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Energy in Europe: The influence of uncertainty on biogas development

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Abstract

Driven by the effects of climate change, renewable energy production is growing at a fast pace. For example, biogas production using anaerobic digestion holds great potential (78 billion m³) in Europe. There has been a significant increase in the number of biogas plants in Europe, with a 40 percent increase in the number of installations between 2020 and 2021, and other development projects in the pipeline to promote renewable energy at European level, such as in the REPowerEU plan. However, for decades now, technical, political, and social uncertainties have limited the development of biogas production in Europe, and especially in France. Methods used to estimate bioCH₄ potential showed a wide dispersion, due to the high variability of biomass and microbial communities. Uncertainty arising from changes in law and regulation has a negative impact on the economics of biogas projects. Another factor is social uncertainty, driven in particular by the “Not In My BackYard” (NIMBY) effect and economic costs, incidents due to the operator’s lack of training, insufficient monitoring by the authorities, and inadequate pollution control measures.

Disciplines: energy, process engineering, biology

Keywords: Biogas, biomethane, renewable energy, methanization, uncertainty, anaerobic digestion, NIMBY effect.

Titre : L'énergie en Europe : l'influence de l'incertitude sur le développement du biogaz

Résumé

En raison du changement climatique, la production d'énergie renouvelable augmente rapidement. Par exemple, la production de biogaz par digestion anaérobie présente un potentiel élevé (78 milliards de m³) en Europe. Le nombre de digesteurs pour la production de biogaz a considérablement augmenté sur ce continent, avec 40 % de digesteurs construits entre 2020 et 2021, et d'autres projets de développement des digesteurs au niveau européen, tels que le plan REPowerEU. Cependant, des incertitudes techniques, politiques et sociales ont limité leur développement depuis des décennies en Europe, et plus particulièrement en France. Les méthodes utilisées pour estimer le potentiel de bioCH₄ ont montré une dépendance à la grande variabilité de la biomasse et des communautés microbiennes. L'incertitude liée aux changements de législation et de réglementation a aussi un impact négatif sur l'économie des projets de biogaz. Un autre aspect est l'incertitude sociale avec l'effet « Not In My BackYard » (NIMBY) et les coûts économiques, les incidents dus au manque de formation de l'opérateur, le contrôle insuffisant par les autorités et les mesures inadéquates de contrôle de la pollution.

Disciplines : énergétique, génie des procédés, biologie

Mots clefs : biogaz, biométhane, énergie renouvelable, méthanisation, incertitude, digestion anaérobie, effet NIMBY

Global warming, or climate change, is mostly due to human activities, with an actual increase of 1.1°C on the total earth surface and is estimated to reach 1.5°C in 2030, according to the 6th report of the IPCC (Mukherji *et al.*, 2023). Indeed, climate change is responsible for the increase of the global temperature due to greenhouse emission, which will increase food insecurity, sickness and decrease water availability and species biodiversity (Mukherji *et al.*, 2023). To limit the increase of global warming, global greenhouse gas emissions need to be reduced¹. One answer lies in the use of renewable energy sources, as shown with the 40% increase in Europe between 2004 and 2021². Austria and Sweden are generating the highest renewable energy percentage (76.2 and 75.7%, respectively in 2021), and demonstrating that achieving high levels of renewable energy production at country level is possible and will reduce the greenhouse gas emissions of a country³. The primary contributors to renewable energy production in 2021 were wind power (37.5%), hydropower (32.1%) and solar power (15.1%). Others contributors to renewable energy production were solid biofuels (7.4%) and other renewable sources (7.9%) such as liquid or gaseous biofuels, biomass, geothermal or wave energy. Indeed, the use of biomass in anaerobic digestion is another way to produce energy in the form of biogas, electricity, or heat, using microorganisms. This biomass could be sourced with organic waste, such as municipal waste⁴, agricultural residues, agricultural crops or even wastewater. In this context, anaerobic digestion offers a promising option to sustainable energy production and waste management, a promising contribution to greenhouse gas emissions reduction, and a promising value creation for operators. However, its development is challenged by multiple factors which will be presented in this article: the variabilities in biogas production technologies, the technical uncertainties in biogas production, the constant regulatory changes and the social local acceptance.

Biogas production technologies

Anaerobic digestion corresponds to the transformation of organic residues, from food, municipal, agriculture, industrial waste or crops into biogas using microorganisms at 35-50°C in anaerobic conditions. Anaerobic digestion has four steps: 1) hydrolysis i.e. organic matter is hydrolysed into soluble monomers and oligomers, 2) acidogenesis i.e. they are converted into volatile fatty acids, 3) acetogenesis i.e. volatile fatty acids are converted to acetate, carbon dioxide (CO₂) and hydrogen (H₂) and 4) methanization or methanisation i.e. acetate, H₂ and CO₂ are converted to methane (CH₄) (40-70%) and CO₂ (30-60%) (Cazier *et al.*, 2015). Biogas needs to be purified by membrane filtration or pressure absorption into water to remove CO₂ and have a purity of 96% CH₄ to be injected in the European natural gas grid. The biogas could also be transformed into energy and heat using cogeneration, with an efficiency up to 15-45% maximum for energy (Tian *et al.*, 2021). 87% of biomethane (bioCH₄) plants in Europe, with 442 biogas plants in France (7.6 TWh/year capacity) are connected to the gas grid⁵. Biogas production in France corresponded to 3.4% of renewable energy

¹ LEE, Hoesung, *et al.* 2023. Synthesis report of the IPCC sixth assessment report (AR6) [En ligne]. Intergovernmental Panel on Climate Change. URL: https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf

² EUROSTAT, 2021. Renewable energy statistics, data code: nrg_ind_ren. [En ligne] [Consulté le 3 avril 2023]. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics#Share_of_renewable_energy_more_than_doubled_between_2004_and_2021

³ LEE, Hoesung, *et al.* 2023. Synthesis report of the IPCC sixth assessment report (AR6) ... *op.cit.*

⁴ In 2020, Europe achieved a recycling rate of 47.8%, while France achieved a rate of 42%. EUROSTAT, 2022. Recycling rate of municipal waste, data code: sdg_11_60 [En ligne] [Consulté le 3 avril 2023]. URL: https://ec.europa.eu/eurostat/databrowser/view/sdg_11_60/default/table?lang=en

