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Abstract

The future European "Green Deal" will set ambitious greenhouse gas emissions reduction by 2030. Reaching these targets will partly rely on the decarbonization of the gas sector and the development of the biomethane. In this context, this article aims to provide a vision of the European biogas sector development from 2020 towards 2030 and beyond. It appears that the biogas sector is facing a shift in its development paradigm. Indeed, this sector is still mainly dominated by a model based on energy crops, high feed-in tariffs and local electrical production via combined heat and power units. However, biogas sector is now moving towards a different model, where organic wastes, agricultural by-products as well as sequential crops are mainly used as feedstocks, biogas is upgraded to biomethane for various applications (transportation, chemical production, heat, etc.) and subsidy schemes are progressively reduced. Overall, current European policies are pushing the sector to increase its sustainability and to reduce biogas production costs. To answer these challenges, the main improvement tracks are identified and discussed. In the future, it is believed that

the biogas sector should address these aspects to ensure its growth towards 2030 and beyond.

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) Special Report *Global Warming of 1.5°C*, the world needs to limit the rise in global temperatures to 1.5°C to avoid unacceptable consequences on ecosystems and populations. This objective is still doable but it means reaching worldwide net-zero emissions by 2050 and implies a quick, strong and long-term international climate action (IPCC, 2018). The Paris agreement adopted in 2015 by 195 countries and its rulebook decided in the COP24, early 2019, are the first steps towards a global energy transition. In the wake of the IPCC Special Report, the European Union (EU) presented its strategic long-term vision to reach a climate-neutral Europe by 2050, in which the EU expresses its willingness to be a global leader in the fight against climate change and to be among the first to reach net-zero greenhouse gases (GHG) emissions by 2050 (European Commission, 2018). The European "Green Deal", recently announced by the European Commission President Ursula von der Leyen, aims GHG emissions reduction of at least 50% by 2030 in comparison to 1990. To reach this target, further decarbonization of the energy system will be essential (European Commission, 2019a).

To reach such targets, recent scenarios agreed on the fact that renewable electricity will be essential to fully decarbonize the energy system. Thus, it is forecasted that the share of electricity in final energy demand will at least double (European Commission, 2018). Renewable electrical production will increase mainly relying on a strong growth in the number of solar as well as on-shore and off-shore wind facilities (EURELECTRIC, 2018). However, for Dr. Klaus-Dieter Borchardt, Europe's Director of the Internal Energy Market

Integration, pathways towards a decarbonized economy only relying on renewable electricity will not be cost-effective and will be technologically impossible mainly due to its storage issue using batteries (Florence School of Regulation, 2019). The optimum solution may lie in a “dual” gas-power network (Bowden, 2019).Indeed, according to Dr. Borchardt : “Gas infrastructure should become the batteries of the future European energy system”(Brun, 2018). The link between the power and gas networks will be ensured by the emerging power-to-gas technologies. They allow converting renewable electricity via an electrolysis process to hydrogen, a high gravimetric energy density carrier, which can be stored, directly used as a fuel (Gür, 2018). Hydrogen can even be further converted through a methanation process into methane, that can be injected and stored on natural gas grid (Götz et al., 2016). As current high cost for these technologies should be reduced in the future, they are expected to become one of the best options for long-term electricity storage (Thema et al., 2019). It could allow decarbonization of sectors that would be hard to electrify such as long-distance heavy transportation or industrial processes using high-temperature heat (Gas for Climate, 2019a).

Integration and decarbonization of the gas sector are currently at the top of the political agenda in Brussels with notably the preparation of the “gas decarbonization package” (Euractive, 2019). This package should set, by the end of 2020 or early 2021, a clear vision on the role of gas up to 2050. It is notably expected to propose a framework (e.g. targets, certificate, etc.) for a “green” gas (Olczak and Piebalgs, 2019). Developments of hydrogen, biomethane and syngas production through power-to-gas, anaerobic digestion (AD) and gasification as well as Carbon Capture & Storage (CCS) are envisioned as decarbonization vectors of the gas sector (Gas for Climate, 2019b).

Power-to-gas (Thema et al., 2019), CCS (Reiner, 2016) and gasification (Sansaniwal et al., 2017) sectors are still in early stage development, while anaerobic digestion is currently most advanced in terms of industrialization (Scarlat et al., 2018a). AD consists in a biological process that allows the conversion of organic matter/waste into biogas (a mix of methane and carbon dioxide). In Europe, AD industrial development is historically based on power generation from biogas trough combined heat and power (CHP) units. After a quick growth up to 2015, the sector has slowed down and is currently at a turning point in its history. Indeed, biomethane recovery through biogas upgrading technologies (splitting biogas into biomethane and carbon dioxide gas streams) and its subsequent broader end-use applications can be envisioned as the next growth driver for the sector. At the end of 2018, annual production of biomethane from AD in the EU corresponded to 2.3 billion (10^9) m^3 (EBA, 2019). By 2050, combining realistic manure biomethane potential (Scarlat et al., 2018b) and methane potentials of other feedstocks provided in the Gas for Climate study (Gas for Climate, 2019a), it can be estimated that it could reach 64.2 billion m^3 in the case of an optimized gas scenario. If integration of the gas sector into the EU decarbonization strategy is validated, AD will continue to grow, but it is clear that the sector should undergo a strong shift in its development paradigm.

The aim of this article is to provide a vision of the European biogas sector development from 2020 towards 2030 and beyond. This vision is based on the identification of (i) the main current market trends and sector challenges from an overview of biogas sector past development and current situation in some representative European countries; (ii) the potential improvement tracks that tackle these challenges and may allow biogas sector a sustainable growth.

2. Methods

This paper is the result of a literature review. In order to provide to the reader a synthetic vision on the topic only scientific articles, reports and web pages that were identified as particularly relevant for understanding the recent evolution of the biogas sector were selected. Additionally, five European countries, presented thereafter, were selected as support cases for this paper. Search was performed using Google, Web of science, Google Scholar and Science Direct. A combination of the following search terms were used to find the selected articles: “anaerobic digestion”, “bioenergy”, “biogas”, “biorefinery”, “biomethane”, “climate”, “digestate”, “digester”, “energy”, “Europe”, “European Union”, “feedstock”, “gas”, “greenhouse gases”, “sequential crops”, “life-cycle analysis”, “manure”, “mixing”, “monitoring”, “nutrient”, “perspectives”, “pilot”, “plant”, “policies”, “power”, “pretreatment”, “renewable”, “review”, “socio-economic”, “storage”, “strategy”, “techno-economic”, “upgrading”. The names of the selected countries were also included in the search terms. The three following precepts were applied:

(i) Scientific papers published in peer-reviewed journals in English language and reports published in English and French languages from recognized organizations were selected for this review.

(ii) A particular attention was dedicated to identify and select works for the relevance of their data (notably for sector/techno-economic reports), for the quality of the analysis and insights provided (notably for the reviews), or for the identified high potential of the presented practices/technologies (in the case of more technical scientific articles related to the anaerobic digestion).

(iii) Finally, a priority was given to most recent works. Thus, 85% of the literature provided in this review (93 references) was published between 2017 and 2020.

