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Biomethane and public policies: Which support for which production model?

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While several articles have already examined the techno-economic characteristics of a given type of biomethane producer, this article focuses on the relationship between various producers and the support policies they may benefit from. To that end, it gives an overview of the biogas-to-biomethane industry by characterizing three production models that policymakers consider differently. Once this distinction is made, a generic production cost function is developed, and its implications regarding support policies are discussed throughout the article, with a focus on plant specific economies of scale and changing cost determinants from one production model to another. As an illustration, a qualitative analysis is conducted on the French support policies and their result since 2010. Various pitfalls to avoid when supporting the industry are then presented, including the sole focus on energy production, and alternatives are proposed. From this perspective, a dynamic vision of the industry considering the challenges posed by biomass availability is developed, and a quantitative assessment of the significant financial benefits that can be derived from biomethane by-products is conducted. A first attempt is finally made to characterize the relationship between industry related externalities, production models and support policies, which questions the interest of supporting biomethane with the same instruments that were put in place for other renewable energy sources.

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Executive summary

As a substitute to fossil gas, biomethane is set to play a significant role in the transformation of energy systems, particularly in Europe as part of the REPowerEU plan of 2022 where it is presented as both a means of reducing greenhouse gas emissions and improving energy independence. So far however, the emerging economic literature on biomethane is mainly composed of techno-economic articles, focusing on a given type of producer. Here, the objective is to try and take a step back from a heterogeneous industry, to discuss the economic mechanisms at play between supporting policies and the emergence of a wide variety of biomethane producers, with implications that extend far beyond energy systems.

Key findings:

- To better understand support policies, the biogas-to-biomethane industry can be divided into three main production models, hereafter referred to as *Waste gas recovery*, *Waste to resources* and *Additional biomass production*.
- Cost determinants vary from one production model to another, justifying the use of adaptable supporting tools such as feed-in-tariffs.
- In the French case, such tools have enabled the emergence of a variety of producers, although at a high cost. Due to potentially low plant specific economies of scale, the success of recently implemented tools aiming at increasing production at a lower cost remains uncertain.
- Without appropriate planning, the increasing number of producers could lead to increases in production costs, cancelling out the effects of potential technological improvements.
- Biomethane by-products can play a significant role in the development of the industry, but the financial benefits derived from these by-products largely depend on considered production models.
- A varying number of potential industry related externalities – either positive or negative – can be observed from one production model to another.

Policy recommendations:

- Questioning the additionality principle enabling the distinction between production models by considering the medium to long-term effects of support policies, namely on the agricultural sector.
- Ensuring the efficiency of local-scale industry planning to avoid the emergence of a competition between producers for feedstock acquisition.
- Being mindful of the effects of changes in support policies on the ability of the regulator to consider and influence on the industry's non-energetic consequences.

1. Introduction

In 2022, the European Commission set a EU production target of 35 billion cubic meters of biomethane per year by 2030, compared with 3.3 billion cubic meters in 2020 [1]. Integrated in the REPowerEU plan, the implementation of this objective was justified by biomethane's potential to contribute to both energy independence and clean energy transition in the EU, by replacing part of its fossil gas imports with a renewable and low carbon alternative [2]. The plan however also specified that "the focus should be on sustainable production, ensuring that biomethane is produced from organic waste and forest and agricultural residues, to avoid impacts on land use and food security". Through this point, the Commission then aimed at highlighting some of the specificities of biomethane production compared to others renewable energy sources, as well as precautions judged necessary with regard to the development of an industry that has implications beyond energy systems.

Biomethane is a gas composed almost exclusively of methane, and whose production was based on the usage of biomass. Even though alternative technical processes exist and are gradually developing, in 2018 the International Energy Agency (IEA) estimated that 90% of the biomethane produced worldwide came from the upgrading of biogas [3]. The latter is generated in an oxygen free environment, either in landfills or in dedicated digesters, by anaerobic digestion (AD) of organic matter. This organic matter can be dedicated crops, crop residues, animal manure, by-products from various industries, the organic fraction of municipal solid waste (OFMSW), or sewage sludge from wastewater treatment plants (WWTP). Biogas is initially composed of methane (50-65%), CO2 (35-50%) and other trace components [4]. Once collected and treated, it can be directly used to produce electricity and/or heat, or it can be upgraded (i.e. brought to a high level of methane purity) through a variety of methods, of which the most used are water scrubbing and membrane separation [5]. Once upgraded, biomethane, also sometimes called renewable natural gas, becomes a substitute for fossil gas and can be used for numerous purposes, including injection into a gas pipeline grid and utilisation as a transportation fuel or in fuel cells [6].

As a renewable substitute for fossil energy sources, biomethane production therefore has direct implications for the challenges faced by energy systems, including reductions in GHG emissions, energy independence, technological evolutions for energy production and distribution, or the match between supply and demand. Unlike renewable energy sources (RES) as PV or wind power however, a unit producing biomethane requires important amounts of inputs throughout its entire lifetime, i.e. biomass that potentially has to be produced, collected and gathered. In the production process, the industry moreover generates significant amounts of non-energetic outputs, namely digestate that is generated in digesters, and that can be considered either as a nuisance waste or as a valuable product [7]. As a result, biomethane production also has important and direct implications for non-energetic sectors, in a context of limited biomass availability and of biomass renewal affected by climate change, and effects as varied as water pollution, soil fertility or biodiversity protection [8].

In 2018, most of the biomethane production took place in Europe [3], where the industry has continued to develop since then, the main producers being Germany, Denmark, France, the Netherlands, and Italy [1],[9]. Great production potentials are estimated to exist all around the world, and studies can be found that try to estimate them depending on biomass availability, both nationwide [10] and worldwide [3], [11], but most of these potentials remain underdeveloped. In fact, with average production costs of around $65 per MWh, biomethane is usually less competitive than fossil gas, and often relies on various sources of public support [3], [9], [12].

Considering landfills, digesters, the variety of available upgrading technologies, and the diverse types of feedstocks that can be used, biomethane can therefore be the result of a great variety of production processes, but the literature interested in the economics of the industry is not yet much developed. On the one hand, several articles deal with project-specific characteristics, often by calculating indicators such as net present value, discounted payback time or internal rate of return [13], [14], [15]. In these articles, biomethane production is often studied within the framework of producers feeding anaerobic digesters with OFMSW and agricultural by-products, that are often presented as contributing towards a more circular economy [12],[16], but represent only one part of the industry. On the other hand, a small number of articles focus on the role of support policies and regulatory framework in the development of the industry between different countries [9], [17]. In this article, a bridge is made between case studies and macro studies, by considering both the techno-economic characteristics of existing producers and the way support policies try to account for the differences between these producers. To that end, all producers upgrading biogas generated through AD are considered, forming what is hereinafter referred to as the biogas-to-biomethane industry. By presenting an overview of this developing industry, this article aims at facilitating the discussion on support policies that were already implemented, identifying areas for improvement, and proposing some ways in which these improvements could be carried out.

In section 2, a simplified representation of the industry is first developed, considering its role as being limited to the development of a RES, and drawing preliminary conclusions for support policies. As an illustration, section 3 then focuses on French policies and their results, and shows how this representation helps us understand the relationship between different biomethane producers and the support they received. Finally, section 4 presents various limitations of this representation, and discusses ways of improving support policies accordingly. Here, particular attention is given to differentiating biomethane from other RES, as an industry with strong implications for non-energetic sectors. An attempt is therefore made to present the numerous externalities associated to the industry and, rather than trying to quantify only some of them, a discussion is made regarding how support policies can take these externalities into account.

2. Some economics of the biogas-to-biomethane industry

Even though the end-product injected into the grid or sold as a fuel can be considered homogeneous, biomethane can therefore be the result of a diversity of production processes. In this section, rather than focusing on a single type of producer, I propose a simplified representation of the entire biogas-to-biomethane industry, by making a distinction between three different models that enables us to better understand biomethane support policies. I then characterize these three models with regard to their respective production costs, and draw some first implications for policy design.

2.1 Differentiating production models

A first production model corresponds to what is usually referred to as "landfill gas". In that case, the collected and upgraded biogas is the result of the naturally occurring decomposition of the organic fraction of the waste in sanitary landfills. Under these circumstances, biomethane production requires only biogas collection and upgrading [18]. Here, I call this model *Waste gas recovery* (WGR). A second model, that is regularly studied in the literature and often presented as contributing towards a more circular economy [12],[16], produces biogas by feeding an anaerobic digester with available biomass, namely OFMSW and agricultural or industrial by-products. On top of an upgrading system, it therefore requires the acquisition and operation of a digester and produces a significant amount of digestate, as an additional output that may in some cases be used as a fertilizer. Within this model, a distinction can be made depending on the amount of pretreatment and transformation required before feeding the organic matter to the digester, as well as the necessary collection and transportation effort to get these feedstocks to the production site. Examples of this model could be a WWTP generating biogas from its sludge, requiring no transportation, or an installation relying on waste from the agri-food industry and the recovery of animal manure transported from several farms. Here, I call this model *Waste to resources* (WtR). The third production model also includes the usage of a digester but relies to a certain extent on feedstocks that are produced specifically for the purpose of producing biogas. Within this model, a distinction can also be made depending on the resources and human labour required for this production, its collection, its transportation and its eventual treatment or transformation. An example of it could be a facility using partially or solely cover or energy crops (produced, collected and transported) from one or several surrounding farms. Here, I call this model *Additional biomass production* (ABP). These three production models are represented in Figure 1.