⁵ Service des Données et Études Statistiques (SDES). 2022. Tableau de bord : biométhane injecté dans les réseaux de gaz, Quatrième trimestre 2021. Données et études statistiques Pour le changement climatique, l'énergie, l'environnement, le logement, et les transports [En ligne] [Consulté le 22 mai 2023]. URL : <https://www.statistiques.developpement-durable.gouv.fr/publicationweb/433>; SAINZ ARNAU, Ángela et LELIEVRE, Gabrielle. 2021. Record-breaking year for biomethane production shows EBA/GIE Biomethane Map 2021. EBA [En ligne]. URL: https://www.gie.eu/wp-content/uploads/filr/5809/Press_Release_Biomethane_Map_2021.pdf

consumption in 2019⁶. The digestate, corresponding to the solid and/or liquid residues at the end of anaerobic digestion, may be used as a source of nitrogen (N) and PO_4^{3-} in the field to replace chemical fertilizers (Samoraj *et al.*, 2022). Therefore, anaerobic digestion has interesting potential due to its versatility in substrates, microorganisms, temperature and even its outputs.

Anaerobic digestion is adaptable to a wide range of inputs and conditions, which increases its versatility. Several parameters significantly influence its performance and feasibility, such as water quantity, bioreactor design, mixing rate, hydraulic retention time, inoculum, inputs pre-treatments and variability over time. For example, dry or solid-state anaerobic digestion (dry matter > 20%), is used in an empirical manner in industry, with a higher number of solid-state anaerobic digestion in Europe since 2008 (60% in 2011) (De Baere *et al.*, 2010), due to a high number of advantages: less water and energy needed to heat the digester, smaller digesters, simplified phases separation and useful for dry substrate (André, Pauss and Ribeiro, 2018). However, the viscosity and inhibition of CH_4 production over 30% of total solid content limits its development and uses, due both to mass transfer limitation and inhibitors production, with a local accumulation of volatile fatty acids, because of the accumulation of the produced gases during anaerobic digestion (Cazier *et al.*, 2022).

The removed CO_2 from biogas may be used for algae production or combined with green H_2 to generate bioCH_4 . Algae production relies on using CO_2 for algae growth and offers potential applications in food production, biopolymers, aviation biofuel, cosmetics, and wastewater bioremediation (Boomadevi *et al.*, 2021; Kartik *et al.*, 2021; Özçimen *et al.*, 2020; Thiyagarasaiyar *et al.*, 2020; Hussain *et al.*, 2021; Khan *et al.*, 2017). Another option for CO_2 involves using green H_2 , produced through water electrolysis using renewable energy, to produce CH_4 through methanation (Rafrafi, Laguillaumie and Dumas, 2020). This approach, known as Power to Gas, offers a possibility to adjust energy production to energy demand at country scale (Reuter, 2014) since bioCH_4 production through methanation is a highly pure and fast process. Methanation is also a possibility for long-term energy storage (1 month) as bioCH_4 can be directly injected into the gas grid (Younas *et al.*, 2022). However, energy is lost due to the transformation of electricity into H_2 (52%) and further into bioCH_4 (*ibid.*). Another limitation is the high cost of electrolysis, estimated at 10.3 \$/kg (*ibid.*). However, this technology corresponds to 4% of the global energy demand in the world and is the most commonly used green technology for H_2 production (*ibid.*). Anaerobic digestion has high potential for biogas production (78 billion m^3 in bioCH_4 for Europe with 20 billion m^3 used in 2020, i.e. 5% of natural gas consumption for Europe) (Scarlat, Dallemand and Fahl, 2018) with 20,000 biogas and bioCH_4 plants in 2021. Biogas plants increased in the last few years with 40% more in 2021 compared to 2020, and an estimated production of 30-40% of the EU gas consumption in 2050 (1,000 TWh) (*ibid.*). The largest increase of bioCH_4 plants in Europe was in France (+91 plants), Italy (+11) and Denmark (+10) between 2020 and 2021 (*ibid.*). Depending on the European countries, the main substrate used will have various origins. For example, in France, majority of the substrate used for anaerobic digestion corresponds to waste (i.e. agricultural residues, manure, food waste, sludge...) with a maximum of 15% of the weight per year of inputs which may come from food or energy crops⁷, which limit the energy potential for AD, but replace incineration or landfill for organic waste disposal. However, in Germany, most of the input corresponds to energy crops, which have a higher energy potential for anaerobic digestion, but are in competition with food production (Auer *et al.*, 2017). France and Germany are 2 extremes cases in their use of substrate in anaerobic digestion, as most countries use both energy crops and organic waste in their digesters. The use of organic waste for

⁶ CUYPERS, Pierre et SALMON, Daniel. *La méthanisation dans le mix énergétique : enjeux et impacts ?* [En ligne]. Rapport de la mission d'information méthanisation. 5 octobre 2021. URL : http://www.senat.fr/fileadmin/Fichiers/Images/redaction_multimedia/2021/2021-Documents_PDF/20211005_MI_Methanisation_dossier_de_presse.pdf

⁷ Ministère de la transition énergétique. Biogaz [En ligne]. 4 février 2022 [Consulté le 3 avril 2023]. URL : <https://www.ecologie.gouv.fr/biogaz>

anaerobic digestion to replace incineration or landfill is interesting since more energy will be produced in the form of biogas and/or heat and/or electricity.

Technical uncertainties

This section will present the various uncertainties in anaerobic digestion due to technical aspects, such as the scientific tests used to predict the methane potential of input/substrate (BioMethane Potential test or BMP), the variation of the composition of the substrate itself during storage, the variation of the input added to the digester, and the variation in time of microbial communities in the digester. All these uncertainties will have consequences on industrial digesters constructions since BMP is used to predict the digester volume, the biogas production and the economic models of industrial digesters.