Besides, to draw lessons from European biogas sector recent development, while remaining synthetic, only five European countries with an existing biogas industry on their territory were selected. Selection criteria were not based on countries having the highest numbers of biogas plant or biogas production. Instead, they were based on diversity in terms of policies, historical and forecast developments both in biogas and biomethane in order to provide a representative vision of the current trends and challenges that exist in Europe. The selected countries are: Germany, as a pioneer and leader in biogas production performing mainly CHP valorization, Denmark and Sweden, as countries among the most advanced in biomethane development and finally, France and Italy, two of the most active European countries on the path of CHP valorization shift towards biomethane.

To support this choice and bring some comparison elements with others European countries, it can be added that: (i) situations in Austria and the Czech Republic are close to Germany state of affairs (Banja et al., 2019); (ii) United Kingdom and the Netherlands are already significant biomethane producers, with respectively 3.3 TWh and 2.2 TWh in 2018 (REGATRACE, 2020). They should continue to develop this sector, similarly to France, for heating & cooling and transportation applications (Schmid et al., 2019). However, contrary to France, current lack of biomethane targets in these countries should make the development pace less dynamic; (iii) Switzerland, Poland, Finland, Republic of Ireland, Spain and Belgium are in early stages of biomethane development. Support systems as well as targets in their legislation for 2030 are still being defined, therefore envisioned biomethane strategy remains for the moment unclear (REGATRACE, 2020).

3. Lessons from European biogas sector development and current situation

3.1. The European biogas production

Over the last 20 years, biogas production worldwide from AD has experienced a strong growth. Between 2000 and 2017, global biogas production was more than quadrupled, from 78 to 364 TWh, which corresponds to a global yearly volume of 61 billion m^3 biogas: it is shared mainly between Europe (54%), Asia (31%) and Americas (14%) (WBA, 2019). Biogas production and its utilization display great disparities between developing and developed countries. For the former, biogas is mainly produced from small-scale low-tech household plants in order to provide gas for cooking and lighting and reduce firewood consumption (Mccabe and Schmidt, 2018). While, for the latter biogas is produced from large scale automated and monitored plants and valorized under the form of electricity or biomethane, which are generally injected in national grids (Vasco-Correa et al., 2018). With 18,202 biogas plants (EBA, 2019) and 12.6 GW installed in 2018, Europe is the world leader in biogas electricity production, far ahead the USA (2.4 GW) and China (0.6 GW) (IRENA, 2019). European biogas electricity production represents 68% of the global electricity capacity from biogas plants estimated at 18.1 GW. This last value represents only 0.7% share of the worldwide renewable electricity production (2,351 GW) mainly dominated by hydropower (52%), onshore wind (23%) and solar (20%), as represented in **Fig. 1** (IRENA, 2019).

In 2018 in the EU, it can be estimated that about 88.5% of the biogas is valorized directly on-site, through CHP units (total primary energy production from biogas was 192 TWh and biomethane upgrading capacity was 22 TWh)(EurObserv'ER, 2019). This is the result of energy policies, set between 2000 and 2015, from several state members based on subsidies incentives for this technology (Vasco-Correa et al., 2018). However, the recent decline in subsidy levels can explain the slowdown of the biogas industry in the last few years (EurObserv'ER, 2018). To better understand the possible future of AD in the EU and current market driving trends, it is relevant to look at its recent history in some European countries.

Figure 1: Worldwide renewable electricity capacity and share of biogas sector in 2018 (IRENA, 2019)

3.2. Market driving trends and challenges in the biogas sector from relevant European countries

Germany, the European biogas leader with 9,500 biogas plants at the end of 2018, has built its biogas sector on the basis of the Renewable Energies Act that started in 2000 (EBA, 2019). This act forced energy supply companies to buy electricity generated from renewable sources at guaranteed feed-in tariffs (FIT) over a period of 20 years. Combined with strong incentives in 2004 and 2009 for energy crops cultivation, the biogas industry boomed between 2000 and 2012. It was mainly technologically based on a "standard" wet digestion, i.e. continuously stirred tank reactor (CSTR), plant using energy crops (especially maize) coupled with cattle slurry that allows ensuring high and resilient biogas production valorized via a CHP unit (Theuerl et al., 2019). From this industry scheme, several drawbacks have been pointed out:

(i) The extensive use of energy crops has led to the "maizification" phenomenon. It corresponds to the wide spreading of maize monoculture over 2.1 million ha with inherent adverse side effects such as nitrate leaching, soil degradation, pesticide use, increased pressure of soil-borne diseases and weed problems, low biodiversity and high water consumption (Markard et al., 2016). This phenomenon diminished beneficial environmental impact of biogas production as well as public acceptance of the technology and created agricultural distortions such as the increase of land rental prices, the increase of energy crops prices (also used for cattle feeding) and therefore the difficulty for smaller farms or biogas exploitations to thrive (Appel et al., 2015).

(ii) Electricity production cost from biogas remains high in comparison to other types of renewable energies. Indeed, solar photovoltaics (PV) and onshore wind have known since 2010 a strong diminution in their leveled cost of electricity (LCOE) that may reach by 2020 respectively 0.06 and 0.05 USD per kWh, while biogas LCOE has remained quite constant over time close to 0.08-0.09 USD per kWh (IRENA, 2018);

(iii) A lack of efficient utilization of the heat produced from the CHP as local heat sink is missing, especially in rural areas. It was thus estimated that at least a third of the biogas produced was subject to such lack of heat recovery (Strauch et al., 2013). This is strongly impacting CHP valorization efficiency (Pöschl et al., 2010) and biogas plant economic viability (Lantz, 2012). Besides, this reduces its interest over biogas upgrading valorization to biomethane (Lee, 2017).

These drawbacks have led to regulatory changes for new biogas plants since 2012. Energy crops intake is limited (the maize-cap), FIT progressively reduced and replaced (except for small biogas plants below 150 kW) in 2017 by auctions (Theuerl et al., 2019). The aim was to control sector development following a "deployment corridor" set at 150 MW annually from 2017-2019 and 200 MW annually from 2020-2022 and only allow construction of the most economically competitive plants that are generally the larger ones (> 1 MW) (IEA, 2020). All these shifts have led to cease the growth of the biogas sector and auctions in 2017 and 2018 did not reach the targeted power set by the German government (only 76.5 MW in 2018)

(Tsanova, 2018). This is the proof that electricity production from biogas is suffering competition notably from solar PV (Hill, 2019). Even flexible biogas plants, using specific equipment (storage facilities, larger generators) that enable them to provide their electricity production offset from wind and solar production, have seen their premium FIT, initially set in 2012, gradually decline, so that today the concept of producing power from biogas flexibly is no longer economically viable (Lauven et al., 2019). By 2020, biogas plants commissioned in 2000 will be the first to see their guaranteed FIT expired and the question of plant shutdown will be raised if no new policy for biogas power generation is undertaken soon (Theuerl et al., 2019).

