HETEROGENEITY OF AGRICULTURAL BIOGAS PLANTS IN FRANCE: A SECTORAL SYSTEM OF INNOVATION PERSPECTIVE

De Boeck Supérieur | « Journal of Innovation Economics & Management »

2022/2 N° 38 | pages 11 à 34
ISBN 9782807398160
DOI 10.3917/jie.pr1.0116

Article disponible en ligne à l'adresse :
Heterogeneity of Agricultural Biogas Plants in France: A Sectoral System of Innovation Perspective

Alexandre BERTHE
Univ. Rennes
LiRIS and LIED (UMR 8236), France
alexandre.berthe@univ-rennes2.fr

Pascal GROUIEZ
Université de Paris
LADYSS (UMR 7533), France
pascal.grouiez@u-paris.fr

Mathilde FAUTRAS
Geosciences department
Fribourg University, Switzerland
mathilde.fautras@unifr.ch

ABSTRACT

Literature on biogas production mainly studies the outputs of production or the technical dimension of its organization. We argue that there is a need to study this process in a more institutional political economy perspective to understand the variety of biogas plants’ organizational models. We draw on the sectoral system of innovation and production perspective (SSIP) to analyze strategies of farmers adopting such an innovation in the agricultural sector. We mobilize data from semi-structured interviews with farmers and

1. Acknowledgements: The authors thank the two anonymous reviewers for their relevant comments and suggestions that helped to improve this article. The authors are also very grateful to the interviewees. This paper is part of the “MéthaRevenus” (CEP 2018 AAP 01) research project. The authors wish to thank Louis Dupuy, Martino Nieddu, all the members of the BIOCA research program, Léa Moliné, and Mickaël HugoNet, for their valuable advice on this research. The authors also wish to thank the PSDR4 programme which has allowed scientific cooperation with other programs addressing biogas production in France.

Financial support: This project benefited from the support of the French Ministry of Agriculture (CEP 2018 AAP 01 project). It also benefited from the support of the Centre des Politiques de la Terre (Idex Université de Paris, Meth’InTer) as well as the APESA. This work has also received financial support from the LabEx DynamiTe (ANR-11-LABX-0046) as part of the “Investissements d’Avenir” program.

DOI: 10.3917/jie.038.0011
institutional stakeholders in France. We highlight a process of heterogenization of agricultural biogas plants, which results from a conflictual but lasting process of new technology appropriation by actors with various strategies within and outside the agricultural sector. We identify four different agricultural biogas production models: internalization and symbiosis, cereal grower using BP in injection, small group of farmers, partial outsourcing, and generic technology. We also discuss the possibility of the emergence of a new one: agricultural cooperative-investors joint projects.

**KEYWORDS:** Agricultural Biogas Production, Energetic Transition, Organizational Models, Sectoral Systems of Innovation and Production, Farmers’ Strategies

**JEL CODES:** O33, Q16, Q42, Q48

Biogas production is a new way of producing renewable energy, through the formation of gas from the decomposition of biomass (as an input) in an anaerobic environment. The development of this technology is recent in Europe and has been implemented to different degrees, depending on the country, from the 2000s onwards. The technology first developed in Germany through biogas plants, mainly using dedicated energy crops. In Italy, while agricultural biogas plants were diversified in terms of size and inputs used to produce biogas, a process of homogenization of agricultural biogas plants has been observed during the 2000s but it remains unfinished (Carrosio, 2014). More precisely, the industrial policy based on investment subsidies dedicated to specific biogas plants and the role of experts and banks upstream of the chain have both led to the development of agricultural biogas plants characterized by a capacity between 500 and 999 kWe and the use of a mix of inputs - animal feedstock and energy crops - to produce biogas (Carrosio, 2013). But beside these large biogas plants there persists an organizational model that is more focused on the farm and its own energy needs. The situation in France is even more heterogeneous in terms of organizational models: after having experienced a certain delay in its development and having started with a homogeneous design of biogas plants, various methods of biogas production coexist today and involve very different actors. The relative homogeneity of French biogas plants at the first stage of their development is related to the role played by public policy, which stimulated investment in biogas plants by livestock breeders to recover their waste, through subsidies and a feed-in-tariff. Therefore, in the 2000s, biogas production in France mainly developed through small-size plants (around 200 kWe) with livestock manure as the main input. In a second stage a process of heterogenization has been observed during the 2010s. This change interrogates the role played both by other private actors and by institutions of this emerging technology in France.
One can wonder why the same technology does not lead to a similar process of homogenization all around Europe. Does the evolution of the industrial policy led by the French government explain this higher level of heterogeneity in the transition pathway that seems to be different in Germany or Italy? Are private actors responsible for this higher level of heterogeneity? Would this heterogeneity be maintained in the future?

A wide range of papers analyzing biogas production underlines the fact that this activity offers a way to provide new renewable energy. The existing literature often addresses the topic through the debate on decarbonization and the ability of green gas to tackle climate change and greenhouse gas emissions (e.g. D’Adamo et al., 2019; Fernández-González et al., 2020). It also interrogates the conditions of implementation of this renewable gas within the energy mix of various countries (in Europe, see Chodkowska-Miszczuk et al., 2017; D’Adamo et al., 2020). While these approaches address very important aspects of the question, they tend to focus on downstream segments of the agricultural sector. However, beside the energy issue, biogas production can serve other purposes, including those of farmers (e.g. recycling of farm residues, soil fertility). Our paper interrogates the configuration of the upstream segments of the sector continuing the work done by Valve et al. (2021) in Finland and by Brémond et al. (2021) in Denmark, Germany, France, Italy, and Sweden.