BMP has been globally used to predict bioCH₄ production in anaerobic digestion. However, this test is mostly based on wet anaerobic digestion (dry matter below 15%) and specific substrate such as wastewater sludge. The high variability of BMP highlighted the need for standardization, especially for solid substrates (Ohemeng-Ntiamoah and Datta, 2019; Ribeiro *et al.*, 2020). Uncertainties therefore exist in BMP measured in laboratory, due to the impact of factors used, such as gas production measurements (pressure and volume), addition of a nutritive solution to enhance the growth, mixing rate, inoculum to substrate ratio and pH buffering (Ribeiro *et al.*, 2020). Indeed, a study with 11 French laboratories, using the same protocol, showed different BMP results for food waste, wheat straw and mayonnaise. The intra-laboratory reproducibility ranged from 5% to 7% while the inter-laboratory reproducibility ranged from 13% to 21% (*ibid.*). Such variabilities in BMP may have a huge impact for evaluating various substrates in industrial applications. Another uncertainty is the variation of CH₄ potential in laboratory compared to industry scale (75%-80% of the BMP at industry scale), which is important for processes scaling-up (Tian *et al.*, 2021).

These BMP variations may be explained by the high variability both of substrate and its composition over time. For example, manure will have high composition variations (cf. Table 1): for average cow manure with a BMP of 193.58 ± 51.99 mL CH₄/g_{VS}, (variation of 27%) from 17 to 33 values in literature. This high variation is due to the manure composition (linked to cow feed and straw used in the stable) leading to high heterogeneity between farms (Møller *et al.*, 2014). Indeed, fat level in the cow feed influences CH₄ yield (increase of 25-31% with high fat level) (*ibid.*). Moreover, due to its high dry matter content, manure itself will have a high composition heterogeneity, even in the same farm. Analysis of the composition of animal bedding, containing both manure and straws, revealed a variation in composition at different depths, up to 26 to 41% of manure in bedding, and up to 20% for fermentable carbohydrates, such as cellulose and hemicellulose (Sanchis-Sebastiá *et al.*, 2020). Storage of manure also contributes to a decrease in CH₄ potential, from 230- 360 mL_{CH₄}/g_{VS} for fresh manure to 70-280 mL_{CH₄}/g_{VS} in pads (50-80% loss) and 60- 200 mL_{CH₄}/g_{VS} (85% loss) in stockpiles, a loss of nitrogen (15-60% in pads and 40 to 90% in stockpiles) and of phosphorus (25-65% in pads and 35-85% in stockpiles) (Gopalan, Jensen and Batstone, 2013).

Table 1. Variation of the characteristic of cattle manure in literature, based on 17 to 33 values⁸

Characteristics	Average	Standard deviation
Total solid content/dry matter (%)	10	6
Total volatile content (% , VS)	81	7
Ammonia (g/L)	1.10	0.65
Total Nitrogen content (g/L)	2,56	1.59
Protein (g/L)	8.37	3.70
pH	7.59	0.41
Volatile fatty acid (g/L)	6.33	3.12
Lipids (g/L)	17.10	5.25
Lignocellulose (%)	31.05	7.66
Cellulose (%)	5.77	3.12
Hemicellulose (%)	9.62	7.58
Lignin (g/L)	14.59	7.22
BioCH ₄ potential (NmL/g _{VS})	193.58	51.99

Even more homogeneous substrate, such as agricultural residues, will have variation of methane yield based on various factors, such as what variety was used, the strain used, or even the harvest time. For example, wheat straw, which may be used directly in digester, but tend to be used as bedding, and therefore mixed with faeces from animals, had a variability of methane potential of 275 ± 41 mL_{CH₄}/g_{VS} from literature, based on 30 to 43 values (cf. Table 2), due to variation in its composition on cellulose, hemicellulose and lignin, used for methane production by microorganisms.

Another variation in agricultural residues may be which part of the plant was used. Indeed, wheat straw varied in its methane yield from 148 to 242 ml of methane per g of volatile matter, depending of which part of the straw was used (cf. Table 3).

The variety and the maturity in agricultural crops during harvest time will also have an effect on anaerobic digestion (cf. Table 4), with a difference maximum between species at node stage (114 mL_{CH₄}/g_{VS}), and between node stage and fully ripe of 92 mL_{CH₄}/g_{VS} for Capo variety. Another example is maize, which may be used as energy crops for methane production in countries such as Germany. The BMP of maize for one variety “KWS 1393” had a biomethane variation from 343 mL_{CH₄}/g_{VS} after 186 days of vegetation up to 407 mL_{CH₄}/g_{VS} at 131 days of vegetation (Amon *et al.*, 2007).

⁸ Estevez *et al.*, 2014; Al Saedi and Lukehurst, 2012; Wang *e al.*, 2012; Borgström, 2011; Krishania, Vijay and Chandra, 2013; Goberna *al.*, 2015; Kaparaju *al.*, 2008; Luo *et al.*, 2012; Crolla *et al.*, 2011; Ahn *al.*, 2010; Seppälä, 2013; Ahring, Ibrahim and Mladenovska, 2001; Nielsen *al.*, 2004; Triolo *et al.*, 2011; Lehtomäki, 2006.

Table 2. Variation of the characteristic of wheat straw in literature, based on 30 to 43 values. VS: volatile content⁹

Wheat straw	Average	Standard deviation
Total solid content (%)	92	3
Total volatile content (%)	85	7
Hemicelluloses (% _{VS})	29	6
Celluloses (% _{VS})	39	6
Lignins (% _{VS})	16	4
BioCH ₄ potential (NmL/g _{VS})	275	41

Table 3. Variation of the composition of the different parts of wheat straw and the methane production (BMP: BioMethane Potential). TS: total solid, VS: volatile solid¹⁰

	Internodes	Leaves	Nodes	Glumes ^(d)	Rachis ^(d)
Hemicellulose (% _{TS})	35 ^(a,b,d,e) ± 7	28 ^(a,b,d,e) ± 4	33 ^(a,d,e) ± 5	43	39
Celluloses (% _{TS})	41 ^(a,b,d,e) ± 6	36 ^(a,b,d,e) ± 2	31 ^(a,d,e) ± 5	40	44
Lignin (% _{TS})	17 ^(a,b,d,e) ± 3	14 ^(a,b,d,e) ± 2	19 ^(a,d,e) ± 4	6	7
Glucose (% _{TS})	37 ^(b,d) ± 5	28 ^(b,d) ± 3	26 ^(d)	29	28
Xylose (% _{TS})	17 ^(d)	17 ^(d)	17 ^(d)	18	21
BioCH ₄ potential (NmL/g _{VS})	148 ^(d)	242 ^(d)	237 ^(c,d) ± 70	171	180