Biogas upgrading to biomethane has been identified as a good alternative to power and heat generation as it can be stored in the natural gas grid. It can then be used for clean transportation or in urban CHP units, where heat is efficiently valorized (Scarlat et al., 2018a). While the biomethane sector remains minor in Germany and has stalled at around 200 biogas plants since the deletion of the biomethane upgrading bonus in 2014, other EU state members have already based their biogas strategy on biomethane instead of power generation (Eyl-Mazzega and Mathieu, 2019). **Table 1** displays a short summary of current situations and applied biogas policies in Germany and countries that are now favoring biomethane.

Table 1: Biogas sector and applied biogas policies in selected European countries

As previously given, in 2018, biomethane contributed to only 11.5% of generated energy from biogas in the EU (EurObserv'ER, 2019). This is because the sector started its expansion later than power generation, due to a lack of associated subsidies and a higher cost for upgrading units than CHP units, especially for small plants (Kampman et al., 2016). However, between 2011 and 2019 the number of plants in the EU has more than tripled going from 187 to more than 660 mainly due to the implementation of incentive policies in several state members (EBA, 2019). Historically Sweden and more recently Denmark have been leaders in the development of the biomethane sector.

Sweden has developed biomethane mainly for the transport sector via a network of filling stations as there is no comprehensive gas grid infrastructure in the country. In 2016, 64% of the 2 TWh annual biogas production were used in transportation under the form of compressed or liquefied biomethane provided to a fleet of 55,000 gas vehicles (Sverige Energigas, 2018). Instead of applying FIT, Sweden has historically supported biomethane for transportation via investment grants and exemptions from fuel taxes that make the sector competitive against gasoline and diesel (Larsson et al., 2016). These funding plans are running until 2020, but the Swedish government, despite the new climate policy framework that aims to achieve a 70 percent reduction in emissions from transport by 2030, is still unclear on how the support system will evolve. A proposal for the biogas production goal for 2030 was recently submitted to the Swedish government with an objective set at 10 TWh (Westlund et al., 2019). To reach this objective it is proposed a prolongation of the tax exemption system and notably the introduction of feed-in-premiums for biomethane upgrading/liquefaction. This would resume biogas sector growth in Sweden, however, at that moment, adoption of this proposal by the government remains to be done.

Denmark has a much more developed gas network and had mainly based its strategy on injecting biomethane into the grid that is subsequently used in town-located CHP with district heating systems. The sector has boomed between 2014 and 2018 due to the introduction of 20-year Feed-in premiums for biomethane injection. Annual biomethane capacity has bounced from almost zero in 2014 to 2.7 TWh and now accounts for more than 10% of volumes transported in the natural gas grid (Eyl-Mazzega and Mathieu, 2019). However, this has been accompanied by a massive increase in subsidies granted that reached 215 million euros in 2017. Therefore, a new subsidy scheme part of the Energy Agreement has been adopted in 2018. It will start in 2021 and is based on a yearly 32 million euros pool that will be assigned to new projects in tenders with price ceilings (Ministry of Climate Energy and Utilities, 2018). Danish biomethane sector growth potential will thus be limited from 2020, similarly to the “deployment corridor” in Germany.

In France, future energy policies may also challenge and contain biomethane sector development. Until now, biomethane has known a strong rise with 107 operating plants mid 2019 (+143% increase versus 2017) due to FIT introduced in 2014 (SDES, 2020). The plants are mainly connected to the gas grid and produce a yearly 1.3 TWh in 2018 (Sia Partners - Energy Lab, 2019). Besides, national studies from ADEME (ADEME, 2018) and the négaWatt association (Association Négawatt, 2017) demonstrated, in several scenarios, the future importance of anaerobic digestion and biomethane to reach both neutral emissions by 2050 and a 100% renewable gas system. However, the recent adoption of the Energy Strategy Plan for 2030 (Programmation Pluriannuelle de l’Énergie also called PPE) has lowered in its main scenario the initial target set to only 7% (14 TWh injected) of biomethane in total gas demand (instead of 10%), has introduced yearly auctions of 700 GWh and has sharply decreased FIT to be implemented in 2023 and 2028. For instance, FIT of an agricultural plant injecting 200 Nm^3/h, will be reduced by 40% in 2028 (from a current average of 102€/MWh to an average of 60€/MWh) and even more for smaller capacity plants. A second scenario is envisioned, where injected biomethane could reach 10% in total gas demand (22 TWh injected) at condition that biogas sector decrease even further its cost production. All of these aspects call for both a limited growth of the sector and a necessary decrease of the biomethane production cost (Ministère de la transition écologique et solidaire, 2020). Potential positive externalities of anaerobic digestion (**Fig. 2**), which are estimated to represent an additional value comprised between 55 and 75€ per MWh produced in 2030, were not taken into account by the French government despite lobbying of biomethane sector on these points (Enea Consulting, 2019). However, these positive externalities may be considered to a greater extent in other European countries.

Figure 2: Identified positive externalities of the development of the biomethane sector (Enea Consulting, 2019)

Finally, Italy is currently the European country that shows the most willingness to develop biomethane. Historically, Italy has developed its biogas sector similarly to Germany. Strong incentives between 2008 and 2012 for biogas CHP valorization (highest FIT in Europe – 280 €/MWh for plants below 1 MW) allowed a quick development of the sector notably based on energy crops. However, revisions of the subsidy scheme in 2013 (lower FIT and incitation to use by-products instead of energy crops) had slowed down the sector growth. By the end of 2017, 1,655 biogas plants were identified in Italy and only one was producing biomethane (Eyl-Mazzega and Mathieu, 2019). This reflects a gap in biomethane legislation that has recently been filled. In March 2018, the Biomethane Decree was adopted. It aims to support biomethane and advanced biofuel development for the transportation sector. It corresponds to a fund of 4.7 billion euros provided by transport fuel suppliers that need to meet increasing biofuel blending obligation (quota system). This fund allocated between 2018 and 2022 should cover the development of the biomethane sector (plants and infrastructure such as filling stations) up to 1.1 billion m^3/year (D'Adamo et al., 2019). Incentives consist in a minimum income for biomethane production that can vary as a function of the type and amount of feedstocks used. The highest income is offered to advanced biomethane that can be obtained from specific types of biomass (manure, sequential crops, agricultural by-products, organic fraction of municipality solid waste). Interestingly, former biogas plants performing CHP valorization can take advantage of this new subsidy scheme to shift towards injection. On that point, a recent study has shown that incentives from the Biomethane Decree are making investment in upgrading technologies profitable for existing biogas plants (investment payback time would range between 3 and 6 years), while it would have not been the case without (Barbera et al., 2019). Early 2019, already 168 requests, corresponding to a potential of 1 billion m^3/year biomethane, have been formalized by SNAM (Italian gas grid operator) and several new biomethane plants started to operate (about ten) (Eyl-Mazzega and Mathieu, 2019). The rapid growth of biomethane for transportation in Italy will pave the way for biomethane use in other sectors notably through the establishment and development of guarantees of origin for injected biomethane.