In order to address this issue, we mobilize a Sectoral System of Innovation and Production (SSIP) approach (Malerba, 2002, 2005). Malerba develops this concept in order to underline the effect of a sectoral configuration on the process of innovation. He demonstrates that the innovation and production process depends on the history of a given sector, on the nature of the networks of actors, and on the institutions that together define it. Consequently, the innovation process differs from one sector to another. In this paper, we mobilize the SSIP approach as a methodological tool in order to apprehend the way organizational models of production can emerge on the basis of the same technology at a micro level. We consider that the organizational models result from conflicts and compromises of heterogeneous actors within the sector (in this case the agricultural sector). The implementation of a given innovation within one or multiple organizational models depends on the ability of different actors to influence the transition pathway.

The paper is organized as follows. The next section presents a review of the literature regarding biogas production in Europe, as well as the theoretical framework that we have mobilized. Section three introduces our empirical case studies which are based on semi-structured interviews with farmers and institutional actors. Section four presents our results. We outline that
the long-term dynamics of change of biogas production are characterized in France by a process of heterogenization of agricultural biogas plants. This heterogenization can be explained by the ability of groups of farmers to cooperate with different kinds of actors and to push forward various institutions to promote their conception of what a biogas plant must be. In Sections five and six, we discuss and draw conclusions from our analysis, pointing to the particularity of French biogas production evolution toward a less agricultural and more industrial model of biogas plant.

**How Is Biogas Production Organized In Europe? The Need to Adopt a New Approach**

In this section, we assess the various possible approaches to study the organization of biogas production. We first show that the literature predominantly considers the outputs of production, then we identify relevant articles on the organization of biogas production and show that they mainly focus on the technical dimension of the organization. Finally, we present a theoretical framework, SSIP developed by Malerba (2002, 2005), that seems able to equilibrate the study of the organizational model including, in the same framework, different dimensions, and especially the importance of technology, knowledge, networks of actors, and the institutional environment.

**The Current Ways of Studying Biogas Production: A Literature Survey**

Biogas production is mainly studied with the objective of conceiving new innovations for the process of the production of biogas. This field of research focuses on the technology of production and the ways it could be improved. For instance, this literature studies the Biochemical Methane Potential of various forms of biomass and its usefulness to improve the efficiency of biogas production (Filer et al., 2019). In this literature, the idea is to identify the optimal size of biogas plants, which could then have consequences for the way biogas production is structured based on technico-economic issues (Walla, Schneerberger, 2008). With the development of biomethane, the question of the sufficiency of inputs to produce biogas also becomes more and more crucial (Hamelin et al., 2021).

In social sciences, the existing literature on biogas production and valorization has largely studied biogas downstream of the value chain, rather than...
considering biogas production input itself or the variety of ways of producing biogas. A significant body of literature focuses on the way biogas is used in the end (i.e. as energy to produce electricity; as biomethane sold to the grid; or transported). These articles reflect on how biogas may contribute to reducing greenhouse gas emissions (e.g. D’Adamo et al., 2019; Fernández-González et al., 2020), and more broadly on the future energy mix (e.g. Chodkowska-Miszczuk et al., 2017), for instance through its use in the transport sector (D’Adamo et al., 2020). In this literature, the way of producing biogas is not very important even if proximity to a highway could drive the design of a biogas plant for car biofuel production or proximity of a transport gas pipeline could favor the building of biogas plants (BPs) optimized for biomethane production.

The biogas production process per se is less emphasized in the literature. Nevertheless, when focusing on how biogas production is organized in biogas plants, the literature faces three questions:

1. What are the main characteristics to isolate different types of biogas production?
2. Is there a uniformity or a diversity of biogas production models?
3. What drives change in biogas production models?

Mainly based on ecological and agronomic sciences, this literature commonly uses technical aspects to characterize biogas plants and the authors rarely mobilize an analytical framework to construct their analysis. Then the academic (Daniel-Gromke et al., 2018; Brémond et al., 2021) and technical literature (see ADEME, 2017, 2021; ADEME, Solagro, 2018) mainly describes biogas plants through the following items:

- The nature of the biomass used (farm residues, cereals, sludge)
- The technology used to valorize biogas: cogeneration to produce electricity and heat; purification to inject biomethane into the gas grid; transformation into fuel or BioNGV2)
- The plant size
- More rarely, the characteristics of the investors (farmers only; group of farmers; farmers and non-agricultural shareholders; non-agricultural shareholders only).

Even if it does not focus on the diversity of organizational models, this literature shows that the process of production of the biogas is not normalized as much as for other technologies. More specifically, there is a diversity of inputs and biogas plant technologies that did not lead to the same way of

2. Bio-NGV is biomethane compressed to 200 bar in order to be used as fuel (Natural gas vehicle or NGV).
producing biogas. In addition, each BP is associated with a specific recipe of input that did not enable huge changes in terms of inputs during the lifetime of the plant. Moreover, the future of the biogas produced is also diversified.