Table 4. Biomethane yield in the straw of 2 variety of wheat (Capo and Levendis) at various maturity during harvest, based on Amon *et al.*, (2007). BMP: Biomethane Potential, VS: volatile solid

BioCH ₄ potential (NmL/g _{VS})	Capo	Levendis
Node stage	343	229
Anther flowering	307	342
Milky grain stage (50% moisture and protein storage)	244	254
Paste stage of grain (moisture loss and starch formation)	243	228
Fully ripe (20% humidity)	251	245

Besides, agricultural substrates are also dependant of climatic conditions, with the uncertainty of its evolution due to climate change in the future (Semeraro *et al.*, 2023). Indeed, climate change will reduce crop production because of extreme temperature changes, which affect the rate of plant growth, and its

⁹ Gao Peiji *et al.*, 1997; The Clean Washington Center, Mckean and Jacobs, 1997; McKendry, 2002; Demirbas, 2004; Kim and Dale, 2004; Amon *et al.*, 2007; Prasad, Singh and Joshi, 2007; Bauer *et al.*, 2009; Buffiere, Bayard and Germain, 2009; Zeitoun, 2011; Abbasi and Abbasi, 2010; Erdei *et al.*, 2010; Naik *et al.*, 2010; Tamaki and Mazza, 2010; Cui, Shi and Li, 2011; Triolo *et al.*, 2011; Brown, Shi and Li, 2012; Chandra, Takeuchi and Hasegawa, 2012; Liew, Shi and Li, 2012; Menardo, Airolidi, and Balsari, 2012; Pohl *et al.*, 2012; Sarkar *et al.*, 2012; Silva *et al.*, 2012; Barakat, De Vries and Rouau, 2013; Krishania *et al.*, 2013; Nkemka and Murto, 2013; Sambusiti *et al.*, 2013; Sapci, 2013; Ferreira *et al.*, 2014; Dargode *et al.*, 2022; Lee *et al.*, 2023; Raveendran, Ganesh and Khilart, 1995; Sander, 1997.

¹⁰ (a)The Clean Washington Center, Mckean, Jacobs 1997; (b)Bertrand et al. 2006; (c)Amon et al. 2007; (d)Motte et al. 2014; (e)Sun 2010.

reproductive ability (*ibid.*). Climate changes reduce as well, both water availability, which increases the hydric stress in plants, and soil fertility, with more erosion episodes and lower nitrogen and organic carbon in soil (*ibid.*).

Other substrates show heterogeneity in composition and during storage. Food waste and/or household and/or municipal waste has a high biogas potential with a production of 132,550 ktonnes/year in 2020 in Europe, i.e. 6.45% of total waste produced, making it one of the largest waste categories after mineral waste¹¹. However, food waste has a high heterogeneity in its composition, which significantly affects its BMP (Kobayashiet *al.*, 2012). For example, in Norway, the average composition of household waste (220 households) corresponded to 27% of bakery products, 24% of fruits and vegetables, 22% of left-over of prepared food, 8% of fish and meat, 6% of dairy products and 22% of other food products (Hanssen, Syversen and Stø, 2016). However, these ratios can vary among European countries (cf. Figure 1). In Denmark, household food waste composition was different with 30% of fresh vegetables, 17% of fresh fruit, 13% of bakery products, 11% of drinks, confectionery and desserts, 10% of other foods types, 7% of meat and fish, 5% of dairy and eggs, 5% stable food, and around 1% for canned foods (Edjabou *al.*, 2016).

Another source of uncertainty lies in the microbial communities inside the bioreactor during anaerobic digestion. Indeed, microbial communities may evolve during a digester lifetime, especially if there is any substrate change (McMahon *al.*, 2004). All parameters in digesters may influence microbial communities (bacterial and archaeal), i.e. organic loading rate, temperature, pH, type of digesters (Xu *et al.*, 2021; Pasalari *et al.*, 2021; Lee *et al.*, 2014; Mercado, Koyama and Nakasaki, 2022) and will bring CH₄ production uncertainty. Moreover, the type of substrate used has a high impact on microorganisms within the digester, resulting in substrate-specific microbial communities (Li *et al.*, 2015; Zhang *et al.*, 2014; Dargode *et al.*, 2022). Any change of substrate leads to changes in microbial communities, with a delay in microbial acclimation to the new substrate, up to 60 days (Xu *et al.*, 2021). When digesters show high variability over time, CH₄ production is negatively impacted. For example, a seasonal digester using kitchen waste in India, displayed daily biogas production variations from 17.99 m³ to 22.88 m³ on average (Isha *et al.*, 2020).

¹¹ EUROSTAT. Generation of waste by waste category, hazardousness and NACE Rev. 2 activity. Online data code: ENV_WASGEN [En ligne]. 13 janvier 2023 [Consulté le 4 avril 2023]. URL: https://ec.europa.eu/eurostat/databrowser/view/ENV_WASGEN__custom_4174595/default/table