What emerges from Sweden, Denmark, France and Italy strategies is that, as for power generation, biomethane upgrading is strongly dependent on subsidies as production cost remains high and makes it currently approximately four times more expensive than natural gas (Eyl-Mazzega and Mathieu, 2019). A recent scenario with a moderate penetration of biomethane technology has estimated 2030 EU potential to reach 18 billion m^3 per year (~180 TWh/year), corresponding to 9 times 2017 production (Prussi et al., 2019). Achieving such an objective for the biomethane sector will depend on the energy market, supporting initiatives from state members, full demonstration of its positive environmental impacts (notably on agriculture), higher acceptation by local population, a better recognition of positive externalities and a reduction of biogas and biomethane production costs. Identified challenges for the biogas sector are gathered in **Table 2**.

Table 2: Identified challenges for the European biogas sector

4. Improvement tracks for the anaerobic digestion biogas sector

To answer the production cost challenge as well as to demonstrate its sustainability, the biogas sector will have to improve all the parts of the industrial value chain and potentially monetize co-benefits. These improvements will be important to make AD process a key technology in the future energy system and bio-based circular economy.

4.1. Biogas sector upstream

AD can treat numerous organic materials. Sewage sludge, food waste, organic fraction of municipal solid waste, unsorted municipal solid waste, industrial waste (e.g. from food industry), animal by-products and agricultural feedstocks are the main groups of feedstocks that can be transformed into biogas. It is important to underline that the AD process is unable to convert woody biomass consisting of lignocellulose, as it is a very dry and insoluble organic matter and that lignin molecules cannot be degraded by microorganisms forming AD consortia. Gasification process would thus be preferred for such types of feedstocks.

In 2018, based on the primary energy production from biogas in the EU (EurObserv'ER, 2019), Europe biogas production share by feedstock (IEA, 2020) and average substrate mix for biogas production in the different European countries (Bahrs and Angenendt, 2019), it can be estimated that energy crops are still the dominant feedstock used (around 35-38% of the net primary energy produced from the EU biogas), in front of livestock manure (33%), municipal solid waste (17%), agricultural residues as well as sequential crops (around 6-9%) and sewage (6%) . Such shares can be mainly explained by the weight of the German biogas sector at European scale and the remaining high use of energy crops in this country (50% of total feedstocks mass in 2018) (EBA, 2019).

In the case of an optimized development scenario of the sector, by combining realistic manure biomethane potential (Scarlat et al., 2018b) and biomethane potentials of other feedsteocks provided in the Gas for Climate study (Gas for Climate, 2019a), biomethane that could be produced via AD from organic materials could reach 64.2 billion m^3 in the EU by 2050. Assuming that roughly, 1 Nm^3 biomethane is equivalent to 10 kWh, this would represent an energetic potential of approximately 640 TWh/year and would require a 30-time growth of the current biomethane sector (22 TWh/year). When compared to the 2017 final energetic consumption of EU-28 members of 13,421 TWh/year forecasted biomethane production would represent 4.8% of this energetic consumption (European Commission, 2019b). This percentage illustrates that development of biomethane from AD represents only a small fraction of the total effort required to reach carbon neutrality by 2050. In the Green Deal, increase in energy efficiency, better energy and transport infrastructure, development of renewables in the power sector, additional transformation in the gas sector (power to gas, CCS, syngas) and development of a circular economy notably for consumer goods are envisioned to be the other pillars to reach this objective (European Commission, 2019a).

Among organic materials, agricultural feedstocks, that are already dominating the biogas production (above 70% of the biogas energy share), are the largest deposit available in the future. Therefore, the market for biomethane plants using these feedstocks has the highest potential growth. As depicted in **Fig. 3**, it was estimated that agricultural feedstocks, in case of optimized development of the AD sector, have a potential in the EU of 62 billion m^3 biomethane produced annually by 2050, thirty times higher than potential from food waste or sludge (2.2 billion m^3). It is estimated that 1,200 million tons (wet weight) of livestock manure are produced every year in the EU and 860 million tons (wet weight) could be collected. From that, a biomethane potential in the EU from manure was assessed at 16 billion m^3 per year (Scarlat et al., 2018b). Crop related feedstocks have an estimated potential of 46 billion m^3 of biomethane per year by 2050. Due to their low sustainability, energy crops are envisioned to be progressively replaced by sequential crops (147 million tons in 2050 to produce 41 billion m^3 of biomethane) and crop residues (30 million tons in 2050 to produce 5 billion m^3 of biomethane) as agricultural practice should evolve concomitantly with the biogas sector growth (Gas for Climate, 2019a).

Figure 3: Share of feedstocks in an optimized scenario for biomethane production in the EU in 2050

Indeed, life-cycle analysis studies on GHG emissions from agricultural biogas plants, despite various methodologies and systems (feedstocks/region), have made analogous conclusions on the most sustainable practices (Ingrao et al., 2019). Here are some of the most important points:

(i) Plants using energy crops are producing biogas with the highest GHG emissions, notably due to their competition with feed production and the phenomenon of indirect land-use change (iLUC) that adds up the carbon footprint of the displaced food production (Hijazi et al., 2016).

(ii) Negative GHG emissions are mainly driven by avoided emissions from livestock manure or other by-products/residues that would instead decay and release GHGs into the atmosphere without delivering any energy services (Bartoli et al., 2019).

(iii) Sequential cropping developed with the Biogasdoneright™ practice can solve energy crop issues and allow additional agricultural benefits (Dale et al., 2016). It consists, for a given agricultural land, to produce two crops within one year instead of only one. Indeed, the main crop occupies soil only a fraction of the year, leaving in conventional practice, the soil uncovered the rest of the year. In this remaining time slot, the newly cultivated and harvested crop is called sequential crop (or also catch crop/intermediate crop). Higher carbon soil sequestration due to continuous soil coverage as well as additional biomass produced and left in the field (roots and residues), soil protection against erosion and lower nutrients leaching are the main advantages of this practice (Valli et al., 2017). It can be added that to even further increase the sustainability of this practice, similarly to other biomass used for energy purpose, the use of fertilizer produced from petrochemical sources should be reduced as much as possible (Sherwood, 2020). Therefore, additional good practices can be applied for this purpose such as optimized soil preparation (with minimum tillage, direct seeding on previous culture residues), finer dosing in time, space and quantity of digestate and fertilizer (precision farming, fertigation) or increase use of leguminous crops to fix additional nitrogen (Pellerin et al., 2013).

From these observations, upstream enhancements will be based on using local, sustainable and low-cost organic residues combined with improved logistics. Sequential crops, manure, residues from landscape management such as grass (Bedoić et al., 2019), perennial crops cultivated on marginal agricultural lands (Von Cossel et al., 2019), agricultural lignocellulosic residues (straw, etc.), as well as food waste are envisioned to be increasingly used (Gas for Climate, 2019a). From these feedstocks, GHG neutral to negative biogas can be produced but it also implies that anaerobic co-digestion will be increasingly used in the future.

4.2. Anaerobic digestion process

Mastering anaerobic digestion process will be necessary to reduce operational costs and maximize gas incomes. This will be possible via better management of the preparation, the co-digestion and the digestion completion steps that will allow to recover most of the methane from a wide variety of feedstocks:

(i) The preparation step will firstly rely on an efficient storage when feedstocks are not directly anaerobically digested to preserve over time the methane potential of feedstocks (Peyrelasse et al., 2017). This is notably based for agricultural feedstocks on optimized ensiling strategies and livestock manure storage practices. Secondly, on the application of additional adequate pretreatments (mechanical, thermal, chemical, biological) to fully unlock the methane potential of feedstocks (Carrere et al., 2016). It is important to highlight that adequate pretreatment will vary from a feedstock to another and there is not an optimal solution that will suit best for all feedstocks.