Nevertheless, these analyses contain some pitfalls. First, the different criteria are not systematically considered simultaneously and the fact that some characteristics make systems, *i.e.* define models or ideal-types, is rarely considered. Second, the institutional and political economy dimensions are scarcely taken into account, which limits understanding of the organizational model of biogas production. Third, existing articles do not examine the path constraints linked with the value chain from which the different actors come. However, one can consider that the way farmers introduce biogas production is related to the model of agriculture from which they come (small-scale farming, agro-industrial production, cooperatives of production, etc.). Therefore, we argue this is crucial to study in a more institutional political economy perspective how the above-mentioned criteria may combine in BPs, and how this leads to various organizational models.

As an exception and in a perspective that is closer than ours, Carrosio (2013, 2014) identified four ways of making biogas production in Italy. He emphasizes four different production models: multifunctional farm, entrepreneurial farm, community bioenergy farm, entrepreneurial bioenergy farm. In his paper, he shows that at the beginning of the 2010s the multifunctional farm model, also called the repeasantization model, is dominant, but that the entrepreneurial model, based on modernization, is emerging more and more in the Italian context. More recently, based on a case study in Finland, Valve *et al.* (2021), for their part, reveal the emergence of new organizational models in biogas production. They analyze the organization of input circuits to highlight organizational model differentiation within uniform institutional conditions. In Table 1, we propose a synthesis on the various models that were identified in their papers and present our own models which pay more attention to farmers’ strategies and the interplay of biogas production actors.

In order to give an overview of the various organizational models of biogas production and to describe the new dynamics of that sector in France, the present article analyzes the strategies of farmers embedded in a sectoral system which can either compel or provide some opportunities for their activities. This analysis is based on the SSIP approach, which, to the best of our knowledge, is used for the first time to study the development of biogas production.
### Table 1 – Diversity of biogas plant models in the academic literature: institutional approaches to Italy, Finland, and France

<table>
<thead>
<tr>
<th>Authors (Year)</th>
<th>Country studied</th>
<th>Survey period</th>
<th>Analysis frontier</th>
<th>Variables to study BP</th>
<th>Theoretical framework</th>
<th>Observed diversity**</th>
<th>Dynamics of change</th>
<th>Reasons of change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrosio (2013, 2014)</td>
<td>Italy</td>
<td>2013 Census</td>
<td>ABP*</td>
<td>Types of farms</td>
<td>Ideal-type building</td>
<td>Four types: multifunctional farm, entrepreneurial farm, community bioenergy farm, entrepreneurial bioenergy farm</td>
<td>Iso-morphism</td>
<td>Ways of doing agriculture and public incentives</td>
</tr>
<tr>
<td>Valve et al. (2021)</td>
<td>Finland</td>
<td>2016-2019</td>
<td>BP</td>
<td>Value proposition, creation and captures, material inputs and outputs</td>
<td>Business models and circular economy</td>
<td>Four types: biogas production as waste management and energy generation, manure processing to support farming, biogas production to support rural energy generation, biogas as centralized manure processing to enhance nutrient recycling</td>
<td>Niches, a dominant model, and a new competing one</td>
<td>Business models and types of inputs and outputs</td>
</tr>
<tr>
<td>The present article (2022)</td>
<td>France</td>
<td>2018-2019</td>
<td>ABP</td>
<td>Knowledge, network of actors, technology, institutions</td>
<td>SSI at a micro level</td>
<td>Five types: internalization and symbiosis, cereal grower using BP in injection, small group of farmers, partial outsourcing and generic technology, agricultural cooperative-investors joint projects</td>
<td>Conflicts and compromises between various actors</td>
<td>Interplay of actors, actors’ objectives</td>
</tr>
</tbody>
</table>

* ABP: Agricultural Biogas Production Plant
** Main types in bold character, emerging types in italics
*** The last row of this table presents the synthesis of the results of the present article. These results are presented in detail in Sections 4 and 5.
An SSIP Approach to Understand the Organization Models of Agricultural Biogas Plants in France

This article analyzes farmers’ strategies through the study of the innovation system of the agricultural sector in France. The SSIP framework allows us to understand the diversity of organizational models of production as a result of a succession of catch-up cycles of products, which lead to the cohabitation of new and former models of production in the same sector (Lee, Malerba, 2017). Similarly, Carrosio (2014) shows that the history of the implementation of biogas plants and their evolution could lead to a dominant design which does not obliterate older models, explaining the diversity. However, beyond this evolutionary explanation, it seems relevant to underline the role played by conflicts of actors within the agricultural sector as a driver of this diversification (Malerba, 2002, 2005).

In order to identify the determinants related to the forms of agricultural biogas plants in France and their evolution, we mobilize Malerba (2002)’s framework on sectoral dynamics. This approach allows us to understand the process of technological change as an evolutionary process. Malerba’s framework offers a historical and conflictual reading of this process. He describes the sectoral dynamics as the result of actors’ strategies determined through five building blocks: knowledge; technology; network of actors; institutions; processes of generation of variety and of selection. In this paper, we mobilize the SSIP framework at a micro level rather than at the meso/sectoral level in order to:

- identify through an institutional political economy perspective the variety of agricultural biogas plants (ABPs) while embedded in the same productive sector
- to understand the reasons for this diversity, and thus to try to understand how ABPs may evolve in the future in France
- to provide an analysis of the French context that is not well documented in this approach.