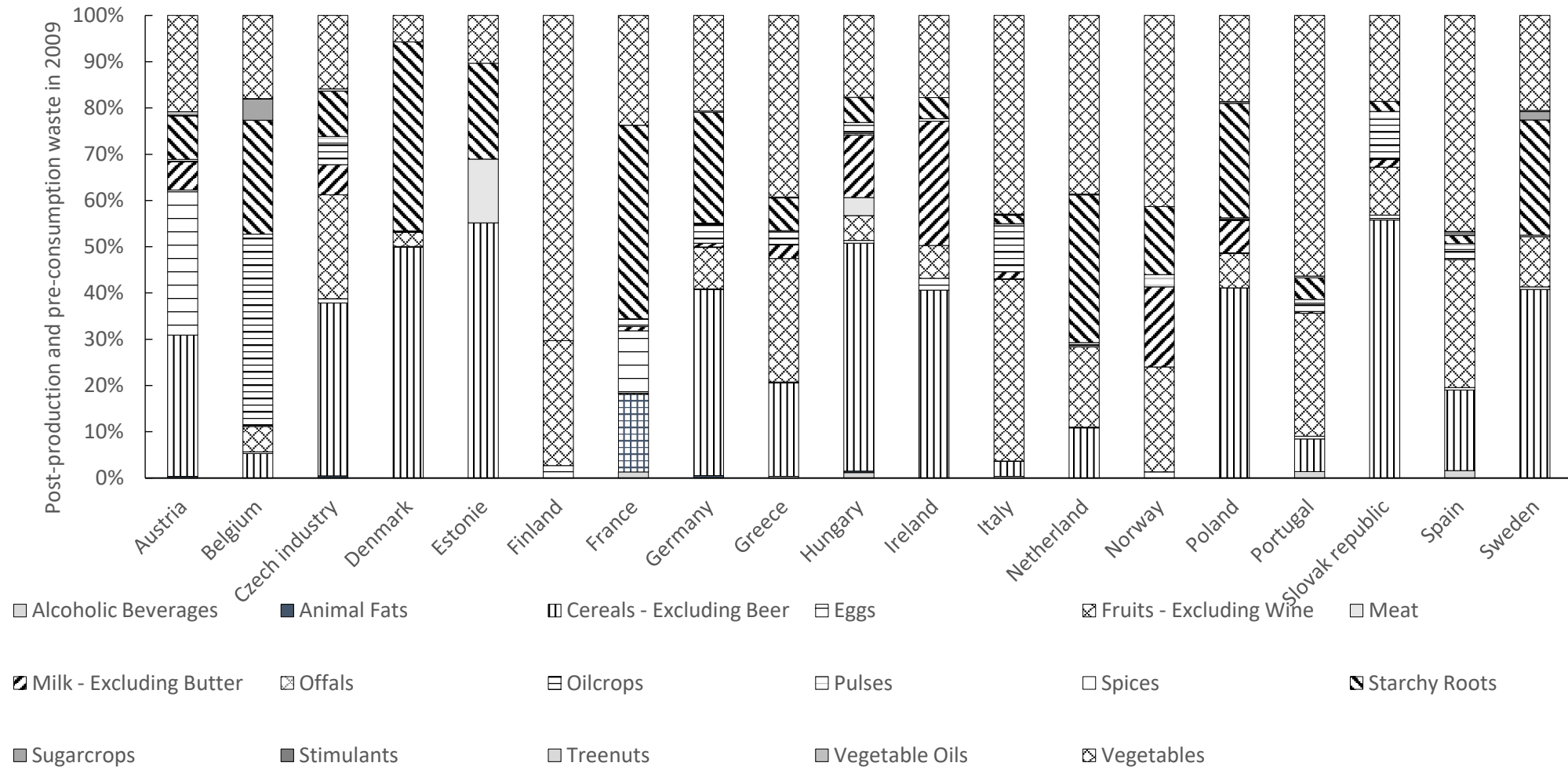


Figure 1. Food waste composition in Europe per countries in 2009 in %, based on data from OECD¹²

¹² OECD.STAT. Food waste [En ligne]. 5 avril 2023 [Consulté le 5 avril 2023]. URL: https://stats.oecd.org/Index.aspx?DataSetCode=FOOD_WASTE

Another uncertainty parameter is the mobilization of biomass at a country level and during time. To limit this uncertainty, various countries such as France with the « *Stratégie Nationale de Mobilisation de la Biomasse* » in 2018, and the United Kingdom with the « Biomass Action Plan » in 2012, presented and applied strategies to: limit climate change, increase the durable valorization of organic waste in bioenergy, preserve the biodiversity and soil quality, limit the impact on the food industry and the use of fossil energy¹³.

Various technical uncertainties presented here: 21% of BMP depending of the laboratories, substrate and microorganism variabilities (especially food waste and manure), biomass mobilization and variation of its production (climate change, storage effect...), will have a direct effect on industrial modelization and digesters production. In fact, biomethane potential (BMP) is currently used for the scale up and modelization of digesters. These uncertainties may therefore have disruptive economic and security effects on industrial digesters, if they are not taken into account during a digester project study. These uncertainties at individual project level, may also lead to cumulative impacts at country level, as anaerobic digestion is used as renewable energy in the various national and European prediction plans to limit carbon dioxide and fossils energy uses¹⁴.

Constant regulatory changes: the French Case

Anaerobic digestion, commonly referred as methanisation or methanization, which emerged in France in the 1940s, underwent a period of limited development after the Second World War, due to the preference for industrial monopolies and cheap fuel fossil oil. The oil crises of 1973 and 1979 sparked renewed interest in renewable energies, but anaerobic digestion had remained marginal compared to the nuclear power favoured since 1981 (Evrard, 2014). Despite the support of the AFME (French Agency for Energy Management), the financial support and the political interest in anaerobic digestion declined, while technical and economic profitability problems further complicated its development in the late 1980s (Cadiou, 2023). The low oil prices were an economical barrier to any renewable energy (EnR) development, especially for biogas post-treatment. Moreover, the biogas needs to be treated before use: Cogeneration engines and mobility engines need the removal of corrosive gases and hydrogen sulphur (H₂S) and authorization of injection in the natural gas network requires a 96% CH₄ purity, and the removal of H₂O, CO₂ and H₂S, according to the French regulation (Tian *et al.*, 2021). At that time, the natural gas network operator, Gaz de France, opposed the idea of injecting bioCH₄ into the natural gas network, citing sanitary issues, despite its debunking in 2008¹⁵. All these factors combined made biogas production impractical and economically unfeasible.