(ii) The anaerobic co-digestion process has inherent positive aspects such as the use of low-cost/waste feedstocks or the potential synergies between feedstocks (e.g. adjustment of C/N ratio, inflow of nutrients and water that would be missing in some feedstocks, etc.) that can occur during AD and increase biogas recovery, but also some technological issues coming from a higher AD process complexity (Hagos et al., 2017). To handle this complexity, better and cheaper monitoring based on modelling and finer understanding of the process will be required to avoid operational issues and to develop optimal strategies to recover most of the methane from feedstocks (e.g. optimized feedstocks supply) (Wu et al., 2019). The use of chemical or biological additives to improve AD performance (Romero-Güiza et al., 2016) and the reduction of biogas plant operational expenditure, based for instance on the optimization of mixing strategy (Singh et al., 2019), are two other key axes of improvement. Finally, regular leakage control surveys on digesters and the use of a flare to avoid methane discharge in some particular occasions (for instance maintenance) are required to ensure high sustainability of the AD process (Liebetrau et al., 2017).

(iii) The digestion completion step, which consists in a proper digestate management, is very important to reduce uncontrolled methane, carbon dioxide and nitrogen emissions and increase biogas plant efficiency (Lijó et al., 2017). Strategies to handle optimally solid and liquid digestates have to be determined. For instance, coverage and heating of storage tank containing liquid digestate (Bacenetti et al., 2016), further energy recovery from solid digestate via various post-treatment (Monlau et al., 2015), were identified as potential good practices.

Combination of these three steps, described in **Fig. 4**, should lead to high methane recovery from co-digested feedstocks, increase biogas plant sustainability (reduced GHG emission from digestate) and potentially decrease biogas production costs, as long as each step remains cost-effective. Development and wider adoption of these AD process optimization strategies at full scale are expected in the future as the biogas sector is gaining in theoretical and practical know-how.

Figure 4: Main stages of an optimized anaerobic co-digestion process

Finally, the possible side recovery of biohydrogen and biochemicals from the AD process such as acids or alcohols, which have a higher added value than biogas, is a very interesting track to enhance the profitability of biogas plants (Moscoviz et al., 2018). This might be possible in the future by coupling AD to other existing technologies such as dark fermentation (Bundhoo, 2017), electrochemical systems (De Vrieze et al., 2018) or membrane separation and solvent extraction systems (Aghapour Aktij et al., 2020). Their implementation will rely on feedstock features (for instance solids content, acid concentrations), on profitable operation and on the mastery of higher processes complexity. Currently, all these kinds of couplings are still in their early stages of development and further improvement, scale up or finer economic studies are required to fully validate their interest for large-scale applications.

4.3. Biogas sector downstream

Downstream processes are also likely to experience great changes that should provide additional revenues to the sector. The current lack of specific legal framing for digestate use is placing it into the “waste” classification, which is rendering its commercialization difficult (Guilayn et al., 2019). Adequate legislation, as well as an enhancement in digestate post-treatment (dewatering, nitrogen or phosphorus recovery, etc.), may procure additional revenues from its commercialization and/or extraction of its by-products (Vaneeckhaute et al., 2017). On this point, a decision-support guide was created that can help biogas plant operators aiming to implement N & P recovery strategies. Based on local fertilizer demands/constrains and digestate features an adequate and optimized recovery strategy can be determined (Vaneeckhaute et al., 2018).

Concerning biogas valorization, several tracks are foresighted. The number of local CHP with no or low heat valorization should be progressively reduced as they are too strongly dependent on subsidies. Instead, large-scale biogas plants that perform upgrading to biomethane should develop, especially in countries that are highly relying on natural gas imports. For smaller or remote biogas plants without a close gas grid access, mobile upgrading and storage systems (Gil-Carrera et al., 2019) or small-scale bio-liquefied natural gas (bio-LNG) units (Baccioli et al., 2018) were recently identified as potential alternatives. Biomethane obtained can be either used on-site in filling stations, similarly to Sweden, or injected into the grid. Grid connection can represent large investment costs, especially when a biogas plant is remote from the gas grid (190 € per meter of pipeline), and system for their coverage varies from a country to another (CEGIBAT, 2018). For instance, in Denmark, Italy or the UK, biomethane plant owners should entirely pay for it, while in France or Germany cost is shared with gas grid operators (REGATRACE, 2020). Once biomethane is injected, it can be stored and used at other points of the grid, thanks to guarantees of origins (also called biomethane certificates) which certify to the company/consumer buying it that the gas used from the grid corresponds to biomethane. Currently, each country has its own policy on the topic and cross-border trade are limited to some countries (for instance between Denmark and Sweden) (REGATRACE, 2020). However, European Gas package is likely to introduce a system of EU-wide certification or guarantees of origin for biomethane that would favor larger and easier cross-border trade (Olczak and Piebalgs, 2019).

In the future, biomethane could be used in combined cold, heat and power (CCHP) units to allow cold applications (Angenent et al., 2018), as a C1 carbon source to produce microbial proteins that could be used to feed animals and humans (Pikaar et al., 2017), or to produce biochemicals and fuels (Verbeeck et al., 2018). On this last aspect, a recent study has shown a promising way to produce biochemicals based on super-dry reforming (SDR). This process combines one molecule of biomethane with three CO_2 molecules produced from industry to form four CO molecules that can be further transformed into chemicals such as methanol. Additional carbon capture and its positive economics without subsidies, in the current context, make this solution particularly attractive. However, the bottleneck remains in the upscaling of the SDR process and more generally of CO_2 to CO technologies (Verbeeck et al., 2018). Finally, technologies that allow higher flexibility in biomethane injection on the gas grid are emerging, such as liquefaction storage (e.g., the LiliBox system by Azola) or backfeeding installations that make gas networks bidirectional (e.g., the West Grid Synergy project conducted by GRTgaz in France). These should enable biogas plant operators, in the future, to bypass network constraints and to perceive more interest towards the optimization of the whole chain of the biogas production process in order to increase plant efficiency as well as biogas production.