Admittedly, this does not directly inform the SSIP of the agricultural sector, but it allows analysis of the organizational model proposed by actors at an on-farm level. Indeed, firm managers may have different ideas on the path to combining their knowledge, technology, networks and institutional environment in order to affect the processes of variety and of selection. For instance, they can devote time to institutional modelling to maintain the way they conceive the design of ABPs, while other groups do the same or are forced to adopt a dominant design in an unfavorable institutional context. The networks of actors will be proxied by the relation of farmers and
their associations with public and private actors (banks, industrial firms like plant designers and grid managers), to see, for instance, how these networks have affected the drafting of legislation on biogas plants. Knowledge will be understood through the proxy of the appropriation of biogas technology by farmers (learning by doing, industrial training, etc.) which informs us on the degree of farmers’ autonomy regarding the downstream and upstream actors of the chain. Technology will be proxied by the day-to-day operation of the plant (input choice; number of employees, type of energy produced, etc.). Institutions will be proxied by formal rules (legislation, conditions for access to subsidies) and informal rules (norms of valuation about the quality of the inputs such as substrates and output such as the digestate). The interaction of the first four building blocks will finally inform us on the processes of generation of variety and of selection (i.e. Malerba’s fifth building block) that we investigate. Consequently, among the five building blocks, the result section will not analyze the fifth one. This block will be analyzed in Section 5, which considers the forces of diversification and homogenization of the environmental innovation of the biogas plants owned by farmers.

**Biogas Production in France: Case Studies Based on Semi-Structured Interviews**

In this section, we present our methodology of data collection to identify the diversity of agricultural biogas production in France. After a reminder of the specificity of French biogas production development in general, we present our sample and the methods mobilized to gather information on our case study.

**Biogas Production: Analysis of the French Case**

The case of France is quite specific. In fact, contrary to many other European countries - except Germany until 2012 - French public policies on renewable energy have supported production rather than consumption of biogas, by specifically supporting on-farm biogas production through a feed-in-tariff and investment grants (Brémond et al., 2021; Bourdin, Nadou, 2020). Consequently, farmers have played a key role in the appropriation of the biogas production technology. Influenced by this regulation policy, they had to select the nature of the biomass, the size of the biogas plant, and the very nature of the energy recovery (power, biomethane, heat). Conducting a survey appeared to be an efficient method to account for these individual and collective choices of appropriation of the biogas production technology.
From the start, biogas production in France has been marked by the German experience of this technology. In Germany, biogas production has raised many controversies related to the fact that biogas plants, essentially agricultural, were relatively homogeneous. Almost all of them – specifically in the mid-2000s – used dedicated energy crops (cereals) as a substrate. The main controversy was about the risk of energy production being substituted for food production.

For this reason, French public policies have encouraged a development of biogas production more focused on the development of agricultural substrates, and in particular livestock effluents (manure and slurry) - the use of the latter offering specific feed-in tariffs for gas and electricity. At the same time, the regulation limits to 15% of inputs the possibility of using dedicated crops in order to benefit from investment subsidies and advantageous feed-in tariffs. Consequently, the policy context has influenced the establishment of plants (location, dimension, objectives), value creation, and the decision-making process. In this context, various ways of producing biogas can be implemented. Some biogas plants are established by single farmers, others by collective farming groups. The technology, the legal configuration chosen, and the substrate used may also differ. The aim of the constitution of our sample is then to select territories enabling us to capture the different existing types of BPs in France, and to analyze the factors that influence the process of homogenization or heterogenization of the biogas production sector.

**Sample Constitution for the Analysis of French Biogas Production**

To identify the existing types of ABPs in France and to grasp the factors for this diversity, we adopted a case study design. We produced three case studies located in various geographical and institutional contexts. The Champagne-Ardenne region, and in particular the Ardennes department, has been the pioneer area for biogas production in France. This case study aimed to investigate the reasons and the path for the sector’s emergence in the early 2000s in a livestock farming area. The second case study is the grain-growing plain of the Aube, Marne, and Seine-et-Marne departments – with the latter being the pioneer region for injection technology in the country from the 2010s onwards. Western France (Nouvelle Aquitaine region) was chosen as a third case study with the hypothesis of a stronger political incentive at the local level to implement anaerobic digestion technology (Bourdin, Nadou, 2020; Gonçalves et al., 2021).
Based on a public inventory of BPs in France made by the French Agency for the Environment and Energy Management (ADEME) and on a snowball sampling, we identified relevant ABPs for our study with various substrates, technologies, sizes, stages of development (project or up and running), and organizational models. The whole sample is summarized in Table 2.