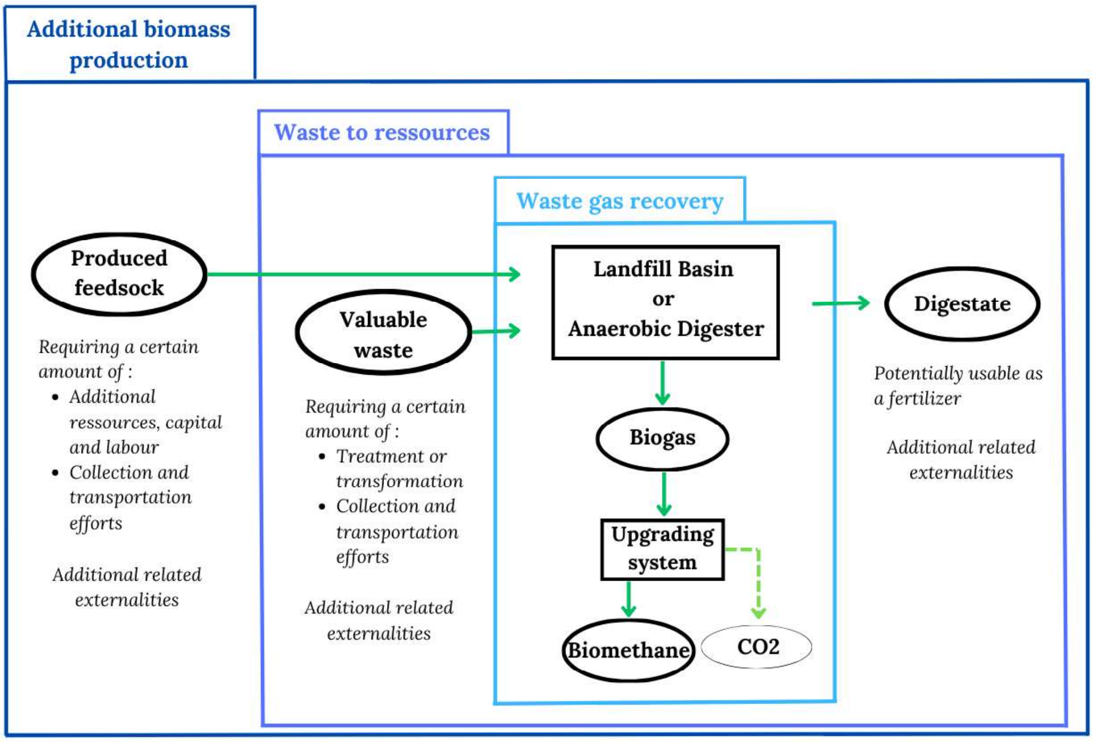

Figure 1 : Simplified representation of the biogas-to-biomethane industry. Source: author

As they have different implications, these three models also have different relationship with public policy objectives. In the EU and in France, it is illustrated by the aim to systematically sort the organic fraction of waste and divert it from landfills, which would result in a fast and strong decrease of the WGR model [19]. Moreover, throughout the implementation of support policies, a certain distance is sometimes taken towards ABP. As mentioned in the introduction, it was the case in the REPowerEU plan published by the European Commission in 2022, which focused on "organic waste and forest and agricultural residues", in order to "avoid impacts on land use and food security". As another example, in France energy crops are legally limited to 15% of the feedstocks that can be used for AD, with the exception of energy cover crops[1].

This distinct treatment between production models can be justified by several technical elements. For a given amount of waste, sorting its organic fraction and using a digester enables to produce more biogas compared to the sole recovery of landfill gas [20]. As for energy crops, they have indeed in some cases been criticized by the scientific literature for their competition with food production, the consumption of water and energy they require as well as some of their effects on pollution and biodiversity [21]. As a broader explanation, it could nevertheless also be argued that this distinction reflects the objective of favouring circularity, understood as a normative concept. In fact, even though no consensual definition of it can be found, regularly cited features of a circular economy are that it should avoid waste production, keep the resources within the economy when a product reaches the end of its life [22],[23] and minimize the use of virgin resources, including energy [23],[24]. Yet,

[1] French decree n° 2016-929, July 7, 2016

within this framework the WGR model is the furthest to a circular system, as even though the organic waste contributes to the production of a valuable product, the rest of its components remain mixed with the other wastes and are therefore lost. Landfilling can moreover be seen as the "*bête noire*" of circular economy ideals and is contrary to the objectives defended by the EU regarding waste management [23],[25]. For its part, the WtR model's contribution to global circularity depends on the characteristics of the associated business model : which are the feedstocks used, what would have been done with them otherwise, how much energy is needed to transport and transform them and whether digestate can be used as a fertilizer afterwards [26]. It can nevertheless in some cases be considered as a "virtuous model of a circular bioeconomy" [12]. As for the restrictions regarding dedicated energy crops in the ABP model, they could then be justified by the will to favour waste and by-products valorisation over additional resources consumption.

As a result, the respective importance of these production models varies around the world. In 2020, the IEA stated that the WGR model represented nearly 90% of the biogas produced in the USA [3]. For the two other models, a clear distinction cannot always be made from reliable available data, but we know for example that the ABP model played a significant role in the German biogas industry [21]. In France in 2024, as per the declarations of more than 400 producers, an average of 32% of the biomass fed into digesters corresponded to ABP (essentially energy cover crops) [27]. By contrast, in 2018 the IEA did not report any biogas produced through crop use in the USA [3]. In France, according to the Agency for Ecological Transition, the OFMSW, WWTP sludges and industrial organic wastes only represent 10% of the potential for biogas production [28]. The other 90% is then considered to come from agricultural biomass, that could be composed of 59% of by-products (animal manure and crop residues), and 38% of energy cover crops [10]. In this perspective, in France both WtR and ABP are expected to play a key role.

2.2 Respective production costs

As a result of the variety of feedstocks, technologies and regulatory environments, the biogas-to-biomethane industry can face variable costs and generate variable revenues. In 2020 the IEA estimated the worldwide production cost of non-upgraded biogas to be between 7 and 70 US$ per MWh, with the average cost in Europe being closer to the upper range, partly due to the legislation diverting organic waste from landfills where the cost of producing biogas is the lowest. Once upgraded, it estimated the average worldwide biomethane production costs to be of $65 per MWh [3], but in the literature cost estimates can be as high as €190 per MWh [12]. Due to this diversity of production models and costs, many articles rely on case studies. Taking a different approach, my objective here rather than highlighting the costs and revenues within a specific context is to design a generic cost function for these different production models. From a policymaking perspective, the objective of such function will then be to discuss its implications regarding biomethane subsidies and other forms of public support.

2.2.1 Which costs for which production model?

On top of the varying cost level of different technologies, an element emerging from the study of articles on biomethane production is the need to clarify which production costs should be considered from the policymakers' perspective. When studying biogas production costs from landfills for example, some techno-economic articles consider all the landfill related costs, including sometimes landfill construction, operation, closure and aftercare [29]. However, considering the use of landfill gas as waste gas recovery rather than as a production process going from waste collection to gas valorisation poses the question of cost additionality. From a policymaker's perspective, as landfills naturally generate biogas and as long as support policies are not meant to support waste management, these policies should solely focus on the additional costs arising from biogas collection and upgrading from existing landfills. From this perspective, the biogas production costs of a WGR system then only correspond to the installation and maintenance of a collection system composed of extraction wells, wellheads, pipes gathering and of knockout, blower and flare systems [20]. To obtain biomethane, the most important costs then are the ones arising from the biogas upgrading system installation, operation and maintenance [30].

Concerning the WtR model, the amount of costs to be considered is higher. In addition to biogas upgrading costs, techno-economic papers studying this model typically highlight the important costs of installation, operation and maintenance of the digester and the costs of acquisition and transportation of the feedstocks [12],[31]. Within operating costs, labour and electricity costs are sometimes considered separately. Additional costs, mainly related to distribution or financing, are not considered here. Here, it is important to note that, in some cases, acquiring feedstock may generate an income rather than a cost. It is especially true for OFMSW, for which biogas companies may charge "gate fees" (i.e. waste treatment fees). When subsidies to biomethane are low or inexistent, "solving the waste problem" may even be their main source of revenue [26]. Overall, the costs of producing biogas then are higher than the costs of its upgrading, the latter representing between 12 and 17% of the initial investment depending on the technology used [15] and in some cases 19% of the total costs incurred over a biomethane project's lifetime [31].

With respect to the ABP model, the relevant costs are similar to those of the WtR model, except that the acquisition of feedstock grown specifically for biomethane production will always have a cost, adding itself to those of collection and transportation.

A generic function representing the costs incurred by a biogas-to-biomethane project over its lifetime can then be given by:

$$C_{Bm} = \sum_{i=\{Bg,Up\}}(I_i + C_i^o) + \sum_{i=F}(C_i^a + C_i^{ct}) \qquad (1)$$

Where:

- Bg represents the production of biogas, and Up its upgrading

- I represents the initial investment in the production and upgrading units, and C^o the operating costs necessary to their functioning (labour, energy, component replacement)
- F represents the list of feedstocks to be used, C^a their respective acquisition cost (purchase price, production cost or gate fee, i.e. a negative cost), and C^{ct} their collection and transportation costs.

In the case of WGR, the second sum in *(1)* can then be considered as null, and I_{Bg} and C^o_{Bg} being limited to the installation and maintenance of the collection system, the main costs will be I_{Up} and C^o_{Up}. In other production models however, the terms of *(1)* may all be decisive. Between WtR and ABP, a major difference can be the determinants of feedstock acquisition costs. In the WtR model, supplying a biomethane producer can enable waste producers and waste management players to reduce their waste treatment costs. A biomethane producer may then benefit from a negative C^a determined according to these avoided costs, which is an assumption made in several previously cited articles. In the case of ABP, it can however be assumed that the C^a of purposely produced feedstocks will always be positive, with a minimum value corresponding to the cost of additional resources, capital and labour required for its production.

2.2.2 Which plant specific economies of scale?

In addition to these varied costs, plant specific economies of scale within a given production model should also be considered.