Second generation upgrading technologies are likely to bring additional economic benefits to the sector in the near future. They are represented in **Fig. 5** and can be defined as techniques valorizing and possibly trapping the CO_2 contained in the biogas (Villadsen et al., 2019). Biogas can be subject to high temperature catalytic reforming in order to produce syngas (Chen et al., 2017). From this syngas, hydrogen can be recovered (Hajjaji et al., 2016) or it can subsequently be used to synthesize liquid organic molecules (Hernández and Martín, 2016). Several types of biogas reforming strategies that convert CH_4 and CO_2 into CO and H_2 have been explored: dry reforming, dual reforming (addition of water) and tri-reforming (addition of water and oxygen) (Zhao et al., 2020). The last two processes would be preferred for subsequent synthesis of methanol or liquid fuel (for instance diesel fuel via Fischer-Tropsch process) as syngas obtained as a high H_2 to CO ratio (comprised between 1.1 and 2.7). Biogas reforming pathway is still in its early stage of development and its cost requires to be further reduced working notably on the improvement of catalysis (selectivity, lifespan), reduction of process temperature, and further synergy with syngas conversion technology (Zhao et al., 2020). Alternatively, biogas can be directly sent to a methanation process that uses hydrogen (green ideally) to produce additional methane. Catalytic methanation via the Sabatier reaction or biological upgrading via in-situ, ex-situ or hybrid strategies are the two existing processes (Angelidaki et al., 2018). The former process has notably been running for long-term operation (> 1000 hours) with promising results (no to low catalyst deactivation and outlet gas with 88-99% of CH_4) in two recent pilot studies using packed (Dannesboe et al., 2020) or fluidized bed reactors (Witte et al., 2019). Drivers for the development of methanation will be the improvement of process conversion efficiency and above all the price as well as the availability of hydrogen (Thema et al., 2019). Profitability and industrial development of such technologies will be dependent on cost reduction of electrolysis. Thus, looking at cost development scenarios for electrolysis, positive business cases for methanation technologies might not be expected before 2030 (Schulze et al., 2017). Finally, carbon dioxide can also be recovered at the outlet of the upgrading unit, after being separated from the biomethane, and used in the methanation process but also for greenhouse or microalgae cultivation enhancement (Theuerl et al., 2019); dry ice or chemical production (notably methanol, formic acid and longer chain hydrocarbons via catalytic hydrogenation) (Li et al., 2018); or food applications (carbonation of beverages, etc.) (Esposito et al., 2019).

Figure 5: Potential pathways for second generation biogas upgrading technologies – CO_2 valorization

5. Research and industrial outlooks

From this overview of the current situation in Europe and the full value chain of the biogas process, several outcomes can be perceived:

- Agricultural feedstocks will remain prominent in the future. Farming of sequential crops appears as a potential solution to conciliate food and energy production. However, it is important that their productions remain sustainable. Thus, further development should occur on the determination of appropriate local practices (varieties to be used, sowing and harvesting dates, fertilization), the diffusion of this practical knowledge within the agricultural community and the supervision to avoid deviations in their use (WWF France, 2020). Such an approach, federating farmers, agronomists, biogas stakeholders and governments are likely to be a long-term learning movement in Europe as anaerobic digestion and sequential cropping for energy production are relatively new concepts in most countries.
- Sustainability analysis (including LCA and social LCA) should continue to develop and be performed to fully support the ecological interest of the sector and identify best practices. Use of primary data (concerning for instance biomass cultivation practice or digestate emissions), reflecting specific local context, should be favored in the future to strengthen analysis reliability and allow comparison between different biogas systems (Ingrao et al., 2019).

- Pretreatments and additives are promising tracks to increase biogas plant energy efficiency. If well described in the literature, their impact on AD have been mainly evaluated using batch biomethane potential tests that have some limitations (Koch et al., 2020). For instance, observed increased in methane yield under batch conditions following a thermochemical pretreatment could not be observed under a long-term semi-continuous trial. This is likely due to the adaptation over time of the inoculum rendering the pretreatment inefficient (Janke et al., 2019). In parallel, direct scale-up to full scale might be difficult to evaluate as many parameters can vary at such process size (e.g. ration, maintenance). Thus, development of semi-continuous pilot studies (from several hundred litters to a few dozen cubic meters), where all parameters are controlled and monitored (feedstocks, pH, temperature, agitation, gas flows and potentially other parameters depending on the experiment specificity), would be valuable to clearly evaluate the most efficient solutions to improve methane yield and degradation kinetics of feedstocks. For instance, a recent study on a 1000 L pilot digester validated positive impact found at lab scale of biochar addition (15 g/L) on food waste AD (Zhang et al., 2020). Thus, average methane yield was increased by 37% following biochar addition. Besides, based on recent methodologies, environmental impact of these additional treatments should be better considered when evaluating them in the future (Fan et al., 2019). For a given AD system, optimal pretreatment or additive solution will be the one with the best trade-off in terms of cost and environmental performances.
- Existing and upcoming biogas and biomethane plants must be attentive to local opportunities to create additional revenue streams and territorial synergy. Thus, CO_2 sinks (e.g. greenhouse, factories) or potential markets for the valorization of

nutrients/biomolecules appear as potential tracks. Spreading of such strategies must go hand in hand with the improvement or upscaling of the associated technologies (e.g. CO_2 upgrading, nutrient recovery, biomolecule production).

- Regarding European countries with no to small biogas sector, political incentives will be key. Growth of a resilient biogas industry will be based on: i) Determination of national and territorial specificities in terms of biomass and organic waste production, product demand (biomethane, CO_2, nutrients, others) and existing infrastructure (e.g. gas grid); ii) Subsequent creation of adapted support systems at national scale that are well relayed by territorial authorities (Bourdin and Nadou, 2020); iii) Development of sustainable AD systems with high local acceptance (based on technical and social feedbacks from more advanced countries on the topic). European union next steps forward, with the “gas package”, may trigger sector development in these countries.

6. Conclusions

Current market trends show that the European AD sector is undergoing a change from a model still dominated by energy crops and local electrical production via combined heat and power units towards a model where organic wastes, agricultural by-products as well as sequential crops are mainly used as feedstocks and biogas is upgraded to biomethane for various applications (transportation, chemical production, heat, etc.). Current main challenges for the sector are: (i) to decrease biogas production costs as the golden era of high feed-in tariffs for biogas production appears to be over. Instead, observed trends in biogas policies are regulation of sector deployment and progressive reduction of subsidy schemes; (ii) to increase AD process sustainability and associated agricultural practices. To tackle these challenges, the following tracks were notably identified: (i) using cheaper and more sustainable feedstocks; (ii) improving efficiency of the AD co-digestion process and the upgrading step; (iii) developing additional sources of revenues (commercialization of digestate/nutrients/biomolecules, CO2 valorization, monetization of co-benefits, etc.); (iv) identifying and diffusing good agricultural practices concerning sequential crops cultivation and digestate management. In the coming decade, research, industries and farmers need to focus on these improvement tracks to increase biogas economic competitiveness and ensure sustainable development of the European AD sector in the long-term.