The 9th of September 1997, a ministerial decree required landfill sites to collect and direct biogas to recovery or combustion facilities. This recovery process paves the way for the renewable energy promise of anaerobic digestion. This was the first step towards reducing greenhouse gas emissions through anaerobic digestion and preferential production of biomethane for injection into the electricity and natural gas networks. In 2008, the Directorate General for Energy and Climate set up a working group to oversee and organize the injection of biogas into the natural gas networks without sanitary issues¹⁶

¹³ Ministère de la transition écologique. *Stratégie Nationale de Mobilisation de la Biomasse* [En ligne]. 2018 [Consulté le 24 octobre 2023]. URL : <https://www.ecologie.gouv.fr/sites/default/files/Strat%C3%A9gie%20Nationale%20de%20Mobilisation%20de%20la%20Biomasse.pdf>; MOURJANE, Ilyas et FOSSE, Julien. 2021. *Biomasse agricole : quelles ressources pour quel potentiel ?* [En ligne]. Note de synthèse. Département Développement durable et Numérique [Consulté le 24 octobre 2023]. France stratégie. URL : https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-ns_-_biomasse_agricole_-_quelles_ressources_pour_quel_potentiel_-_29-07-21.pdf

¹⁴ *Ibid.*

¹⁵ AFSSET. 2008. Saisine Afsset n° « 2006/010 » : Risques sanitaires du biogaz : évaluation des risques sanitaires liés à l'injection de biogaz dans le réseau de gaz naturel.

¹⁶ *Ibid.*

In 2011, the support package for biogas valorisation – injection of biomethane into natural gas networks¹⁷ – specifies that "any biogas producer may conclude with a natural gas supplier [...] a contract for the sale of biogas produced on national territory". The decree of May 2011 increased the electricity purchase tariff dating from 2006 giving preference to smaller cogeneration installations that generates both electricity and heat. Additionally, the decree of November 2011 created a new purchase price for biomethane injected into the natural gas networks.

In 2013, the Nitrogen Autonomy Methanisation Energy Plan (EMAA Plan) launched by the French government¹⁸ aimed to develop 1000 on-farm digesters by 2020, made possible by modification of the purchase prices and in 2011 more public aid, research and regulations' relaxation. In 2014, new regulatory texts authorize the injection of biogas produced in the treatment plant into the network. In September 2014, the French government announced a call for projects to develop 1 500 additional biogas plants in 3 years in rural areas.

In 2019, the Ecological Transition Ministry¹⁹ published an operational tool, the Energy multi-year Plan²⁰ 2019-2028 for public decision makers describing the path and measures to decarbonate energy and achieve the target of carbon neutrality in 2025. The target for biogas production was 24 to 32 TWh in 2028 (compared to 0,4 TWh in 2017) injected or directly used which should correspond to 6 to 8% of the national consumption. Another target was bioCH₄ injection of 6 TWh in 2023. Though, as of March 2023, according to the Ecological Transition Ministry²¹, there are 1 023 facilities producing electricity from biogas connected to the electricity grid, with a combined installed capacity of 578 MW. Additionally, potential projects have a total capacity of 44 MW. 551 facilities are injecting bioCH₄, produced and purified from biogas, into the natural gas networks. These facilities have a combined annual capacity of 9.9 TWh. Furthermore, there are 844 potential projects for CH₄ with a capacity of 15.4 TWh/year (2% decrease compared to 2022). These official figures indicate a higher progress in the biogas sector compared to the expectations outlined in the PPE 2019-2028²².

One significant issue that arises from false estimate of bioCH₄ potential production is the economic difficulties it creates for stakeholders, regarding the design of the plant and the estimated profits. In France, the average investment of a biogas plant is around 5 M€ (Marechal and Thual, 2022). To ensure profitability, a minimum input of 10 000 to 15 000 tonnes/year, equivalent to more than 30 tonnes per day is necessary²³. However, the competition between the requirements for the animal feed and anaerobic digestion input lead to an increase of input price. If the input comes directly from the anaerobic

¹⁷ INERIS. Circulaire du 09/11/12 relative à l'injection de biométhane dans les réseaux de gaz naturel suite à l'entrée en vigueur des textes réglementaires ouvrant droit au tarif d'achat du biométhane injecté. Aida La réglementation de la prévention des risques et de la protection de l'environnement [En ligne]. 2023 [Consulté le 22 mai 2023]. URL : <https://aida.ineris.fr/reglementation/circulaire-091112-relative-a-linjection-biomethane-reseaux-gaz-naturel-suite-a>

¹⁸ Ministère de l'agriculture, de l'agroalimentaire et de la forêt et Ministère de l'écologie, du développement durable et de l'énergie. Le plan Energie Méthanisation Autonomie Azote [En ligne]. 2013. URL : <http://agriculture.gouv.fr/Plan-Energie-Methanisation>

¹⁹ Ministère de la transition écologique et de la cohésion des territoires. Programmation pluriannuelle de l'énergie. Présentation de la stratégie française pour l'énergie et le climat [En ligne]. 3 janvier 2019 [Consulté le 22 mai 2023]. URL : <https://www.ecologie.gouv.fr/presentation-strategie-francaise-lenergie-et-climat>

²⁰ PPE – Plan Pluriannuel de l'Énergie.

²¹ Ministère de la transition écologique et de la cohésion des territoires. Tableau de bord : biogaz pour la production d'électricité – Premier trimestre 2023 [En ligne] [Consulté le 10 juillet 2023]. URL : <https://www.statistiques.developpement-durable.gouv.fr/tableau-de-bord-biogaz-pour-la-production-deelectricite-premier-trimestre-2023-0>; Ministère de la transition écologique et de la cohésion des territoires. Tableau de bord : biométhane injecté dans les réseaux de gaz - Premier trimestre 2023 [En ligne] [Consulté le 10 juillet 2023]. URL: <https://www.statistiques.developpement-durable.gouv.fr/tableau-de-bord-biomethane-injecte-dans-les-reseaux-de-gaz-premier-trimestre-2023-0#:~:text=Au%2031%20mars%202023%2C%20551,par%20rapport%20C3%A0%20fin%202022.>

²² Ministère de la transition écologique et de la cohésion des territoires. 2019. Programmation pluriannuelle de l'énergie... *op.cit.*

²³ LALLOUËT-GEFFROY, Julie. Enquête sur la méthanisation en Bretagne. « Ceux qui se font avoir, ce sont les agriculteurs ». *France 3 Bretagne* [En ligne]. 14 septembre 2022. URL : <https://france3-regions.francetvinfo.fr/bretagne/enquete-sur-la-methanisation-en-bretagne-ceux-qui-se-font-avoir-ce-sont-les-agriculteurs-2611520.html>

digestion facilities, the price may not have a significant influence. However, operational studies show that, if anaerobic digesters are filled with input from external partners, the fluctuation in input prices could become a major uncertainty that can undermine the economic viability of a project and potentially impact the profitability of the installation. In this context, the regulatory framework is finally changing in France. One decree and two bylaws published to support biogas should make it possible to address the concerns of project promoters about labour, energy and industrial costs²⁴. These measures should strengthen the deployment of the biogas sector.