In the case of WGR, most of the production costs are those of biogas upgrading. As these decrease sharply with production capacity [30],[31], WGR is expected to benefit from important plant specific economies of scale. This can be illustrated by Sales Silva et al. (2022), who find a strong linear relationship between capital costs and net present value for the installation of biomethane production units on existing landfills in the Southeastern region of Brazil [30]. For other production models, plant specific economies of scale are also likely to be observed, but they will most likely be less important. On the one hand, in addition to those benefiting biogas upgrading units, economies of scale are observed for both the installation and the maintenance of units producing biogas through digesters [32],[33]. On the other hand, the cost of feedstock supplying, i.e. acquisition, collection and transportation costs, could produce an opposite effect. In fact, in the case of WtR, a producer can minimize its costs per unit of energy generated by selecting feedstocks with the lowest acquisition costs, i.e. waste potentially exchanged against a positive gate fee, and with the lowest collection and transportation costs, i.e. ones geographically close or easier to collect. As installing a greater capacity means acquiring more feedstocks, a greater producer will most likely have to select second choice feedstocks, that for an identical methane potential will be more expensive, harder to collect or further away, therefore increasing its supplying costs. The latter is for example illustrated in D'Adamo et al. (2021), who find transportation costs to be higher when the size of installations is greater [14]. In the case of ABP, a producer growing its own crops could benefit from economies of scale similar to those generally observed in agriculture, whose significance is debated in the literature [34]. Overall, the importance of plant specific economies of scale are therefore likely to be reduced in WtR and ABP models due to the high weight of operating costs compared to initial capital costs [35]. As shown by Skovsgaard and Jacobse (2017), high transportation costs associated to plant capacity increases could partially offset or even outweigh reductions in capital costs and other operating costs [33].

It is therefore important to note that in the case of WtR and ABP, considering feedstock acquisition, collection and transportation costs to be independent from a plant capacity is likely to lead to underestimate the costs faced by high-capacity plants, and that additional studies are still required to account for the respective importance of these economies and diseconomies of scale effects. In France, the latest report of the Energy Regulatory Commission (CRE) on biomethane production through AD highlights an absence of economies of scale for total operating costs and limited ones for overall production costs, with a Levelized Cost Of Energy of the greatest units that is only 12% lower than the median one [27].

2.3 First implications for support policies

In a situation where biomethane production costs are higher than natural gas market prices, policymakers willing to promote the development of the industry face a wide range of possibilities. To develop RES such as PV or wind power, the respective advantages and disadvantages of a variety of instruments have been widely discussed, as for example in Finon & Perez (2007) [36]. In this subsection, the objective therefore is to draw on the elements developed in sections 2.1 and 2.2 to apply these arguments to the case of biomethane.

In the public economics perspective, a simplified representation of a government's objectives when supporting RES refers to two main aspects. On the one hand, it aims at maximizing the amount of renewable energy produced, with the objective of enabling a substitution between RES and fossil fuels. On the other hand, it aims at minimizing the cost of this support for both the state and consumers. To this end, welfare economics suggests the implementation of an environmental tax based on the damages caused by GHG emissions. As such a tax can however be either insufficient or hard to implement, alternative demand-side strategic deployment policy instruments have been used in several countries for PV or wind power, namely Feed in Tariffs (FiT), Bidding Instruments (BI) and Exchangeable Quotas (EQ) [36]. With FiT, energy is bought from any new producer, at a minimum guaranteed tariff per kilowatt-hour that is fixed by policymakers over a long period of time. With BI, producers also sell energy through a long-term contract, but the beneficiary producers are selected through auctions that also determine the purchase price in these contracts. Finally, with EQ, policymakers oblige final energy suppliers to buy either renewable energy or renewable energy certificates to RES producers, until reaching an amount of RES corresponding to a legally defined percentage of their total sales.

Given the objective of cost minimization for the state and consumers, the support to biomethane production could then be directed towards the production model facing the lower cost. To that end, policymakers may implement undifferentiated systems of BI or EQ, with the expectation that competition between producers to be selected during the bidding or to sell their certificate at a low price should drive production prices down [36]. The first beneficiaries of this system would then theoretically be the producers facing the lower production costs, i.e. in most cases those of the WGR model [3]. Other production models would then only begin to develop once the maximum potential production through WGR has been reached, in ascending order of cost. This approach however is not the one that most favours research and development and a smooth development of RES [36]. As a result, when supporting PV or wind power, alternative approaches have been implemented with the aim of enabling the simultaneous development of a variety of producers, by differentiating support between producers and technologies depending on their respective costs. In order to introduce such a differentiation, BI can be adapted to some extent, for example by separating auctions in different technology bands. These adaptations however are limited, and differentiation is more easily implemented with FiT, that are more suited to adaptability [36]. In the case of a developing biomethane production, the great variety of costs and production models described in section 2.2 can therefore be a strong argument in favour of implementing FiT, rather than solely BI or EQ, in order to differentiate public support granted to producers, both between production models and within production models.

Once we acknowledge the interest of FiT to enable the simultaneous development of a variety of actors, a major difficulty is still to design effective tariffs while complying with the cost minimization objective. In this respect, knowledge of the supply curve (and therefore of the production costs described in section 2.2) is essential to adapt FiT depending on investment costs, operating costs, and feedstock supplying costs. As for other RES, FiT may for example be differentiated depending on the technology used by a producer, e.g. for biogas upgrading to biomethane. A differentiation based on production capacity is also likely to be applied in order to account for eventual plant specific economies of scale. Contrarily to PV or wind power, in the case of biomethane, a significant cost item however is feedstock supplying, and a differentiation could then also be introduced depending on the feedstock used. As an example, in case of equal collection and transportation cost, a producer benefiting from a negative feedstock acquisition costs for OFMSW treatment is likely to require a lower level of support than one using by-products for which it doesn’t get paid [35].

3. An illustration from the French case

In 2020, France was the third largest biomethane producer in Europe, with a production of around 2 TWh [1]. Since then, the industry has continued to grow, and in 2023 around 9 TWh of biomethane were injected into the French gas grid, corresponding to about 2,3% of the country's gas consumption[2]. In this section, a detailed analysis of the French support policies was conducted, which illustrates a vision of the industry by policymakers similar to that described in section 2.

3.1 French policy milestones

In order to describe the evolution of French support policies to biomethane, a selection of three French sources of different origins focusing entirely or partially on biomethane support was first made, combining views of industry players, regulators and the academic sector. The first one was the "Overview of renewable gases" report of 2023, published by the French Renewable Energy Trade Association and several other major national industry players, a part of which is dedicated to the chronology of the industry's regulatory framework [37]. A second one was the latest and most complete report of the French Energy Regulatory Commission (CRE) on biomethane, that was published in December 2024, with a section dedicated to the development of the industry [27]. A third one was a PhD thesis on agricultural AD realised by J. Cadiou in 2023, whose third chapter focuses on the evolution of French agricultural AD public policies from 2002 to 2022 [38]. After analysing these three sources, a list of policy milestones was drawn up, and a systematic analysis of the legal texts implementing these public policies was conducted. When applicable, the deliberations of the CRE associated to the various orders and decrees were also analysed. The rest of this subsection presents the main outputs of this qualitative analysis.

As a first outcome, the analysis reveals the preferences of French policymakers regarding technology choices and biogas uses. First, support policies have been oriented towards AD, that is considered as the most mature technology, long before alternative ways of producing biogas and biomethane. Whereas the support to injected biomethane production through AD and biogas upgrading was legally introduced in 2010[3], the possibility of implementing support policies for methanation, gasification or pyrolysis was only legally introduced in 2023[4]. Then, as has been the case in several European countries, French government and industry players have over the years shown a growing interest for biogas upgrading to biomethane rather than biogas direct use for electricity and/or heat generation [9], [38]. Lastly, among the possible uses of biomethane, grid injection was also widely favoured over direct sale as vehicle fuel, as the possibility of implementing support policies for the latter was only legally introduced in 2019[5].

[2] French Ministry of Ecological Transition "Chiffres clés de l'énergie, Édition 2024, Gaz naturel"
[3] French law n° 2010-788, July 12, 2010
[4] French decree n° 2023-809, August 21, 2023
[5] French law n° 2019-1428, December 24, 2019

Focusing on support policies for biomethane injection, a second outcome is the superposition of a succession of instruments, after the injection of biomethane into the grid was authorized in 2010. In 2011, FiT were first implemented, that granted access to 15-year contracts[6]. These FiT were then calculated depending namely on the year the contract was signed, the contract's progress, the type of producer, the unit's production capacity and, for producers using a digester, the feedstock used. In 2011 as well, a system of Guarantees of Origin (GO) was also implemented, whose relationship with FiT and the EU Emissions Trading System varied over the years[7]. In 2018, the EGalim law was passed, which led to the creation of an instrument financially supporting new producers' connection to the grid, depending on technical and economic criteria [27]. Between 2016 and 2023, a legal framework was gradually defined for the implementation of BI[8] for producers with a capacity greater than 25 GWh per year, who could not benefit from FiT anymore. Following the publication of tender specifications for these BI in 2023, the first auctions took place in 2024. Between 2021 and 2024, a legal framework was also gradually defined for the implementation of EQ, mutually exclusive from FiT, GO and BI[9]. As per several decrees published in 2024, the main French gas suppliers will then be obliged to buy biomethane production certificates from producers, up to an amount respectively corresponding to 0.4%, 1.8% and 4.2% of their sales in 2026, 2027 and 2028, or to pay a penalty of €100 per missing certificate[10]. Lastly, throughout the industry development, many producers have benefited from investment subsidies from several institutions, either European, regional or national agencies, in addition to the other support instruments [27].

Another key outcome of the analysis is the desire to differentiate the French industry from the German one, that relied heavily on energy crops. According to Cadiou (2023), the German biogas production model acted as a foil, from which energy actors wanted to differentiate themselves in a rather consensual way [29]. As a result, as mentioned in section 2, the use of energy crops was legally limited to 15% of the feedstocks used by a producer, with the exception of energy cover crops, that theoretically do not compete with other agricultural productions[11]. An important support was also granted to small capacity producers. As an example, in the FiT mechanism implemented in 2011, most of the producers benefited from a base tariff that was 48% higher for a capacity of 50 cubic meters of biomethane per hour than for a capacity above 350 cubic meters of biomethane per hour.