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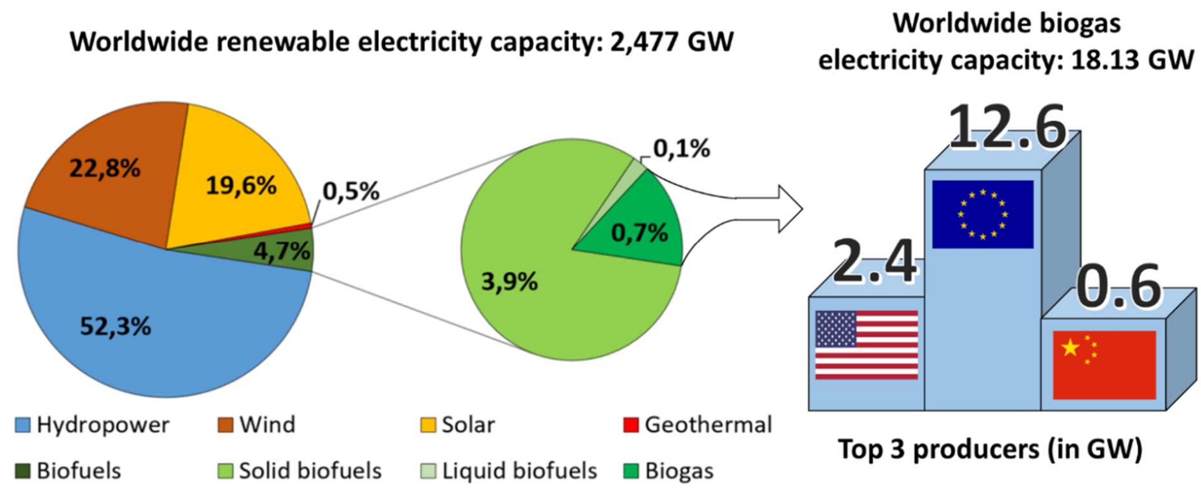


Figure 1: Worldwide renewable electricity capacity and share of biogas sector in 2018 (IRENA, 2019)

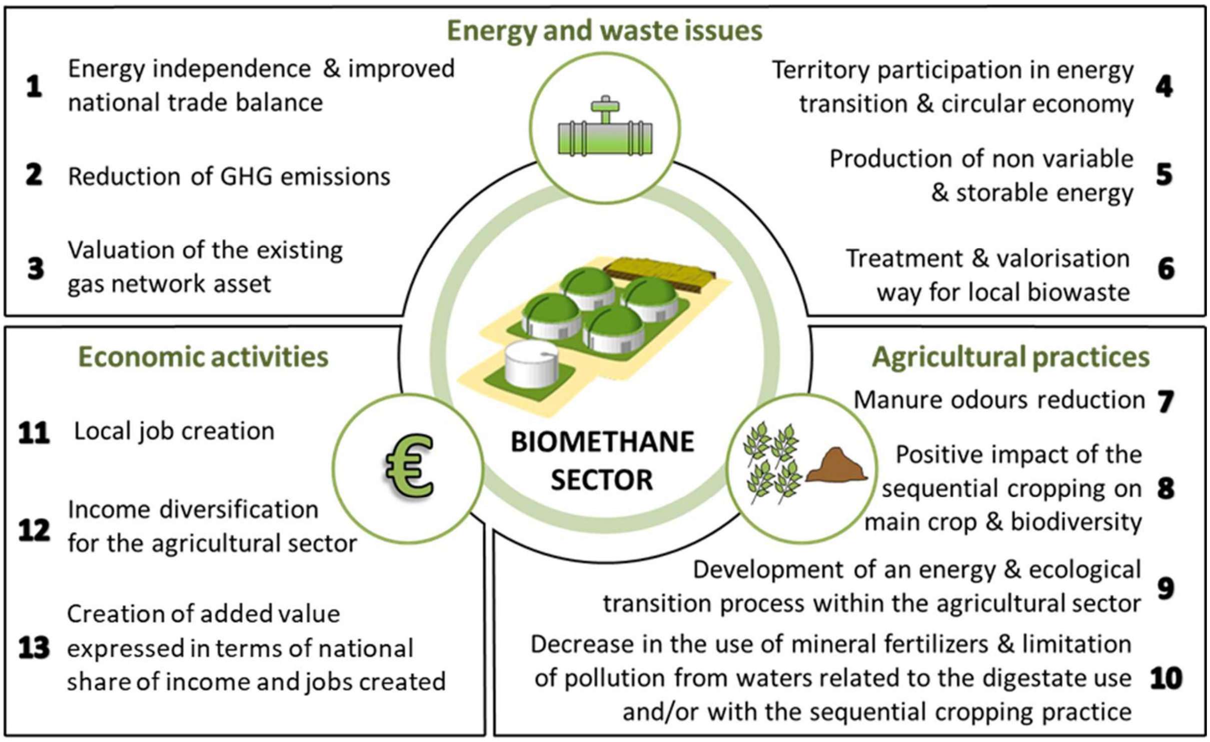


Figure 2: Identified positive externalities of the development of the biomethane sector (Enea Consulting, 2019)

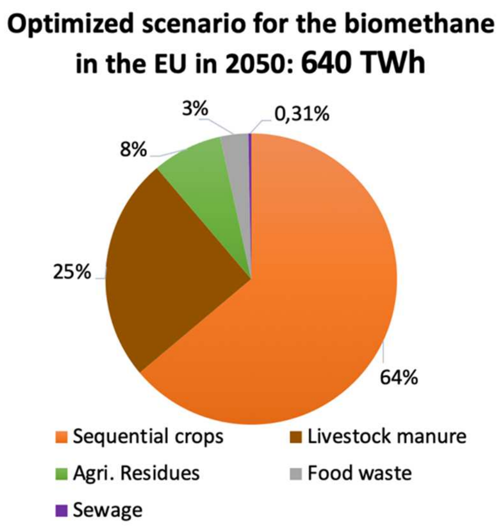


Figure 3: Share of feedstocks in an optimized scenario for biomethane production in the EU in 2050