**Table 2 - Primary qualitative data**

<table>
<thead>
<tr>
<th>Type of interviewee</th>
<th>Number of interviewees</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmers involved in biogas production</td>
<td>Ardennes department: - 10 (individual BP) - 2 (collective BP) Champagne (Aube, Marne, and Seine-et-Marne departments): - 7 (individual BP) - 10 (collective BP) Western France: - 13 (individual BP) - 11 (collective BP)</td>
<td>2018-2019 2019 2018</td>
</tr>
<tr>
<td>Public and para-public institutions</td>
<td>9</td>
<td>2018-2019</td>
</tr>
<tr>
<td>Agriculture and Biogas production unions</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Consultants</td>
<td>4</td>
<td>2019</td>
</tr>
<tr>
<td>Engineer organizations and firms</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Agro-industry firms</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Waste collecting firm</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Energy and digestate management firms</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Banks and insurance companies</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Association</td>
<td>1</td>
<td>2018</td>
</tr>
</tbody>
</table>

The sample is mainly constituted by farmers, some with an ABP on their own (30 farmers), and others involved in a collective ABP (23 farmers). In each territory, but also at the national scale, we tried to identify the other actors that are involved in biogas production. We thus added 44 organizations to our sample, including representatives of public institutions, engineering organizations, agro-industry, consultants, and firms involved in biomass-energy chain support, supply, or output management (Table 2).

According to the Sinoe database mentioned above, 691 agricultural biogas plants (ABPs) are nowadays in operation in France. This database

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lists 987 BPs, which means that the ABPs account for around 70% of all the BPs running in France. Thus, our sample accounts for almost 7.5% of all the ABPs in France. Among the 53 ABPs we investigated, 72% are owned collectively or individually by farmers as unique shareholders; while 28% are owned by farmers as majority shareholders, the minority shareholders being cooperatives and/or agro-industrial companies. As reported in Table 2, 58% of our sample are ABPs owned by an individual farmer, and 42% by a group of farmers as unique or majority shareholders. Among the ABPs run by a group of farmers, 54% include minority shareholders outside the agricultural sector. This figure drops to only 0.6% in the case of ABPs managed by farmers individually. Our data do not include farmers who contribute to biogas production just as a substrate supplier. Nevertheless, this sample enables us to embrace the diversity of opinions from various types of farmers actively involved in biogas production and BPs ownership.

**Semi-structured interviews methodology**

Based on our sample, we have conducted individual semi-structured interviews following a protocol that ensured that the questions were open-ended. Each interview lasted approximately two hours. This methodology is relevant here to capture non-measurable and qualitative information, and to encourage actors to provide and share their knowledge and thoughts more thoroughly (Blanchet, Gotman, 2006). The interviews with farmers were all transcribed and followed three steps: the first one compiled data on the farm and its agricultural purposes; the second was based on the visit of the ABP and on the interviewee’s path to biogas production; the last one fleshed out farmers’ business models. This three-step organization makes the capture of information possible, both on agricultural and biogas issues. It also allowed us to collect quantitative technical and economic data on ABPs and biogas production income, in addition to qualitative data. These qualitative and quantitative data provide rich information on the strategic choices and aims of on-farm biogas producers. With regard to the SSIP framework, these data also inform on the internal and external factors that influence the biomass-energy sector through on-farm biogas production. It allows us to draw the results that we will present in the following section.
Results: Current Models of Biogas Production in France

In what follows, we identified through the SSIP framework presented in Section 2 the coexistence of four organizational models of ABP in France: 1) the internalization and symbiosis model (which represents 40% of the ABPs of our sample), 2) the small group of farmers model (38% of our sample), 3) the cereal grower using BP in injection model (12%), and 4) the partial outsourcing and generic technology model (10%). The following subsections present each of the organizational models of biogas production that we identified. The structuring of each model presentation is based on four of the building blocks proposed by Malerba (2002): knowledge, technology, networks, and institutional environment.

Internalization and Symbiosis Model

On technological aspects, the “internalization and symbiosis” model of ABPs is based on a “resourcefulness” logic in the sense that livestock breeders seek to control maintenance costs as much as possible by internalizing them. Favoring “low maintenance costs”, without external intervention (Interview in the Ardennes, 2018), these ABPs have few employees. This has an impact on their personal working time and often leads them to expand their agricultural production specialization further - for example by withdrawing dairy farming or fattening - when investing in the biogas plant. Finally, they reduce the cost of their substrates as much as possible by favoring the use of their own livestock effluents. Consequently, in terms of knowledge processes, farmers of this model have used the “learning by doing” base to innovate. The plant is sometimes even designed according to a “homemade” principle. On the networks of actors aspect, some interviewees are thus entirely self-sufficient for their inputs in effluents, grass, and corn silage, and the dimensioning of the BP has been precisely thought out to guarantee this autonomy (Interviews in the Ardennes, 2018). Consequently, these farmers do not integrate any association or lobby group. Regarding the institutional dimension, this model is mainly based on the first generation of BPs in cogeneration (investment before 2015), which have benefited from significant public subsidies. The recovery of heat is most often integrated into the equation that led the farmer to invest in biogas production). Thus, cogeneration technology is often a deliberate choice and rarely an obligation (due to the absence of gas

grid or the age of the project, imagined before the decree allowing injection into the gas grid\(^5\).