Finally, one last outcome is the fact that the support granted to the industry has evolved in phases. Has highlighted by Cadiou (2023), the implementation of FiT in 2011 marked the start of a period of strong support for the biogas industry, directed primarily to injected biomethane [38]. From 2017

[6] French order on biomethane FiT, November 23, 2011

[7] See in particular: French decree n° 2011-159 (November 21, 2011), article L446-22 of the Energy Code and decree n° 2022-1540 (December 8, 2022)

[8] See in particular: French order n° 2016-411 (April 7, 2016), decree n° 2020-456 (April 21, 2020), decree n°2021-1273 (September 30, 2021) and AO PPE2, Biomethane injection tender specifications (December 2023)

[9] See in particular: Law n° 2021-1104 (August 22, 2021), decree n° 2022-640 (April 25, 2022) and decree n° 2024-718 (July 6, 2024)

[10] The sales considered are however limited to the residential and tertiary sectors, which according to the CRE only corresponds to around half of the French consumption

[11] French decree n° 2016-929, July 7, 2016

however, the government started considering to decrease these FiT, namely because the support was costly, because the CRE highlighted a probable excessive profitability of supported producers [39], and because the objectives of the French Pluriannual Energy Programming were likely to be reached earlier than expected. As a result, in 2020, access to FiT was limited to producers with a capacity lower than 300 cubic meters per hour, tariff premiums that benefited producers using cover crops and agricultural or industrial by-products were limited to those using animal manure, a penalty for producers who received investment subsidies was introduced, and it was established that FiT for new producers would fall gradually by a minimum of 0.5% at each quarter, depending on the industry's development speed[12]. The years after 2020 were therefore characterized by a lower support, and by the will of the state to control better the cost of its support to the industry. Nevertheless, Cadiou (2023) soon highlighted the possible beginning of a new period of renewed support from 2022 onwards, in the context of slowing industry development and of greater emphasis on energy independence due to the war between Russia and Ukraine. Since then, such an hypothesis seems to be confirmed, with FiT increasing again in 2022 and 2023 [27], as well as the concrete implementation of BI and EQ instruments that was described earlier.

3.2 Resulting developments: a brief overview of the French industry

In France, the units injecting biomethane into the grid are all listed in "Open Data Réseaux Énergies" (ODRE), along with information such as the type of producer, the region where it is located, the year it started operating, its production capacity, or the type of network it is connected to (i.e. transmission or distribution). This subsection therefore briefly presents the development of the industry after grid injection was authorized in 2010, based on the ODRE data as of January 2025.

At the end of 2024, France had 731 units injecting biomethane into the grid, 86% being connected to the distribution network, and 14% to the transmission network, with a much higher density in the northern part of the country[13]. Their average production capacity was of 211 cubic meters of biomethane per hour (m^3/h), and their median production capacity of 164 m^3/h[14], which is much smaller than in other European countries [40]. The most common type of producer is by far the "self-sufficient agricultural plant", that is defined as a project supported by one or more farmers, producing through a digester and with more than 90% of feedstocks being agricultural materials coming from their own farm. These producers, that usually rely partially on additional biomass production (mainly cover crops) [27], represent 65% of the operating units. They often have a smaller capacity than other producers, with an average capacity of 178 m^3/h, and a median capacity of 150 m^3/h. Producers using a wider variety of feedstocks, which may be agricultural, OFMSW, WWTP sludge or other industrial

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[12] French order on biomethane FiT, November 23, 2020

[13] A map showing the location of all production sites is regularly updated on the ODRE website at https://odre.opendatasoft.com/pages/observatoire-biomethane-v2/?flg=fr-fr#implantation-des-sites

[14] Since 2021 in France, the capacity of production units is expressed in GWh per year. As the literature however generally uses m^3/h, a conversion was made assuming an annual production of 0.09 GWh per m^3/h of capacity, as per the hypothesis made by the law at the time of the change of units.
Here, it should also be highlighted that many units are already connected to the grid but plan to increase their capacity in the coming years.

by-products represent 24% of the units, and producers relying solely on WWTP sludge 7% of the units. The ABP and WtR production models therefore already represent the bulk of French industry. Landfill gas, which corresponds to the WGR production model, only constitutes 3% of the production units.

From 2010 onwards, the implementation of supporting tools, mainly FiT, contributed effectively to the development of the industry. Figure 2 presents the evolution of the number of units and corresponding total production capacity connected to the grid after 2010, showing a strong increase for both after 2018, until reaching 731 units in 2024, for an annual production capacity of 13.9 TWh.

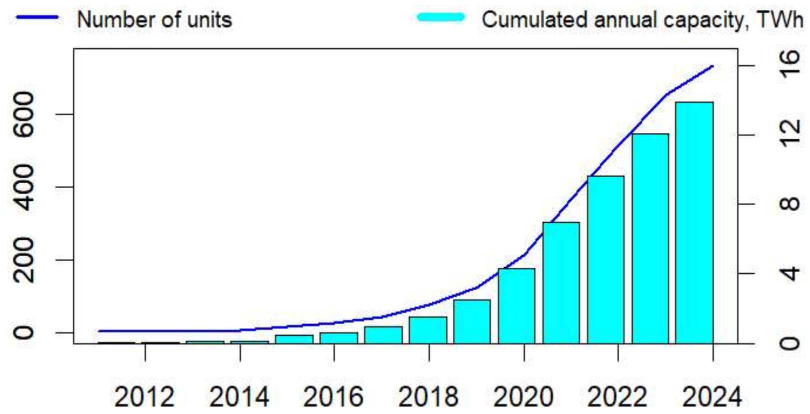

Figure 2 : Evolution of the number of units and corresponding total production capacity connected to the grid after 2010. Source : ODRE data, January 2025

In the last years, the industry's growth rate has nevertheless varied. As is shown in Figure 3, whereas the additional capacity installed every year grew between 2016 and 2021, it remained stable between 2021 and 2022 and started decreasing afterwards.

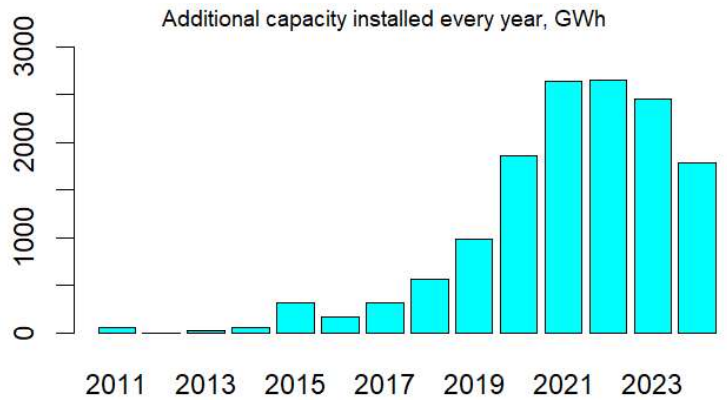

Figure 3 : Additional capacity connected to the grid every year after 2010. Source : ODRE data, January 2025

Given what has been said in the preceding sections, a first explanation for this slowdown could be the reduction of FiT implemented in 2020, along with the uncertainty regarding the implementation of BI and EQ instruments, whose legal framework still had to be clearly defined. Another possible explanation could however be that the industry's development was also affected by an announcement effect. According to the CRE, when producers realized in 2017 that the state planned to reduce FiT, many rushed to sign contracts before the reduction was actually implemented in 2020, which led to a spike in new contracts in 2019 and 2020, and therefore in new connected units in the following years [27].

Lastly, as higher FiT were granted to small capacity producer, whose development the state wanted to encourage, it is interesting to observe which size of producers were able to develop themselves. Figure 4 therefore shows the distribution of units connected to the grid depending on their production capacity. As it shows, many small capacity producers were indeed able to develop, and 80% of producers have a capacity of between 80 and 350 m^3/h.

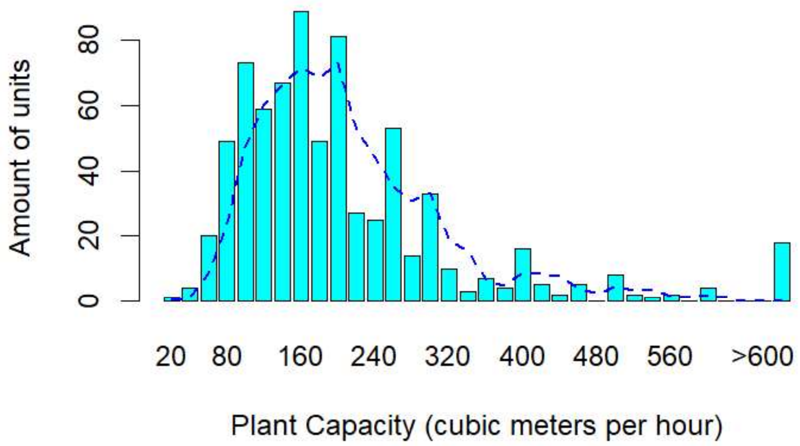

Figure 4 : Distribution of units depending on their production capacity. Source : ODRE data, January 2025

3.3 An illustration of the previously described framework

In section 2.3, it was highlighted how, in the case of biomethane, the great variety of costs and producers acts as an argument in favour of implementing FiT that can be adapted to simultaneously support various producers while minimizing the collective cost of this support. Here, the French case can serve as a good illustration of how policymakers can use the adaptability of these instruments to try to achieve this dual objective.

In fact, as per the French decree n° 2011-1594, the FiT implemented in 2011 were to be designed in a way that producer would benefit from a "normal return on capital, given the risks inherent in their activity". Thus, the excessive returns highlighted by the CRE in 2018 are likely to have played a key role in the FiT reduction in 2020[15] [38]. As an example, as it argued that some investment subsidies contributed to excessive returns [39], the new FiT of 2020 included a penalty for units who had been benefitting from them.

