, *Sci. Total Environ.*, 2018, **615**, 404–411, DOI: **10.1016/j.scitotenv.2017.09.254**.
50 IRENA, *Renewable energy statistics 2021*, 2020, p. 460, **https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Aug/IRENA_Renewable_Energy_Statistics_2021.pdf**, accessed May 2023.
51 WBA, *Biogas: Pathways to 2030. Full report*, 2021, p. 128, **https://www.worldbiogasassociation.org/biogas-pathways-to-2030-report**, accessed May 2023.
52 CEDIGAZ, *Global biomethane market – 2021 assessment. The overall momentum of RNG is accelerating*, 2021, p. 32, **https://www.cedigaz.org/global-biomethane-market-2021**, accessed May 2023.
53 IEA Bioenergy, *Task 37: A perspective on the state of the biogas industry from selected member countries*, 2021, p. 65, **https://www.ieabioenergy.com/blog/publications/a-perspective-on-the-state-of-the-biogas-industry-from-selected-member-countries-of-iea-bioenergy-task-37**, accessed May 2023.
54 IRENA, IEA and REN21, *Renewable Energy Policies in a Time of Transition. Heating and Cooling*, 2021, p. 150, ISBN 978-92-9260-289-5.
55 EBA and GIE, *European biomethane map. Infrastructure biomethane production 2020*, 2020, **https://www.europeanbiogas.eu/eba-gie-biomethane-map**, accessed May 2023.
56 SEDIGAS, *Study of biomethane's production capacity in Spain*, 2023, p. 80, **https://estudio-biometano.sedigas.es/wp-content/uploads/2023/03/sedigas-report-potential-biomethane-2023.pdf**, accessed May 2023.
57 MITECO, *Annual Report on Waste Generation and Management under Municipal Jurisdiction 2020. Secretary of State for the Environment. General Directorate of Quality and Environmental Assessment*, 2020, p. 24.
58 Ministry of Agriculture, Food and Environment (MAPAMA), *Waste Management Framework State Plan (PEMAR) 2016-2022. Secretary of State for the Environment. General Directorate of Quality and Environmental Evaluation and Natural Environment*, 2016, p. 192.
59 European Commission, *Directorate-General for Energy. The Impact of the Use of the Biomethane and Hydrogen Potential on Trans-European Infrastructure*, Brussels, 2020, April 2020, final report.
60 EBA, *EBA Statistical Report 2021*, 2021, **https://www.europeanbiogas.eu/eba-statistical-report-2021**, accessed May 2023.
61 S. Alberici, W. Grimme and G. Toop, *Biomethane Production Potentials in the EU. A Gas for Climate Report*, Guidehouse Netherlands B.V., 2022.
62 Trovant, *2022, a Key Year for Biomethane in Europe and in Spain*, 2022, **https://trovanttech.com/2022-biometano/**.
63 Naturgy, *Biogas and biomethane as a key lever in the decarbonization of the Spanish economy*, 2022, p. 92, **https://www.fundacionnaturgy.org/en/producto/biogas-and-biomethane-as-a-key-lever-in-the-decarbonization-of-the-spanish-economy**, accessed May 2023.
64 Madrid Council, *Valdemingómez Technology Park. Report 2019, Madrid Environment and Mobility*, 2019, p. 100.
65 Naturgy, *Renewable gas. The circular energy of the present for a decarbonized future*, 2021, p. 5, **https://www.naturgy.com/en/about-us-naturgy/the-energy/gas/renewable-gas**, accessed May 2023.
66 *Gas Renovable*, **https://www.gasrenovable.org/proyectos/biometano/**, last access on 11 april 2022.
67 GASNAM, *Map of biomethane production plants*, 2023, **https://gasnam.es/terrestre/mapa-de-plantas-de-produccion-de-biometano**, last access on 24 March 2023.
68 OTLE, *2020 Annual Report. Ministry of Transport, Mobility, and the Urban Agenda*, 2021, p. 279, **https://**

observatoriotransporte.mitma.es/inform/es/2021//indice, accessed May 2023.

69 IDAE, 2020, https://www.idae.es/en/support-and-funding/lines-aid-investment-renewables-thermal-and-electrical-feder-funds, last access on 15 june 2022.

70 GASNAM, *Map of biomethane production plants*, 2023, https://gasnam.es/mapa-estaciones-gas-natural-hidrogeno/, last access on 24 March 2023.

71 SEDIGAS, *Renewable gas development plan. Roadmap to 2030*, 2018, p. 40, https://www.sedigas.es/dochome/PNGR_v1.pdf, accessed May 2023.