**Small Group of Farmers Model**

The “small group of farmers” model is made up of a group of cereal farmers and breeders, who are sometimes led to rethink their agricultural project as a collective one (creation of a group of employers, collective work for the harvests, setting up of a CUMA (cooperatives sharing agricultural material, etc.). The networks of actors are at the basis of this model. In this model, the investment is more recent. As the construction sector of biogas plants is better structured, the investment is greater (mainly due to groundwork costs and the almost systematic presence of design consultants, assistants to the contracting authority, etc.) while the subsidies received are lower than in the previously presented model. As far as the technology is concerned, the plant operates through hiring more employees than in the internalization and symbiosis model, mainly because the project is more collective. Sometimes the remuneration takes the shape of a bonus for one or more of the partners, in the order of a few thousand euros per year per person, often below the salary level. “Considering the time spent [in the running of the BP], the pay should be more than that, and if we had to find someone to do it, it would be more expensive”, said a farmer receiving this type of bonus (Interview in the Marne department, 2019). The greater amount of substrates purchased (generally from cooperatives and more rarely from the agro-industry) weighs more heavily in costs. In this model, everything is billed because the on-farm BP is almost always legally separated from the agricultural entities, even when it is formally an exchange between the BP and the farmers who are members of the group (the purchase of intermediate crop for energy purposes (ICEPs), the cost of spreading, *i.e.* a form of “sale” of the digestate). In terms of energy production, it can be either an injection or a cogeneration BP. The choice of cogeneration is sometimes due to a technical constraint (absence of grid), but also of a deliberate choice linked to the desire to use surplus heat. On the knowledge aspect, this model is based on the principle of professional experience and knowledge transfers between breeders and grain producers. Breeders use their knowledge on animal digestion to teach how to operate the biogas plant, while the grain producers mobilize their knowledge on crop growing to offer training on digestate specific spreading. As far as the institutional dimension is concerned, the model - as the previous one - benefits from

\(^5\) Decree n° 2011-1594 dated 21 November 2011 relating to the conditions of sale of biomethane to natural gas suppliers.
important public subsidies in terms of investment support and a subsidized price on energy sold.

**Cereal Grower Using BP in Injection Model**

*Technologically speaking*, the cereal grower using a BP in injection model is based on the injection technique, run by an individual or operating on the basis of a very small group led by a cereal grower holding the majority of the capital, and which may include breeders. In this model, the BP is almost always legally separated from the farm. This generates very significant costs for the purchase of substrates, which actually remunerates the cereal grower himself. Indeed, a large part of the inputs consists of ICEPs and more rarely of dedicated crops. This share of ICEPs and/or dedicated crops tends to increase in the farms associated with this type of BP. This model almost always implies creation of a new position which is often offered to someone coming from the industrial sector. This job creation increases the wage bill more significantly than in the previous model because the work, which is more qualified, is well-paid. In return, the partners devote less time to the BP and specialize in the administrative management of the project. Consequently, the knowledge process is based on explicit training of the BP employees, mostly provided by the biogas plant builder and the crop grower himself. In terms of the networks of actors, BPs most often supplement their input needs through agreements with their cooperatives (in particular for highly methanogenic cereals) and agro-industrialists. New supply strategies seem to be emerging today with the establishment, by certain farmers, of a bio-waste management sector due to their strong concern regarding the quality of this type of input (quality of digestate derived from bio-waste). As far as institutions are concerned, it is in this model that one can identify farmers at the origin of the association of farmers producing biogas in France (AAMF). This association has played a key role in the Government’s adoption of the decree of 13 December 2016 about the conditions for purchasing the electricity produced by biogas plants. Farmers have lobbied in order to become producers of gas injected in the natural gas grid.

**Partial Outsourcing and Generic Technology Model**

On the networks of actors aspect, partial outsourcing and generic technology BPs are made up of farmers who are often alone or in very small groups, most of them breeders, who have invested in biogas production at a later date (after 2015). They do not integrate any association or lobby group but are highly dependent on actors upstream of the value chain (especially constructors).
Thus, on the technology aspect, the investment cost is higher than in the internalization and symbiosis model. This is due to a greater number of players and trades involved in the construction of biogas plants, which now involves assistants to the contracting authority, project managers, consulting firms, etc. This technological change is related to institutional dynamics, especially the arrival of new “construction companies” which has reduced the reliability of the actors upstream of the value chain: several cases of such companies declaring bankruptcy have been observed, particularly in the western part of France, as well as equipment breakages due to the inadequate technical characteristics of substrates (Interviews in Nouvelle Aquitaine region, 2018). Other farmers report problems with the initial oversizing of the BP engine in relation to the available input, due to a design fault by the contractors (Interview in the Aube department, 2019). As a result, maintenance costs are higher. In the case of small groups of farmers, the choice of employing paid workers certainly creates jobs, but generates additional costs that are sometimes difficult to bear for relatively small BPs (around 200 kWe). At the same time, the fall in subsidies leads to an increase in the debt burden. Furthermore, the desire of some of the farmers belonging to this group to optimize the biochemical methane potential (BMP) of substrates has led them to include more inputs bought from their cooperatives (derived from cereals) and from agro-industrialists. Finally, on the knowledge process aspect, farmers are highly dependent on the construction companies’ training program since the process is not based on a “learning by doing” principle but rather on a “turnkey model”. Overall, this latter model combines the shortcomings of the cereal injection and small group of farmers models (high cost of substrates, high wage bill, heavy investment) without the advantages of the internalization and symbiosis model (low dependence on inputs, low maintenance costs).

It should be noted that these four models remain representative of our sample of respondents and not of agricultural biogas production in France, or of all French biogas production (agricultural and non-agricultural). Notably, our survey did not allow us to include in our analysis interviews of farmers who invested in the micro-biogas production type of BPs, or the judicial representative type (gathering dozens of farmers who delegate the entire activity to an outside agent and simply providing substrates). Finally, as we have already pointed out, this SSIP approach does not include farmers who position themselves as simple suppliers without taking part - directly or indirectly - in the productive organization of the BP, whether the latter is agricultural or non-agricultural.