In order to better illustrate how policymakers tried to adapt FiT to producers' costs, the tariffs granted in 2011 to different new producers depending on their production model and size are represented in figure 5. Three types of producers are represented, respectively corresponding to the three production models described in section 2. One produces from a landfill, within the framework of WGR. Another produces using a digester, with feedstocks composed of 100% OFMSW, within the framework of WtR, as is the case in several previously cited articles. Lastly, one produces also in a digester but using 5% of OFMSW, 30% of manure, 25% of other agricultural or industrial by-products, and 40% of cover crops, as is representative of self-sufficient agricultural plants in France [27], within a partial ABP framework.

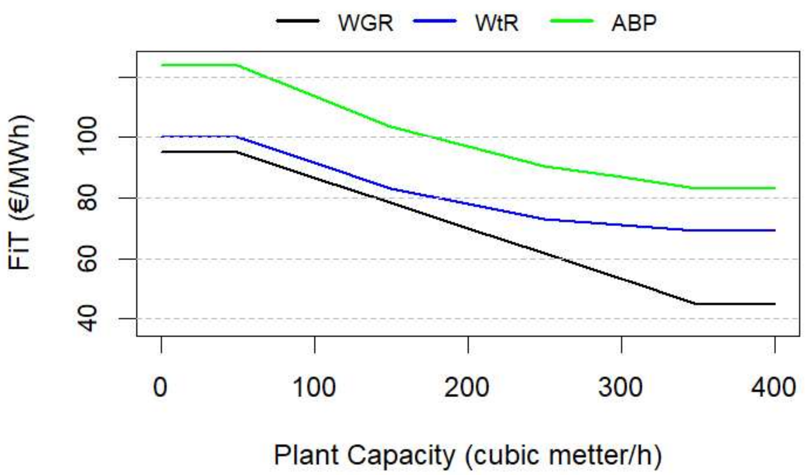

Figure 5: FiT granted in 2011 depending on producers' characteristics. Source : author's calculations, based on JORF n°0272 from November 24, 2011

A first point to be noted here is that the analysis conducted in section 3.1 largely confirms the will to design tariffs according to a principle of input availability and cost additionality, as described in sections 2.1 and 2.2. As an example, the CRE stated that tariff design should consider the fact that WGR producers do not face any cost linked to the acquisition of a digester or to feedstock transportation[16]. As figure 5 shows, these elements do indeed seem to have been taken into account, as ABP receives a stronger support than WtR, that is more likely to perceive gate fees, or than WGR, whose main costs only are of biogas upgrading. It can nevertheless be noted that the support to WGR is not always much lower than the one granted to WtR, even though the latter needs to invest in a digester and to collect and transport feedstocks. This could however be justified by high gate fees perceived by WtR, or by higher upgrading costs for the WGR as suggested by the CRE in some of its

[15] French Energy Regulatory Commission, Resolution 2020-223 from September 10, 2020
[16] CRE's deliberation on biomethane of July 26, 2011

deliberations. A second point is that two different tariff structures are clearly visible, with a stronger decrease of support depending on capacity for WGR than for WtR and ABP. Taking care not to over-interpret probably imperfectly designed FiT, such a difference is nevertheless coherent with the most likely higher plant specific economies of scale benefiting the WGR compared to those benefiting WtR and ABP, that were described in section 2.2[17].

In this context, a legitimate question is that of the effects that the new instruments (i.e. BI and EQ) will produce, and the type of producers to whom they will benefit. On the one hand, as they introduce competition, they are expected to lead to the emergence of high-capacity producers willing to benefit from economies of scale (see section 2.3)[18]. Between 2011 and 2020 however, no further FiT decrease was implemented after the threshold of 300 m^3/h of capacity. With economies of scale, producers should then theoretically have been encouraged to install larger capacity plants to reduce their cost per unit of energy generated while benefiting from a constant tariff. As highlighted in figure 4, the number of new units with a production capacity higher than 350 m^3/h has however been limited. One potential explanation for this relative absence could then be important effects of diseconomies of scale. In that case, the potential of BI and EQ to foster the emergence of larger producers with a lower production cost may be limited. Another potential explanation could also be the existence of barriers to the deployment of larger plants unrelated to production cost, that may for example be stronger local opposition or legal constraints. In that case, policymakers should then also take an interest in whether BI and EQ are likely to help the producers overcome these barriers, and whether they want these producers to be able to do so.

Lastly, a point worth noting is how even though BI and EQ are less adaptable than FiT, policymakers do try to adapt these instruments to producers' costs. As an example, in the case of BI, the tender specifications published in 2023 introduces distinct price caps for WGR than for WtR and ABP, respectively of €65 per MWh and €120 per MWh. In the case of EQ, a modulation coefficient was introduced, so that for a given amount of biomethane produced, WGR producers will receive less biomethane production certificates than WtR or ABP ones[19].

[17] It can also be noted here that in the specific case of a WWTP producer, that is not represented in figure 5, support granted from 2014 onwards was higher than for other producers, which is hard to justify or criticize given the scarce literature on the costs faced by these producers. It however has in common with WGR a strongly decreasing FiT depending on plant capacity, which may be justified by the fact that like for WGR, a WWTP has feedstock available on the production site, with feedstock supplying costs limited to more or less dewatering and pretreatments [41], and could therefore benefit from high economies of scale.

[18] Independently of these effects, BI are only directed toward producers with a capacity higher than 25 GWh per year (i.e. around 280 m^3/h) who cannot sign new FiT contracts since 2020.

[19] French order on the biogas production certificate scheme, July 6, 2024

4. Looking ahead: the prospects for support policies

In section 2, a simplified representation of the biogas-to-biomethane industry was developed, and section 3 showed how this representation can be useful to better understand the relationship between existing support policies and the different producers. This representation however has important limitations. In this section, the objective therefore is to list the main ones and to enhance our vision of the industry, in order to be able to adapt support policies accordingly.

4.1 Limitations so far

A first limitation of the representation in section 2 is of course its simplicity. In fact, more precise typologies based on qualitative analysis are required to better understand the motivations and behaviour of the great variety of biomethane producers. In the French case, such a typology was for example developed by Grouiez et al. (2020), who consider every project's type of initiator, size, type of biogas valorisation, positioning regarding digestate use, type of feedstock used, and specific associated risk. They then differentiate units that they call industrial, territorial, partially or entirely agricultural, or micro-units [42]. In Finland, Valve et al. (2021) also conducted a qualitative analysis and differentiated 4 business models, within the WtR framework, depending on whether value creation relied more on energy production, waste management or digestate production [26]. In both of these typologies, waste gas recovery from landfills however was not considered. In addition to presenting a simplified representation of the industry, our interest in support policies was limited to FiT, BI and EQ, whereas alternatives like feed in premiums or contracts for difference could also be considered. The potential role of GO in the French industry was also omitted as they theoretically cannot generate revenue for producers who benefit from FiT, but some non-compliant practices have been observed by the CRE, which may have had some limited effects [27]. However, here, I argue that the framework developed in the preceding sections actually has four main limitations, which are discussed in the following subsections. These are the weaknesses of the principle of additionality based on which it considers feedstock (i), the fact that it only partially considers aspects relating to the dynamics of the industry (ii), and the fact that, focusing too much on energy production, it does not consider all the revenues biomethane producers may benefit from (iii), and omits numerous externalities associated to biomethane production (iv).

4.2 The principle of additionality

In figure 1, models were mainly differentiated depending on the additional actions required to obtain biomass for biomethane production. In WGR, biomass is assumed to be brought into landfills independently of a will to produce biomethane, whereas in WtR available biomass (waste or by-products) must be collected and gathered for transformation. In ABP, biomass is produced specifically for the purpose of selling biomethane. As explained in section 3, in France this vision largely corresponds to that of the state and the regulator, but additionality cannot always be that easily assessed.

A good example of this limitation is that of energy cover crops (i.e. crops that are seeded and harvested between two cash crops, without competing with food crops for land use [8]). Throughout this article, cover crops were considered as ABP, with associated production, collection and transportation costs. Growing cover crops however is in some cases a legal obligation, due to the various ecosystem and soil protection services they provide. In France according to Malet et al. (2023), if cover crops were grown only in the areas where they are mandatory, they would nevertheless represent 9% of the country's potential for biomethane production [10]. In these cases, it could then be considered that cover crops do not correspond to ABP, but rather to one more agricultural by-product, that only requires to be collected. This reasoning would however not be entirely valid either, as energy cover crops are differently managed than regular cover crops, to produce more biomass [8]. The additionality of biomass production can therefore be only partial, which can again complicate the proper dimensioning of the support granted to producers. In a similar way, considering other agricultural by-products as available independently of biomethane production is only completely valid if we consider that the possibility of using them to produce biogas does not encourage the generation of a higher quantity of these feedstocks. As shown by Cadiou (2023), this hypothesis is however not verified, as the implementation of AD has led farmers to adopt a variety of strategies, including sometimes increases in farm size in order to collect higher amounts of manure [38].

For policymakers, reasoning according to a principle of additionality therefore requires in-depth reflection on which costs they wish to compensate, and which behaviours they want to encourage.

4.3 Feedstock availability from a dynamic industry perspective

In the previous sections, producers were considered as operating at a given time, and independently of each other. Here, the objective therefore is to enhance our vision of the industry in a dynamic perspective.

When supporting the development of a RES, an important concern from a dynamic perspective is the evolution of production costs. For policymakers, one objective can be to foster the reduction of these costs, until the RES potentially becomes cost competitive with its fossil alternatives. To that end, FiT have the advantage of favouring investment in research and development [36]. When support policies are successful and cost reductions are achieved, another objective is then to anticipate and adapt the support to these reductions in order to keep minimizing its cost for the state and for consumers. In the case of PV or wind power, progressive tariff declines were therefore implemented by anticipation of learning effects for producers entering the market latter and benefiting from enhanced technologies [36]. In the case of biogas-to-biomethane, the IEA estimates that the technologies for biogas production and upgrading already are relatively mature and anticipates cost reductions to be limited in the years to come [3], but similar support declines can nevertheless be implemented. In France, according to the CRE one of the objectives of the quarterly degression of tariffs that was implemented in 2020 was to take into account potential cost reductions over time, in addition to limiting the costs of the support in the event of a faster-than-expected development of the industry[20]. In 2020, the French Multiannual Energy Plan also implemented cost reductions targets for 2023 and 2028, according to which the volume of projects eligible for BI were to be defined[21].