In a more global view, in Europe, in response to the global energy market disruption caused by Russia's invasion of Ukraine, in 2022, the European Commission has launched the REPowerEU Plan²⁵. The primary objectives are to achieve energy savings, to promote the production of clean energy and to diversify energy supplies. The EU Commission targets a development up to 35 bm^3 annual bioCH₄ production by 2030 (estimated to 340 TWh)²⁶. In the REPowerEU plan, the increase of bioCH₄ production will mean energy independence by replacement of imported fossil gas, economic prosperity, energy system flexibility using gas storage and network interconnection in Europe, and an environmental impact with the waste recovery and carbon neutrality of the whole system.

As described, over the past 80 years, the various participants in the biogas sector such as players in the biogas industry, energy operators, and regulators have continuously evolved. For example, GrDF, the natural gas distribution network operator, embraced biogas in 2009 by becoming a member of the Biogas Club established in 1999 by the ATEE²⁷. Similarly, in March 2023, GRTgaz, the transmission network operator, held a press conference with the main operators in France to present the 2030 perspectives²⁸: 50 TWh of biomethane production by methanation and 13 TWh of biogas for electricity production by cogeneration. Evolving terms and conditions for purchasing biogas, which are constantly adjusted to comply with regulations may offer a heightened sense of stability in the present time. This stability, alongside the involvement of energy stakeholders (ENGIE, TotalEnergies...), could potentially encourage industrial investors to approach investments in anaerobic digestion plants with greater confidence.

Social acceptance of biogas infrastructure: local uncertainties

One of the challenges in implementing biogas facilities is the uncertainty surrounding public acceptance. In 2020, Bourdin *et al* conducted an analysis of stakeholder discourses in the French regional daily press (Bourdin, 2020; Bourdin, Jeanne and Raulin, 2020). The "Not In My BackYard" effect (NIMBY)

²⁴ Ministère de la transition écologique et de la cohésion des territoires. Décret n°2023-456 du 10 juin 2023 relatif à la modification de la production annuelle prévisionnelle ou de la capacité maximale de production des installations de production de biométhane [En ligne]. 10 juin 2023. URL : <https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000047670220>; Ministère de la transition écologique et de la cohésion des territoires. Arrêté du 10 juin 2023 fixant les conditions d'achat du biométhane injecté dans les réseaux de gaz naturel [En ligne]. 10 juin 2023. URL : <https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000047670236>

²⁵ European Commission, Secretariat-General. 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. (Document 52022DC0230) [En ligne]. 18 mai 2022 [Consulté le 10 juillet 2023]. URL: <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2022:230:FIN>

²⁶ European Commission, Secretariat-General. Implementing the repower EU Action Plan: Investment needs, hydrogen accelerator and achieving bio-methane targets. Document 52022SC0230 [En ligne]. 18 mai 2023 [Consulté le 10 juillet 2023]. URL: <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=SWD:2022:230:FIN>

²⁷ ATEE: Association Technique Énergie Environnement is an industry association set up in 1978 to focus on energy saving, energy efficiency and waste treatment.)

²⁸ GRTGAZ, Gaz Réseau Distribution de France, syndicat des énergies renouvelables, SPEGNN et TEREKA, 2023. Gaz renouvelables, une énergie stratégique indispensable pour la France. Panorama des gaz renouvelables en 2022 [En ligne]. Conférence de presse. 8 mars 2023. URL : <https://www.grtgaz.com/sites/default/files/2023-03/conference-de-presse-panorama-gaz-renouvelables-2022-08032023.pdf>

corresponds to the opposition of local communities towards the installation of new facilities due to concerns about potential nuisances. In the case of biogas plant projects, local residents often raise concerns about odour, noise, traffic, and perceived negative environmental impacts (Bourdin, 2020). All these factors could diminish the appeal of the location due to the presence of a digester (touristic and/or leaving)²⁹ (Martinát *et al.*, 2022) and contributes to the fear of the unknown or accidents due to insufficient attention to safety within the biogas industry. In France, for example, 61% accidents have resulted in pollution of soil, air or water³⁰ (Hedlund, 2017;). Providing a clear and comprehensive explanation of a biogas project before its installation and actively involving the local community help alleviate opposition (Martinát *et al.*, 2022). In France, if the digester uses less than 30 tonnes/day, public consultation or enquiry is not necessary³¹. This aspect of the law is likely to alienate the population, who will feel that their concerns are not taken in count³². Lack of awareness and understanding about biogas technology lead to scepticism, uncertainty and even resistance³³. Public perception regarding the safety, the reliability and the efficiency of biogas as a main source of energy influence acceptance levels. Educating and engaging with the public to raise awareness and address misconceptions can and should improve local acceptance.

Two main factors effect local uncertainty. First, incidents in the operation of biogas facilities (Hedlund, 2017; Martinát *et al.*, 2022). Normally in France, only anaerobic digesters with an input between 30 and 100 tonnes/day will need to register and anaerobic digesters with an input over 100 tonnes/day will need a public enquiry. However, one third of anaerobic digesters expand within 5 years of construction, as a “*fait accompli*” strategy, which allows them to avoid a public enquiry³⁴. This practice increases the risk of pollution incidents. According to the French government (ARIA), there have been 130 incidents reported between 1996 and 2020, increasing since 2016 with 18.8 accident per year, with 74% due to discharge of hazardous or polluting materials such as biogas in the atmosphere (53% of the accidents) or digestate in soils or water (32%)³⁵. These incidents are mainly due to lack of operators training (7% in France in 2020), work condition (17%), insufficient security control (20%), poor safety culture (4%), risk identification (22%), poor equipment choice (27%) and undersized facilities (85% of the controlled digesters in 2020 in France)³⁶ (Hedlund, 2017). Another uncertainty is the pollution from input such as animal by-product i.e. manure, milk, stomach content, eggs, slaughterhouse waste from healthy animals (Categories 2 and 3 of European waste regulation)³⁷. Regulation requires them to be heated at 133 or

²⁹ GRANNEC, Marie-Laure et LOUSSOUARN, Aurore, 2015. Perception sociale de projets de méthanisation agricole en Bretagne. Analyse croisée des regards d’acteurs des territoires, favorables ou opposés aux projets. Rapport d’étude. Chambre d’agriculture de Bretagne. pp. 12.