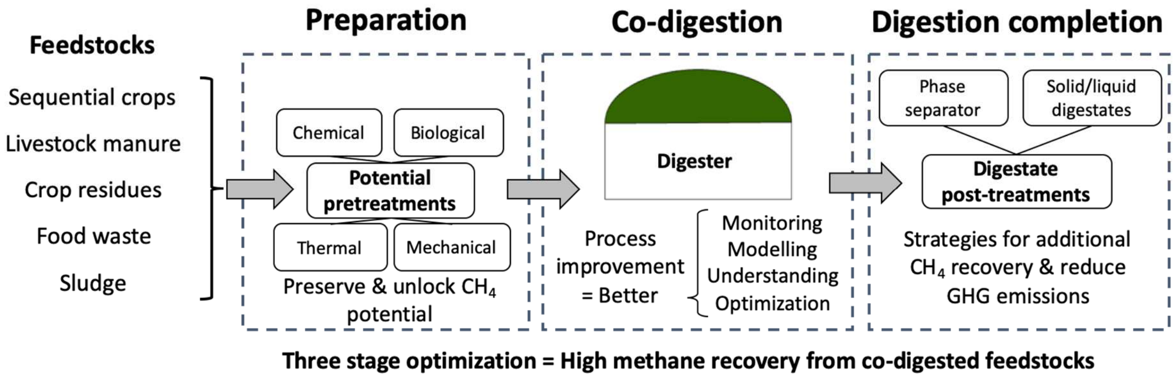


Figure 4: Main stages of an optimized anaerobic co-digestion process

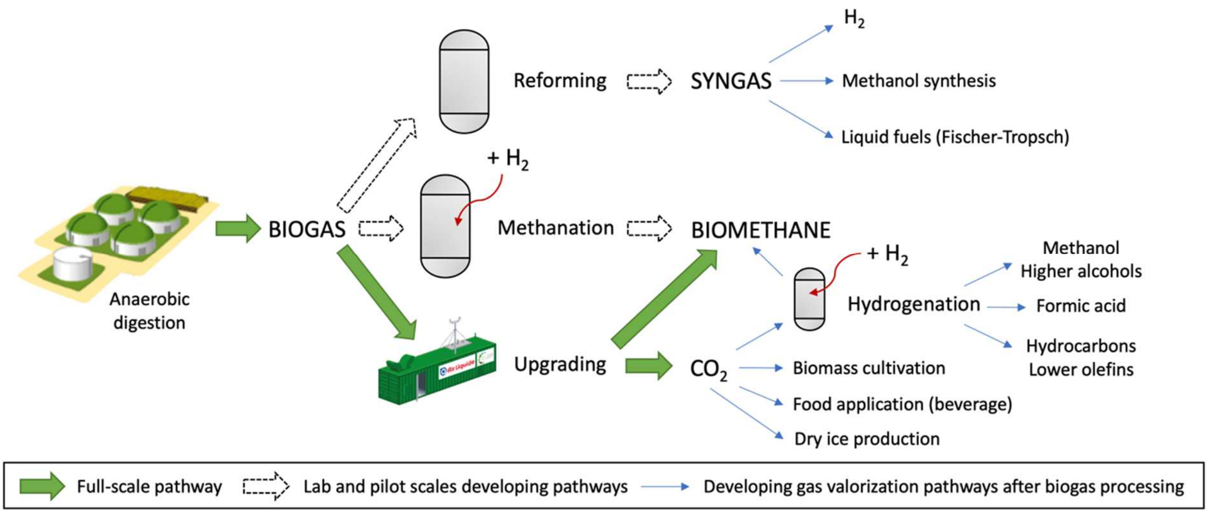


Figure 5: Potential pathways for second generation biogas upgrading technologies – CO_2 valorization

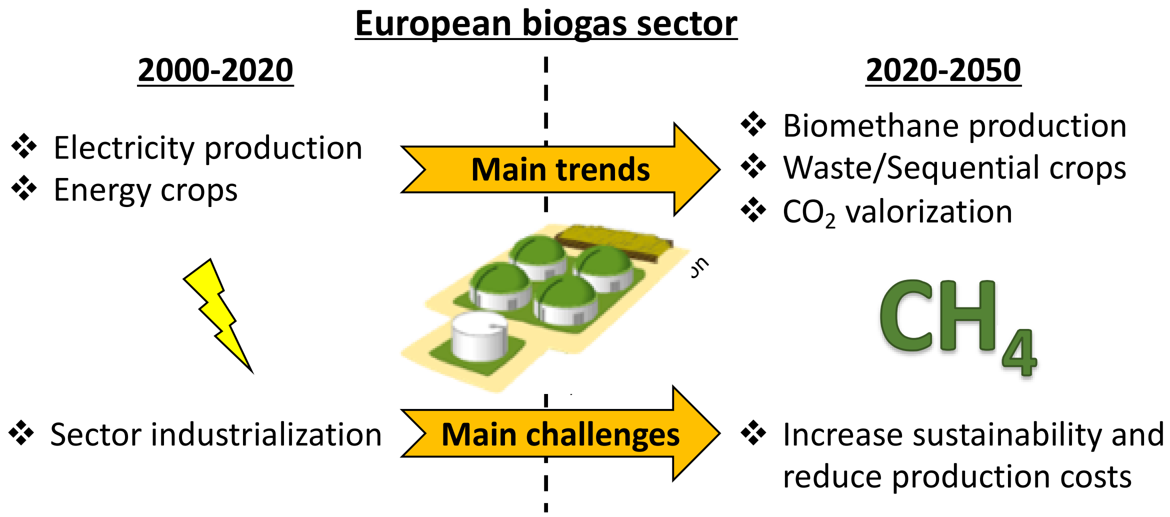
Table 1: Biogas sector and applied biogas policies in selected European countries

Country	Germany	Denmark	Sweden	France	Italy
Biogas sector and policies					
Main biogas valorization pathway	CHP	Upgrading	Upgrading	CHP	CHP
Sector evolution	Stagnant sector	Sector slowdown since 2018	Stagnant sector	Growth	Sector stagnant since FIT reductions in 2013
Biomethane policy	FIT deleted in 2014 -No biomethane incitation scheme	Premiums tariffs - Replaced by auctions in 2020	Fiscal incentives - Potential positive evolution of the support system	FIT since 2014 - Dynamic growth but auctions/reduced FIT from 2020	Favorable quota system set in 2018. Forecasted dynamic growth
Biomethane dominant end-use	CHP with high heat valorization	CHP with high heat valorization	Transportation	Heat & cooling and transportation	Transportation
Envisioned strategy	Uncertain	Slower extension of upgrading development	Resume of upgrading development	Shift from CHP toward upgrading	Shift from CHP toward upgrading
Associated figures					
Number of biogas plants in 2018	9,500[1]	172[2]	279[3]	712[4,5]	1,555[1]
Primary energy production from biogas (TWh/year) in 2018[6]	88.7	3.7	2.1	10.2	21.9
Evolution of the primary energy production from biogas between 2017 and 2018[5]	-1.2%	+21%	-1,1%	+7%	0%
Number of biomethane plants in 2018	213[7]	25[7]	69[3]	76[4,5]	1[1]
Injected biomethane (TWh) in 2018	10.2[7]	2.7[1]	1.3[7]	1.2[5]	0.3[1]
Percentage of total biogas energy upgraded in 2018	11.5%	73%	63%	11.8%	1.5%

[1] (Eyl-Mazzega and Mathieu, 2019); [2] (Danish Energy Agency, 2018); [3] (Sverige Energigas, 2018a); [4] (SDES, 2019a); [5] (SDES, 2019b); [6] (EurObserv'ER, 2019); [7] (REGATRACE, 2020)

Table 2: Identified challenges for the European biogas sector

Dimension	Main challenge	Associated sub-challenges
Economic	Reduce biogas production cost	• Increase biogas recovery from feedstocks (AD process optimization: pretreatments, better monitoring, etc.) • Reach full valorization of the biogas energy potential (avoid no to low heat valorization for cogeneration) • Adapt process to local/cheap sources of biomass • Decrease in capital expenditure linked to sector growth and gain in expertise • Find additional sources of revenues (nutrients, CO_2 use, valorization of co-benefits, etc.)
Environmental	Increase sector sustainability	• Identify and diffuse good practices for digestate management and sequential crops cultivation • Development and higher adoption of tools to assess biogas plant sustainability (LCA notably) • Fully demonstrate integration of AD within the agroecological transition • Exemplarity of the sector concerning methane leakage (tools development and regular check)
Political	Set viable and sustainable support schemes	• Identify in each country adequate biogas development model as a function of the regional specificities (feedstocks deposit, gas infrastructure, etc.) • Foster local implementation of the support scheme
Societal	Increase acceptance by local population	• Increases communication notably on environmental benefits • Increase consultation and involvement of local population


European biogas sector
2000-2020
2020-2050
Electricity production
Energy crops
Main trends
Biomethane production
Waste/Sequential crops
CO_2 valorization
CH_4
Sector industrialization
Main challenges
Increase sustainability and reduce production costs