An element that is however of importance for WtR and ABP, contrarily to RES like PV or wind power, is feedstock supplying. Coming back to *equation 1* of section 2.2, even if enhancements could be expected regarding the costs of installation and operation of the biogas producing and upgrading units, the evolution of feedstock acquisition, collection and transportation costs should also be considered. In fact, the development of a great number of actors in a limited area could lead to effects similar to that of diseconomies of scale that were described in section 2.2.

Assuming a constant feedstock availability, the coexistence of a greater number of producers entails the selection of less interesting feedstocks (i.e. more expensive, harder to collect or further away for a given methane potential), which would lead to an increase in acquisition costs (C^{a}) and collection and transportation costs (C^{ct}). Corroborating the likelihood of such an increase, in France in 2022 FranceAgriMer estimated that, given the feedstocks available, the efficient functioning of all the agricultural AD projects that were waiting for administrative approval at that time would require significant inter-regional trade of feedstocks, most likely involving increased transportation costs [43]. What is more, the development of the industry is likely to produce effects on feedstocks' price determinants. For WtR, it was stated in section 2.2 that C^{a} could be negative, due to avoided costs for those generating waste or by-products. For ABP, it was stated that C^{a} could be limited to the cost of producing the biomass. These cost determinants however are valid only in the absence of competing usage of these feedstocks. In fact, with the development of the industry and in a context of limited biomass availability, a competition for feedstock supplying could emerge between biomethane producers. Such a competition would then lead to the creation of a market where C^{a} would be determined mainly by a feedstock's interest for biomethane production, i.e. its methane production potential, at a higher level than when the industry first emerged[22]. In France, the emergence of such a market is corroborated by two studies : in 2022, the French Agency for Ecological Transition already highlighted producers' anticipations of increasing feedstock prices and falling gate fees due to increased competition for feedstock supplying [44]. In 2024, the CRE also highlighted a correlation between feedstock acquisition prices and their methane potential, as well as higher prices in the regions were the industry is more developed [27]. In that context, an increase in feedstock supplying costs (or an anticipation of such an increase) could also be a potential explanation for the slowing down of the industry's development after 2022, in addition to effects of the regulatory changes that were described in section 3.

In a dynamic perspective, leaving aside feedstock supplying is therefore likely to lead to an overestimation of the potential of the industry to reduce its costs. In fact, the emergence of

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[20] CRE's deliberation of September 10, 2020, N°2020-223
[21] Multiannual Energy Plan of 2020, page 105
[22] Here, it should be noted that this effect could also be amplified by the emergence of other biomass intensive industries, with different price determinants.

competition between producers for feedstock supplying could invalidate the results of several articles that assume feedstock acquisition costs to be negative and constant throughout the lifetime of a project. For policymakers, in light of these elements one approach could be to try to measure and anticipate cost increases and to dimension the support accordingly. To that end, the adaptability of FiT would once more offer a clear advantage, with the possibility to implement different premiums for each feedstock depending on their respective cost evolution. Such an approach would however entail an increase in the cost of energy for the state and consumers which would not benefit energy producers but feedstock producers, with the risk of feedstock supplying costs and support tariffs pulling each other upward. Another approach could then be to try to prevent these cost increases. To that end, a first possibility is to increase feedstock availability. This can be done by improving waste sorting and by-product collection processes, but only with a limited potential given biomethane production objectives [28]. Increased feedstock availability is therefore likely to rely also on the production of additional biomass. In addition to improving feedstock availability, a second possibility might also be to prevent the emergence of competition for feedstock supplying. This could for example be done by directly preventing feedstock suppliers from increasing their prices, or through local-scale industry planning, with authorities ensuring that producers needs do not exceed feedstock availability within a given area.

4.4 What benefits associated with biomethane by-products?

In the previous section, the description of the industry was made by considering producers whose commercial activity would be limited to biomethane production, which they sell and for which they benefit from subsidies and other decarbonation instruments, and eventually receiving gate fees that were considered as a negative cost. In fact, financial gains that should also be of interest for policymakers can also be obtained from two biomethane by-products, that were represented in figure 1. The first one is digestate, that is generated in both WtR and ABP models, and whose associated financial benefit often is only partially evaluated. The second one is biogenic CO2, that is generated in all of the three production models and accounts for between 35 and 50% of the produced biogas depending on feedstocks and production model [4]. The latter is still not frequently marketed (in the French case, by around 2% of the biomethane producers in 2024), but its commercialization could become much more frequent in the medium term [27]. Rather than measuring the gains associated to these by-products under specific conditions, the objective of this subsection therefore is to assess their general potential, as well as the conditions under which they may be obtained.

4.4.1 Digestate usage or sale

Depending on the cases and on the articles, digestate can be considered either as a waste or as a valuable by-products [25]. Thanks to its composition, it is most often used as a fertilizer [7], but this recovery faces a certain number of challenges, namely the presence of contaminants such as heavy metals and microplastics, risks of water contamination and of nutrient surplus, seasonality of demand for fertilizers, storage related GHG emissions and costs, transportation cost, and market acceptance [45],[46]. Key determinants for the potential of digestate to be used as a fertilizer are its composition and characteristics with respect to certain contaminants thresholds, which themselves depend mainly on the feedstocks used [47]. Whereas digestate produced from crops and agricultural by-products can often be directly applied to agricultural fields, the one produced from OFMSW generally requires further treatment in order to meet regulatory standards [45]. Digestate produced from WWTP sludge faces similar challenges and is often disposed of in landfills or burned in waste-to-energy plants [48]. In addition to issues related to its composition, the production of digestate also implies a certain number of costs. These include storage cost, as digestate produced continuously must be covered to prevent residual methane emissions, and must only be applied in agricultural fields during the growing season in order to limit water and air pollution [47]. Other significant costs are implied by digestate treatment and processing, which generally consist in separating its liquid and solid phases that may have different applications, and in order to facilitate its transportation and eventual sale [45],[47]. Finally, transportation costs should also be considered, as they can in some cases account for the highest share of digestate related costs [49].

Once all these costs are considered, the eventual financial benefit of digestate production may take three main forms. When the biomethane producers have an agricultural activity, digestate may be used directly by the producers, enabling to reduce fertilizer purchases [7]. It may also be entirely or partially sold and generate a direct revenue [50]. In France, some producers also exchange free feedstocks for free digestate, therefore reducing their feedstock acquisition costs [44]. In order to evaluate this financial benefit, one method is to measure the amount of nitrogen, phosphorus, and potassium (NPK) contained in the digestate and to assess its value given the market price of the amount of fertilizer it can replace. It is the "avoided cost methodology" used for example by Gonçalves et al. (2024), who estimate the benefits of using biofertilizers for a biogas based electric power generation system in the Brazilian market to be between 50 and 160 US$ per MWh of generated electricity [51]. In the case of biogas upgrading rather than combustion, this benefit could then be between 18 and 59 US$ per MWh of biomethane produced[23] depending on digestate composition. It is important to note that this range however does not consider volatility on commodity markets, where the price of commonly used fertilizers varies on average of 29% every year[24]. This method nevertheless doesn't consider any of the additional costs mentioned above, assumes that feedstocks wouldn't be used as fertilizers if it were not for the biogas production, and considers digestate and fertilizers to be homogeneous products. In practice, Dahlin et al. (2015) highlighted that "the prices of digestate products used for fertilization do not fully capture the products' intrinsic nutrient value" and estimated that raw digestate only reached a maximum commercial value of 60% of this nutrient value during spring. According to the authors, sale prices for raw digestate then ranged from a positive 5€/t to a negative 18€/t depending on the season, transportation costs, nutrient content and legislation. Once upgraded, fertilizing digestate products could reach much higher prices, up to 100€/t [50]. Such products are however also more expensive to produce, and D'Adamo et al.

[23] Gonçalves et al. (2024) assume the calorific power of biogas to be 6 kWh/m^3, and an electric generation efficiency of 2,2kWh per m^3 of biogas.
[24] Calculation based on the World Bank Commodity Price Data between 2000 and 2024 for phosphate rock, DAP, TSP, urea and potassium chloride.

(2019) estimated that the revenue generated from selling upgraded digestate only outweighed the costs linked to its production at around 50€/t [35]. Digestate and commercial fertilizers being non-homogeneous products, I therefore argue that the results given by the avoided cost methodology should be seen as a theorical maximum financial benefit. To the best of my knowledge, in France the only study considering both empirical avoided costs and revenues from digestate sale was realized by the French Agency for Ecological Transition in 2022. For agricultural producers, it estimated the average financial gain to be of 10€ per MWh of biomethane produced [44]. From a policymaker's perspective, it would then be of interest to study the effect of a unit's size or type on its ability to capture more or less of the theorical maximum digestate benefit. On the one hand, digestate processing can be subject to plant specific economies of scale due to high initial investment costs [49]. On the other hand, large amounts of digestate require to be applied on large areas for environmental reasons. As in the case of feedstock supplying (section 2.2), producers with greater capacity could therefore also face plant specific diseconomies of scale due to higher digestate transportation costs.