³⁰ Ministère de la transition écologique, ARIA et BARPI. 2020. Accidentologie du secteur de la méthanisation [En ligne] [Consulté le 16 octobre 2023]. URL : <https://www.aria.developpement-durable.gouv.fr/wp-content/uploads/2021/09/synthese-methanisation-VF.pdf>

³¹ CUYPERS, Pierre et SALMON, Daniel, 2021. *La méthanisation dans le mix énergétique : enjeux et impacts ?... op.cit.*

³² GRANNEC, Marie-Laure et LOUSSOUARN, Aurore. 2015. Perception sociale de projets... *op.cit.*

³³ FIORITO, Léana. 2021. Méthanisation et conflits d’aménagement en Auvergne-Rhône-Alpes, Rapport de fin de mission, GRTgaz [En ligne]. URL : https://www.biogaz-aura.fr/fileadmin/user_upload/mediatheque/enr/Documents/Biogaz/RESSOURCES/Etudier_et_Developper_son_projet_de_methanisation/Rapport_GRTgaz_App_locale.VF.pdf

³⁴ LALLOUËT-GEFFROY, Julie. Enquête. Méthanisation en Bretagne : un développement sous contrôle. France 3 Bretagne [En ligne]. 13 septembre 2022. URL : <https://france3-regions.francetvinfo.fr/bretagne/enquete-methanisation-en-bretagne-un-developpement-sous-controle-2610304.html>

³⁵ *Ibid.* ; Ministère de la transition écologique, ARIA et BARPI. 2020. Accidentologie du secteur de la méthanisation... *op. cit.*

³⁶ LALLOUËT-GEFFROY, Julie. 2022. Enquête. Méthanisation en Bretagne : un développement sous contrôle... *op. cit.* ; Ministère de la transition écologique, ARIA et BARPI. 2020. Accidentologie du secteur de la méthanisation... *op. cit.*

³⁷ HAUMONT, Adeline *et al.* 2021. Guide de mise en œuvre de l’hygiénisation en méthanisation. Aile, Utilities Performance, GRDF ; Ministère de la transition écologique. Arrêté du 9 avril 2018 fixant les dispositions techniques nationales relatives à l’utilisation de sous-produits animaux et de produits qui en sont dérivés, dans une usine de production de biogaz, une usine de compostage ou en « compostage de proximité », et à l’utilisation du lisier [En ligne]. URL : <https://www.legifrance.gouv.fr/eli/arrete/2018/4/9/AGRGI1809743A/jo/texte>

70°C for 1h to destroy the pathogens, and reduced to 12 mm particle size³⁸. However, if the global quantity of animal and vegetable waste is below 30 000 tonnes/year or if more than a dozen farms supply the input, derogations are accorded in France and the sterilization or pasteurisation are not compulsory³⁹. In Brittany, one of the main livestock regions in France, almost all anaerobic digesters are below this threshold, thus avoiding the high costs and choosing profitability over safety⁴⁰.

Secondly, the regulatory framework for biogas production has undergone changes since the 1990s. However, the lack of a clear policy at national level and local civil society support for biogas initiatives has contributed to lower acceptance levels and reduced confidence in such projects. The absence of a well-defined and supportive policy framework creates uncertainty among stakeholders, including investors, project developers, and, much more importantly, the local communities. Clear and consistent policies that provide incentives, streamline procedures, and ensure environmental and safety standards should help foster greater acceptance and confidence in biogas initiatives with reducing the number of industrial incidents⁴¹.

Conclusions

In recent years, biogas production has experienced significant growth, driven by its potential to contribute to both political and climate change objectives. Industry has advanced at a faster pace than the accompanying political and regulatory frameworks, as shown by the high number of accidents due to safety problems. However, positive signs of change, such as new laws and regulations in EU and especially in France, are encouraging the development of biogas projects. Nevertheless, a better framework and supervision to avoid incidents and pollutions and to alleviate the uncertainties of the population is needed.

Beginning of 2023, the different infrastructures operators (GRTgaz, GrDF, Terega, SER, Spégnin) showed an expected potential bioCH₄ production by anaerobic digesters with 50 TWh in 2030⁴². These projections highlight the positive outlook for biogas in France, indicating its potential to play a significant role in meeting energy demands, reducing greenhouse gas emissions, and fostering a more sustainable energy landscape.

Continuous support from regulators, and collaboration with infrastructure operators, will be essential in realizing this future potential and maximizing the benefits of biogas production in the country. Enhanced communication about biogas technology, improved professionalism and training of the operators, and improved plant safety measures, would enable to minimize uncertainties related to its environmental impacts, thus fostering local acceptance and the advancement of biogas plants technology.

³⁸ *Ibid.*

³⁹ *Ibid.* ; HAUMONT, Adeline *et al.* 2021. Guide de mise en œuvre...*op.cit.* ; LALLOUËT-GEFFROY, Julie. 2022. Enquête. Méthanisation en Bretagne : un développement sous contrôle... *op. cit.* ; LALLOUËT-GEFFROY, Julie et BALDOS, Raphaël. Enquête. Méthaniseurs, les clusters potentiels des maladies de demain. France 3 Bretagne [En ligne]. 16 septembre 2022. URL : <https://france3-regions.francetvinfo.fr/bretagne/enquete-methaniseurs-les-clusters-potentiels-des-maladies-de-demain-2613624.html>

⁴⁰ *Ibid.*

⁴¹ FIORITO, Léana. Méthanisation et conflits d'aménagement en Auvergne-Rhône-Alpes... *op.cit.*

⁴² GRTGaz, Gaz réseau distribution de France, Syndicat des énergies renouvelables, SPEGNN et TEREKA. 2023. Gaz renouvelables, une énergie stratégique indispensable pour la France... *op.cit.*

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