6. We encountered a single case of an on-Farm BP with power of 50 kWe.
Discussion: What Models for the Future of French ABPs? An Evolutionary Analysis of the SSIP

For the future of biogas production in the agricultural sector, we have yet to understand what types of current ABP models could develop and maintain a significant position in the future. The diversity of ABPs’ organizational models reflects the existence of actors’ strategies associated with the networks and institutions that influence them. In return, these structural elements are themselves shaped by the actors. We focus on the idea proposed by Malerba (2002, p. 248), who considers that the “sectoral system of innovation and production is a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production, and sale of those products. [...] They interact through processes of communication, exchange co-operation, competition and command, and their interactions are shaped by institutions”.

Based on this evolutionary analysis of the SSIP, we consider that the system of innovation undergoes a permanent process of change through the co-evolution of actors and institutions which can lead to a homogenization or diversification of the organizational models. Within the agricultural sector, biogas production could thus evolve in such a way that certain organizational models could disappear. On the other hand, the path dependence associated with the appropriation of biogas production technology by farmers could be a source for maintaining the diversity of organizational models. We mobilize the results of our survey with institutional actors of biogas production activity in order to identify key variables that determine what role the agricultural sector could play in this business in the future. Such an exercise provides room for the analysis of strategies of private players and public decision-makers in terms of productive organization.

Since 2015, the observed trends show an increasing use of injection of biomethane in the gas grid, confirming the result of Brémond et al. (2021). Thus, according to ADEME (2021), 70% of the current ABP projects are plants dedicated to the production of biomethane. Two of the models presented in Section 4 are more likely to develop injection of biomethane valorization: the “cereal grower using BP in injection” and the “small group of farmers” models. There are two explanatory factors to this: economic and regulatory.

In economic terms, injection technology requires a higher investment than for cogeneration (according to our sample, an average of €4.8 million for injection against €1.9 million for cogeneration). Consequently, these investments are heavier to bear for farmers in ailing segments of the French...
agrifood sector (Lambaré et al., 2018). In the context of a steep downturn in the livestock products market, cereal producers tend to be considered more solvent by the funders and therefore more likely to successfully complete a project. Then, on a biological level, plant materials have a greater BMP than animal excrement (ADEME, 2019), and are therefore very attractive, even if they do not entitle the producer to a specific premium for the feed-in of energy.

In regulatory terms, above 300 kWe (approximately 75 Nm3), BPs located in a municipality served by a public natural gas grid for which an adequate injection capacity has been certified cannot benefit from an obligatory purchase of electricity contract - unless the Prefect of the region decides differently7. Consequently, the regulations make the injection process compulsory for larger projects which could, otherwise, also be implemented in cogeneration (for example, because heat is one of the joint products sought), regardless of the state of the gas grid. This threshold requires approximately 10 000 to 15 000 tonnes/year of substrates (depending on their nature and their BMP). This tonnage may be difficult to collect for breeders who mainly provide slurry with low BMP; especially since funders often require a high level of autonomy in incoming materials (around 80% according to our sample). Thus, constituting a group of farmers in order to run a BP can be an effective way to comply with the legislation8.

Consequently, the dynamics observed in the future could be as follows. First, there is likely to be increased competition for substrates due both to the enlargement of BPs – in response to the development of injection technology – and the emergence of a more agro-industrial model of BP (see below). This situation would potentially lead to withdrawal from the sector by ABPs that systematically turn to the substrate market for part of their supply. We are referring here in particular to the partial outsourcing and generic technology model. In many respects, this model appears to be a transitional model. It was not thought of in connection with the needs of farmers who run it but more for the builders of BPs to establish their business. An analysis of the level of revenue generated by this model showed that it was not profitable (Berthe et al., 2020).

7. Decree of 13 December 2016 on the conditions for purchasing electricity produced by biogas plants, Article 4 (version of September 12, 2019). This critical threshold comes from the fact that ADEME and GRDF (the French gas grid company) consider that, below this level, it is not profitable to inject biomethane because of in-built costs, particularly connecting the plant to the grid.
8. However, the size of the groups of farmers seems to influence the speed at which projects are implemented and their successful completion. According to our observations and other interviews with officials of various institutions, the projects set up individually or involving 3-4 farmers are created more easily than those developed by very large groups (7-8 and sometimes up to 20-30 farmers) or by groups in association with local authorities.
Furthermore, the French government regularly informs on its wish to reduce its subsidies, both in terms of investment support and the energy sale feed-in tariff. This evolution, in addition to the dynamics toward biomethane production, could be such that a strategy to substitute any agricultural waste by cereal grown on the farm’s land may prove to be the only possible short-term response to the competition. A process of homogenization of biogas plants owned by farmers may then be observed in the future.