4.4.2 Sale of Biogenic CO2

After being separated from methane and other trace components during the biogas upgrading phase, biogenic CO2 can be subject to several commercial uses, including in the food, chemical and pharmaceutical industries, or to produce e-fuels. Depending on the regulation and eventual emission trading schemes, Bioenergy with Carbon Capture and Storage (BECCS) may also be considered [52]. Even though it is not a common practice nowadays, commercializing the biogenic CO2 can contribute to a biomethane plant profitability [53]. As an example, Horschig et al. (2019) highlight the interest of selling biogenic CO2, especially as dry ice, to secure an on-going biomethane production [54]. Another option could be to use biogenic CO2 to produce e-fuels by combining it with hydrogen. According to Brynolf et al. (2018), capturing CO2 from biogas upgrading could indeed be an interesting option for e-fuel production thanks to the high CO2 concentration in biogas (i), the increase in the yield of biomass use it enables (ii), its non-fossil origin (iii), and the low cost of CO2 capture from existing biomethane plants (iv). In the long term, this cost is estimated to be lower than 20€ per ton of CO2. In comparison, a low estimate of 30€/tCO2 is given for CO2 capture from oil refining plants, cement or iron and steel industries. For CO2 capture from natural gas and coal power plant, the price could be as low as 10€/tCO2, but with high uncertainty (higher estimates are of 60 and 100€ respectively) and without the advantage of having a biogenic origin. As for direct air capture, the price variability is even higher [55]. Biogenic CO2 from biogas upgrading could therefore be of interest for several transportation industries. In several studies, the capture cost of CO2 only represents a minor share of the total e-fuel production cost [55], whereas other consider for example that a drop in CO2 purchase price from 50€/t to 30€/t could reduce total transportation cost by between 5 and 9% [56]. Overall, the economic feasibility of e-fuels production is still deeply influenced by regional variables, technological developments, and the used energy sources [57]. In Turkey, Tozlu (2019) estimated the potential production cost of methanol using CO2 from an existing biomethane WWTP to be of 0.69 $/kg [58]. As a comparison, between 2010 and 2020 the commercial price of methanol (mainly produced from fossil sources) fluctuated between 0.2 and 0.4 $/kg [59]. As for digestate, from a policymaker's perspective it would then be of interest to estimate the financial gain a producer may obtain from selling its biogenic CO2.

Leaving aside eventual transportation and storage costs, a first estimate of this benefit in € per MWh of biomethane produced can be given by:

$$V_{CO2} = \left(\frac{1000}{h_{CH4}}\right) * \left(\frac{\%CO2}{\%CH4}\right) * r_{CO2} * \left(\frac{w_{CO2}}{1000}\right) * (P_{CO2} - C^{c}_{CO2}) \qquad (2)$$

Where:

- h_{CH4} is the heating value of biomethane, in kWh per cubic meter
- $\%CO2$ and $\%CH4$ are the percentages of CO2 and methane contained in the non-upgraded biogas
- r_{CO2} is the CO2 recovery rate
- w_{CO2} is, in kg, the weight of one cubic meter of CO2
- P_{CO2} is the assumed selling price of one ton of CO2
- C^{c}_{CO2} represents the cost of capturing one ton of biogenic CO2 from an existing biomethane plant

Assuming a heating value of 10 kWh/m^3 for biomethane[25], a CO2 recovery cost of 20€/ton [55], a CO2 recovery rate of 97% [12] and a CO2 weight of 1,84 kg/m^3 [12], figure 6 shows additional revenues from CO2 sales depending on P_{CO2}. Two producers are represented, whose non-upgraded biogas CO2 contents respectively are of 35% (low CO2 content) and 50% (high CO2 content) [4]. As the figure shows, in case of high market prices, CO2 sales could represent significant additional revenues and partially compensate for the higher upgrading costs the high CO2 content biogas producer might face. It should nevertheless be highlighted that here, in addition to neglecting storage and transportation costs, the effects of plant size on CO2 capture costs were not considered.

[25] French order on biomethane FiT, November 23rd, 2011

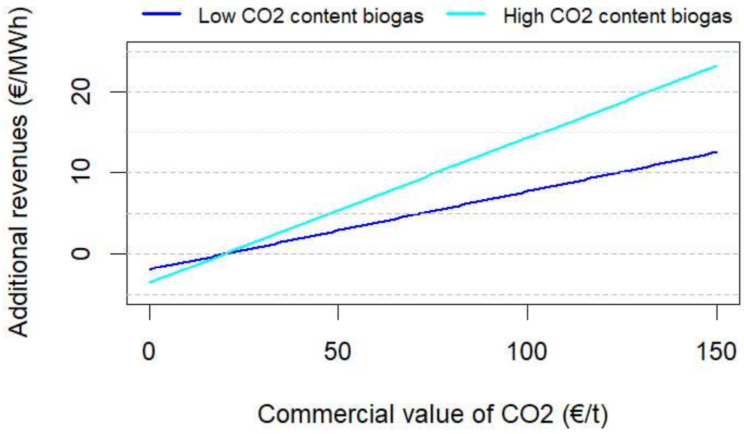

Figure 6: Potential financial gain from CO2 marketing. Source: author's calculations

If not commercialized, the CO2 fraction of biogas could also be used for further biomethane production through biological methanation, which is the preferred option in most of the French Ecological Transition Agency's scenarios for 2050 [60]. The methanation process can either be realized by combining the CO2 obtained from biogas upgrading with hydrogen, or by directly combining non-upgraded biogas and hydrogen. In the latter case, CO2 could however hardly be considered as a by-product of AD, the combination of AD and methanation then requiring to be studied as a whole [61], [62].

4.5 Externalities associated to biomethane production

Throughout this article, the only two policymakers' objectives considered were maximizing biomethane production and minimizing the cost of the support. In fact, the literature highlights the variety of implications of producing biomethane and its by-products, including for example agricultural or waste management implications. It was also highlighted in section 2 how not only energy production but also the contribution of biomethane to circularity most likely played a role in the differentiated treatment of the distinct production models. Support policies could then have been adapted in order to reach alternative objectives, like circularity, which often require to consider the detail of producers' motivations as well as the business models in which they fit [26]. Although the analysis carried out so far can therefore serve as a good basis, understanding the design of existing support policies and suggesting ways to improve them therefore requires considering broader objectives than energy production. In this perspective, the objective of this subsection is to consider a wide range of externalities associated to the biogas-to-biomethane industry and to integrate them into the framework developed in the preceding sections.

4.5.1 Which externalities for which production model?

In 2019 in France, the CRE published a report on "The greening of gas", most of which was dedicated to AD, including the externalities associated to the industry. The main cited externalities were reduction in GHG emissions, the utilization of already existing gas infrastructures, the strengthening of the national energy independence, the development of a circular economy, and benefits for the agricultural sector through the production and usage of digestate and the development of cover crops [40]. The objective then was to try to quantify several positive externalities other than GHG emissions, that could help justify the public support to an expensive RES. This report was then published in a context of growing interest of industry players for biomethane related positive externalities, as a reaction to the will of the state to reduce the cost of its support (see section 3) [38]. In this report as in some of the articles cited above, the distinction between externalities and by-products is however not clearly made. Most importantly, as shown by Cadiou et al. (2023) most of the studies on the future of AD in France, including this report, adopt a normative rhetoric on the evolution of agricultural systems, by focusing on good practices to be adopted without discussing the possibility that farmers may not do so [63].

Here, externalities are considered as "a side effect without compensation" for the producer [64], and potential financial benefits derived from the usage or sale of digestate or biogenic CO2 that were described in section 4.4 are therefore not considered as such. Moreover, rather than quantifying some of these externalities in a partial way, the objective here is to establish links between these externalities, production models and support instruments previously described. To that end, a list of externalities of interest was made based on a selection of articles. On the one hand, the potential positive externalities that were highlighted by a variety of actors are listed by Cadiou (2023)[26] [38]. On the other hand, several articles that list both potential negative and positive externalities linked to different production models were considered [8], [46], [65], [66].

The analysis of these articles reveals a variety of potential externalities, other than just GHG emission reductions and energy independence. On the positive side, important potential externalities for example are the creation economic activity, better waste and manure management, contribution to the national and farmers' nutrient independence through digestate production, and ecosystem services provided by cover crops. Potential negative externalities are also numerous, with for example soil contamination due to digestate use, competition with food production, or neighbourhood nuisances like smell or noise due to feedstock and digestate storage and transportation. These externalities are listed in figure 7, which also shows how their number increases from one production model to another. Indeed, externalities of WGR only are those associated with naturally produced biogas collection and upgrading. As WtR requires additional actions and produces digestate, it also generates externalities linked to feedstocks collection and digestate usage. As for ABP, it additionally produces negative or positive effects due to the cultivation of dedicated or cover crops.

[26] In her work, Cadiou does not focus on externalities but on the concept of socio-technical promise, derived from sociology of expectations to highlight how various players mobilize the industry's potential benefits to justify support policies. Here, this work was however considered as the best source listing, among other things, the potential positive externalities of interest for policymakers.