In a transition phase, the reduction in investment support could steer the financially weakest small groups of farmers toward opening up their capital to players whose interests do not systematically coincide with theirs. In the first place, this process could reduce control of biogas production by farmers. However, non-agricultural investors are more or less indifferent to the specificities of local agriculture and their expectations (in terms of the symbiosis between BPs and the agronomic needs of the soil, etc.). In the long run, the size of the group of farmers could grow while their power of control over the BP could disappear to the benefit of agro-industrial players. This would tend to transform this model into a more industrial one. For instance, there are already some ABPs where agro-industrial bio-waste represents an increasing part of the raw materials provided. In these cases, agricultural materials have been reduced to less than 50%, thus switching the BP from “agricultural” status to “industrial” status (a case observed but not investigated in the Vosges district in eastern France). Moreover, some cooperatives or agro-industrial companies have invested in very large-scale BP projects that upgrade up to 70,000 tonnes of bio-waste (see for instance the Total Energies projects). However, these non-agricultural BP projects could face opposition from the local population through, for instance, a “not in my backyard” (NIMBY) phenomenon (Bourdin et al., 2020). This phenomenon is amplified by the nuisance related to the size of the plants (traffic, risk of large-scale pollution, etc.).

Simultaneously, the increased competition in substrates that such a process is likely to generate could lead cereal producers either to claim removal of the limitation to a maximum of 15% of dedicated crops in the total tonnage of inputs to respond to tensions on the substrate market or to grow more ICEPs. However, vigilance seems necessary, because increasing their place

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9. This raises the question of the diversity of possible financing methods for green energy production. Regarding bioenergy, this question is currently little analyzed (Elie et al., 2021). During the interviews, we were able to see, for example, the influence of commercial banks, particularly those involved in the agricultural sector, on how biogas plants are set up. An alternative to this could be to use other financing methods related to green finance (Falcone, 2020).

10. The incorporation of energy crops dedicated to the biogas plant is limited to 15% of the tonnage over three rolling years (Decree n° 2016-929 of 7 July, 2016).
in the supply chain would contribute to accentuating the tensions between the different missions assigned to agriculture (food and energy). French ABPs might then move toward a more Germanic organizational model of BP. Faced with this development, farmers that have substrates with lower BMP, particularly breeders of the “internalization and symbiosis” model, may simply become suppliers to other agricultural and/or non-agricultural biogas plants.

An alternative evolution of the sectoral system of innovation and production could be to maintain the “internalization and symbiosis” model. This would require recognition of the multifunctional role of biogas production in the agricultural sector (Guenther-Lübbers et al., 2016). The possible symbiosis between the development of biogas production activity and the development of a more sustainable agriculture could be at the heart of targeted public policies. This is especially true since large-scale agro-industrial BP models may face strong opposition from a population that is increasingly aware of agroecological issues (see above).

In a related issue and in connection with the CAP reforms (Koloszycz, 2020) that systematically favor large farm models, the current challenges regarding the survival of the family farm model may find an issue with the development of the “small group of farmers” model of ABP, in France but also probably in other European countries. Indeed, we have emphasized in the French case that this model leads farmers to collectively rethink their agricultural activity with pooling within the same structure of their assets and their employees. Biogas production innovation could therefore more broadly support changes in the agricultural production system itself.

**Conclusion**

In this article, we have shown that biogas production in France is not structured around a single form of BP. As a renewable energy source that is promising for the French energy mix, biogas production cannot therefore be analyzed as a homogeneous activity.

By mobilizing four of the five building blocks - namely, technology, knowledge process, networks of actors and institutions – we analyze the strategies of 53 farmers that invested in biogas production. We identify four possible models of integration within the SSIP and evaluate the value added that they ensure: 1) Internalization and symbiosis; 2) Small group of farmers; 3) Cereal grower in injection; 4) Partial outsourcing and generic technology. The analysis of the fifth building block - namely the processes of generation of variety and of selection - emphasizes that the dynamics of the sector seem
to go toward homogenization through strengthening biogas production led by cereal producers and by industrial firms.

Our article highlights that the existing typologies identified in the academic literature do not offer a good understanding of the decisions and strategies of biogas production actors. Moreover, the existing literature does not grasp the present and future evolutions of the sector, nor prospective scenarios to be put forward. On this point, we show that by mobilizing Malerba’s building blocks framework, we are able to better understand the process of competition and selection of biogas production models. This framework also helped us to understand how the various actors could adapt to policy changes and to the arrival of new players in the sector.

From a public policy point of view, faced with the diverse types of BP and their different potential advantages and disadvantages, the question arises of which biogas plant model should be sustained, given the different types of existing plants, from the micro-biogas plant set up by a struggling farmer, to the industrial BP led by a waste management giant. The multidimensionality of this question is hard to identify as issues of the necessity of economic and technical effectiveness are at stake at the same time as environmental justice issues or the types of countryside that seem desirable in Europe. In fact, on this last point, the way biogas is produced is linked to the ways of doing agriculture. Then, the choices on biogas could reinforce or disadvantage different kinds of agriculture, from small-scale peasant farming to giant agroholdings. Then the political decision needs to be informed, beyond the techno-economical assessment, about the consequences of their decision and policy modalities for the future of rurality and agriculture and related social and environmental issues.

Another possible model for the development of the sector could also be studied, based on the maintenance of a diversity of biogas production plants best adapted to each territory and its problems. Two questions of public policy would then still remain: how to maintain biogas production models that are less competitive from a financial viewpoint, in the context of a reduction in development subsidies for the sector? How can public policy, rather than encouraging the homogenization of the biogas production plant models by supporting certain types, on the contrary be a fertile ground for diversity within the ecosystem of biogas production companies?
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