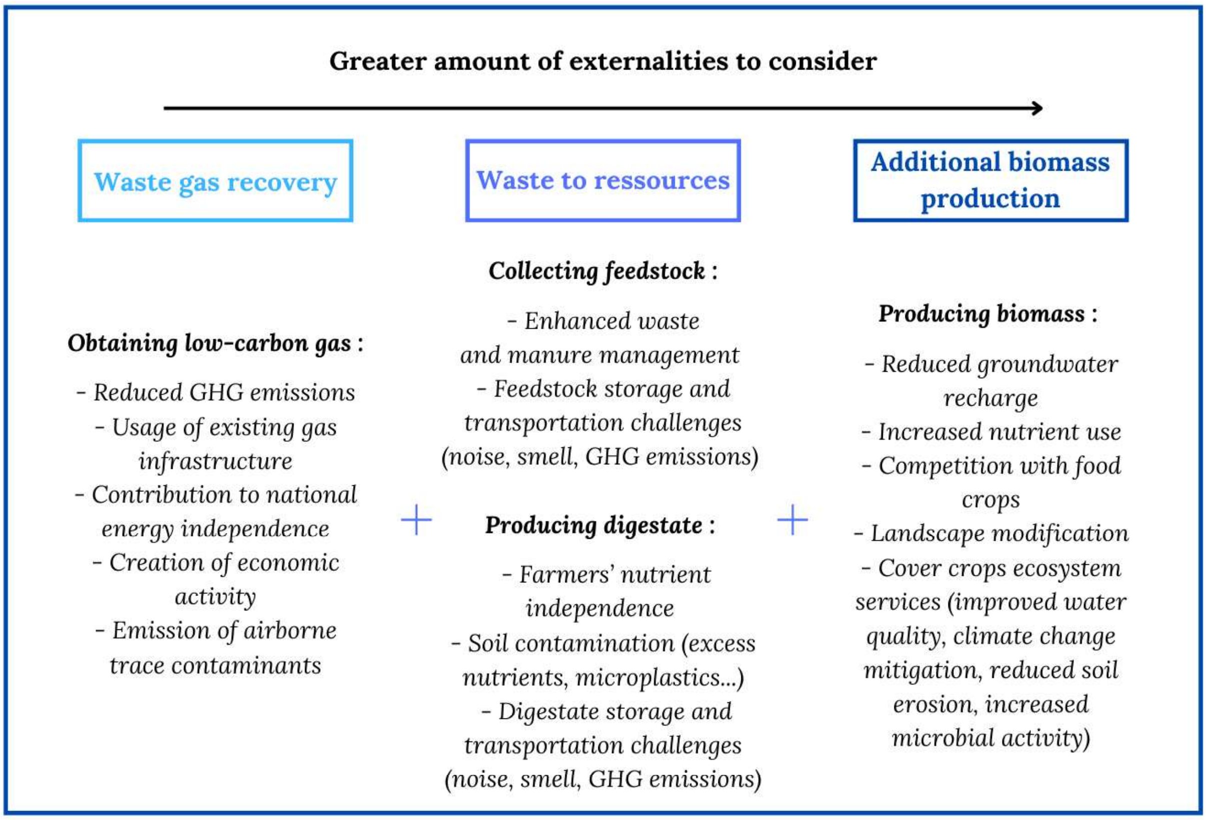

Figure 7: Additional potential externalities associated to each biomethane production model. Source: author

Here, it should again be highlighted that these externalities are only potential ones, as many of them depend on the producing units' characteristics and industry players' behaviours. As examples, the affective assessment of GHG emissions reduction requires to realise life cycle analysis and consider potential methane leakage from digester and upgrading units [46], and ecosystem services provided by cover crops depend on how they are managed [8]. It should also be noted that this list of externalities was developed based on a limited number of sources, and that a broader analysis could probably be conducted to develop a more exhaustive one.

4.5.2 What role for support policies?

Once the list of externalities of interest has been determined, a question that naturally arises is that of the relationship between these externalities and support policies. In this subsection, the objective therefore is, based on the analysis that was conducted in section 3, to discuss how these externalities were considered in the French case.

In France, since 2010, two main approaches have been adopted by policymakers to consider externalities of the biogas-to-biomethane industry. The first one has been to regulate and prohibit certain practices, while creating the conditions for all others to be financially viable. The second one, less developed, has been to introduce certain financial incentives within the support to favour certain practices over other ones. Regarding the approach of prohibiting certain practices and supporting all the others, a first example is the legal limitation of dedicated crops to 15% of the feedstock used by a producer, except for cover crops, with the objective of limiting the negative externalities linked to ABP while maximizing the positive ones (see figure 7). Another example of it is how, since its creation in 2011, the FiT mechanism includes an interdiction of using fossil energy sources for meeting several of a producer's energy needs[27]. By doing so, policymakers' objective most likely was to ensure that the GHG emission reduction externality is actually observed. For their part, illustrations of the second approach of incentivizing or disincentivizing certain practices are more recent. As examples, in 2023, a penalty was introduced in FiT for producers consuming high amounts of electricity from the grid[28]. By doing so, policymaker wanted to ensure that biomethane production enabled a substitution of fossil gas, without increasing the use of other energy sources. As per the tender specifications published in 2023, the same penalty will apply to producers benefiting from BI[29].

In fact, in this regard, the role of tariff premiums granted to French producers depending on the feedstock used can be discussed. On the one hand, the creation in 2020 of a specific premium for the usage of animal manure could be partially explained by the additional costs induced by the usage of manure, as highlighted by the CRE in 2018 [39], thus falling within the first approach. On the other hand, Cadiou (2023) considers this premium as illustrating how some support policies took into account not only energy production, but also the objectives of the Ministry of Agriculture, that is particularly favourable to the use of manure [38]. In 2020, the CRE itself highlighted how this premium met objectives other than energy production[30]. Manure premiums, that exist both for FiT and BI instruments, are therefore probably the result of both approaches at the same time. In a similar way, the stronger support granted to small capacity producers most likely did not only aim at maximizing the amount of energy produced, but also at incentivizing the development of self-sufficient units installed within a farm facility, to which local communities are more favourable as they are likely to generate less of the neighbourhood nuisances described previously [66].

In this framework, an important question is that of the relationship between the latest support instruments implemented in France (i.e. BI and EQ) and biomethane externalities. As highlighted in section 2, BI and EQ are less adaptable than FiT. Yet, although the approach of regulating and prohibiting can be implemented independently of the instruments used, the approach of incentivizing so far relied on the adaptability of support instruments, through the implementation of tariff premiums or penalties. As they implement BI and EQ for producers to be more subject to competition and selected based on energy price criteria, policymakers therefore also renounce to the possibility of incentivizing their development based the externalities they are likely to generate. In the case of biomethane where these externalities are numerous, adaptability can then serve as a further argument in favour of FiT over other instruments. In that context, the implementation of BI and EQ are likely to lead either to a lower influence of support policies on externalities, or to a renewed importance of the first approach of regulating and prohibiting certain practices regarded as undesirable. These effects nevertheless are likely to be more pronounced for EQ than for BI, that can more easily be partially

[27] French order on biomethane FiT, November 23, 2011
[28] French order on biomethane FiT, June 10, 2023
[29] AO PPE2, Biomethane injection tender specifications, December 2023
[30] French Energy Regulatory Commission, Resolution 2020-223 from September 10, 2020

adapted, as illustrated by the premiums, penalties and price caps included in the tender specifications of 2023 that were previously described.

Finally, it should also be highlighted that no matter the preference of policymakers between regulating and incentivizing, effectively observing which practices are adopted by an increasing number of producers is likely to be complex. In the same way as for the management of available biomass mentioned in section 4.3, implementing an effective monitoring of these practices may therefore require not only national but also local-scale industry planning.

5. Conclusion

Rather than focusing on a single type of producer, this article gave an overview of the biogas-to-biomethane industry, with the aim of better understanding the relationship between producers and support policies. To that end, it differentiated three production models based on a principle of additionality. In these different models, biogas generation before its upgrading to biomethane can be considered as independent from any will to produce gas in the case of *Waste Gas Recovery*, as the result of a production process reusing available organic matter in the case of *Waste to Ressources*, or as a process requiring *Additional Biomass Production*. It was shown how policymakers consider these production model differently, a potential explanation of it being the respective relationship between these models and the concept of circularity. This overview of the industry was then extended to its techno-economic aspects, by defining a generic production cost function, discussing the variations of its main components from one model to another, and highlighting how plant specific economies of scale could be overestimated for *Waste to Ressources* and *Additional Biomass Production* models. Re-examining arguments developed regarding other RES, it was also highlighted how, when supporting the industry, cost differences between production models acted as an argument in favour of the implementation of adaptable instruments, such as FiT.

Through a detailed analysis, French support policies and their results since 2010 served as an illustration of the relevance of the previously developed framework. It confirmed the construction of support policies according to a principle of cost additionality, and the efficiency of FiT to foster the simultaneous development of a variety of producers. It also showed how policymakers gradually introduced competition between producer through BI or EQ, in order to limit the cost of their support, with future results nonetheless uncertain due to the potentially low economies of scale.

Once the relevance of our framework had been confirmed, the aim was to enhance it in order to better understand existing support policies, and to propose ways of improvement. The difficulty of assessing additionality was first highlighted, which sometimes blurs the line between additional biomass production and reuse of available biomass. The strong differences between biomethane and other RES were then put forward, with major implications for support policies' design. From a dynamic perspective, the competition between producers for biomass acquisition in *Waste to Resources* and *Additional Biomass Production* models is likely to induce cost increases, that could outweigh eventual cost reductions due to learning effects and invalidate techno-economic articles considering feedstock acquisition cost to be negative and/or constant over time. As a result, not only national but also local-scale planning could be needed to ensure that producers needs do not exceed quantities of available biomass within a given area. As a second point, biomethane by-products that are digestate and biogenic CO2 can have significant financial implications for producers, that however cannot be considered independently of production models. First ranges of these potential financial benefits were estimated, and some of their determinants were listed, including the feedstock used, the size of the production unit, and the composition of biogas before its upgrading. Finally, a first attempt was made to consider the non-energetic implications of the biogas-to-biomethane industry, and to integrate them in the framework previously developed.

Externalities are often considered in a partial way, and their quantification is often limited to potential benefits of the industry without considering the practices effectively adopted by producers. Here, a list of potential externalities to consider was therefore developed, showing how their number increase from one production model to another. In France, two policymakers' approaches with regard to these externalities were observed, one of regulating by prohibiting certain practices while creating the conditions for all others to be financially viable, and one of using the adaptability of support instruments to incentivize certain practices over other ones. It was then highlighted how policymakers willing to limit the cost of their support were likely to abandon their capacity to introduce such incentives, which again raises the question of the interest of the latest support instruments implemented in the country, especially if their potential to foster cost reductions is limited.

Overall, the implementation of policies supporting the biogas-to-biomethane industry therefore requires in-depth reflexion on the business models and behaviours these policies can favour in the medium to long term. Effectively monitoring these behaviours, that are likely to have decisive non-energetic consequences, namely on agricultural systems, may require not only national but also local-scale industry planning. For future research, in addition to the numerous elements that could only be partially covered in this article, two points of particular interest stand out. On the technical side, the interactions between the directly used biogas industry and the upgraded biogas industry were not developed here. In fact, many producers selling electricity generated through biogas combustion could redirect their activity towards biogas upgrading for biomethane commercialisation, with potential additional implications for the design of support policies. Finally, beyond gas production, the future of its transmission and distribution must also receive special attention as total gas consumption is expected to decrease, entailing significant increases in gas grids management costs for every unit of gas sold to final consumers.

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