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# Building an Agricultural Biogas Supply Chain in Europe: Organizational Models and Social Challenges

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**Abstract**

As Europe is the world's leading producer of biogas, this article examines how agricultural anaerobic digestion (AD) is organized and governed, and explores the social challenges involved in structuring the sector around a possible "European model". Following a social science perspective, it presents a systematic review of 64 French- and English-language articles drawn from 16 academic databases. The findings highlight five key dynamics. First, there is a shift from farmer-led to increasingly industrial models of AD. Second, diverse and hybrid business models are emerging, involving new forms of multi-scale coordination. Third, the sector remains structurally dependent on public subsidies and on regulatory frameworks. Fourth, the economic viability of AD for farmers remains uncertain, driving a transition from cogeneration to biomethane injection. Fifth, tensions develop between rural place-based imaginaries and the realities of globalized energy networks. These patterns underscore the complexity of biogas sector-building in Europe and the competing narratives shaping its evolution. We argue that agricultural AD cannot be reduced to a unified trajectory, but reflects ongoing negotiations over energy models, territorial development and socio-technical legitimacy. This paper concludes by discussing the implications of these dynamics for the sustainability and fairness of future biogas trajectories across Europe.

**Keywords:** anaerobic digestion; farming; renewable energy; biogas; ecological transition; sustainable agriculture; rural development; viability; social sciences; Europe

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Academic Editor: Michael Blakeney

Received: 22 April 2025
Revised: 10 June 2025
Accepted: 18 June 2025
Published: 24 June 2025

**Citation:** Hamman, P.; Dziebowski, A. Building an Agricultural Biogas Supply Chain in Europe: Organizational Models and Social Challenges. *Sustainability* **2025**, *17*, 5806. https://doi.org/10.3390/su17135806

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## 1. Introduction

Anaerobic digestion is the technically controlled breakdown of organic material in the absence of oxygen [1]. This process has economic, social, technological, energetic and environmental implications [2,3]. From this relational perspective, we offer a synthesis of the organizational and social issues involved in the challenge of building an agricultural biogas supply chain in Europe.

### *1.1. Context and Scope*

This review focuses specifically on agricultural anaerobic digestion, based on knowing that several biogas generation systems coexist distinctly, involving the digestion of sewage sludge, solid waste from local communities and landfills and industrial waste. They have their own regimes and actor configurations (see for instance, on Wales: [4]); national and

European coordination between these systems is limited [5] (p. 15). We also focus here on biogas due to its increasing importance, especially in the production of biomethane, i.e., refined biogas [6,7]. At the intersection of these two configurations—agricultural residue and digestion methods—it is important to examine the processes through which sectors develop and organize, looking both at the actors and at the conditions of this development. This will be our overarching concern in this review, which draws on social science approaches.

In practical terms, *upstream*, digesters installed on or near farms are fed agricultural residue, which is a process valorized economically and ecologically, as well as energy crops; maize, beet or sorghum, for instance, can be grown for the purpose of serving as inputs for digestion. Then, *downstream*, the degradation process produces biogas—valorized as a renewable energy for the carbon-free transition—as well as digestate, the byproduct of digestion, which can be spread on cultivated soils as an alternative to mineral fertilizer. As calls to act in response to climate change are voiced with increasing urgency, this technology has raised interest precisely as a means to valorize residue from farming and livestock and/or of dedicated crops by transforming this residue into resources with an environmental and social added value through biogas [3]. In that sense, the example of agricultural anaerobic digestion gives us a window into the connections—or lack thereof—between energy transition and ecological transition, and between levels of action, from the farm to the globalized energy market, with implications on career development for farmers, market viability and public policy implementation.

Anaerobic digestion has now carved an important place in the energy mix: it is no longer a niche, and according to multiple forecasts, it is likely to expand further. This is particularly the case in Europe, the world's leading biogas electricity producer (Table 1).

**Table 1.** Europe's position in biogas production and utilization at a global scale (Source: Brémond et al. [7]).

| Indicator | Europe | Global |
| --- | --- | --- |
| Share of global biogas production (2017) | 54% of global production (364 TWh) | Asia: 31%, Americas: 14% |
| Number of biogas plants (2018) | 18,202 plants | China: ≈6000 plants (mostly small-scale); USA: ≈2200 plants |
| Installed capacity for electricity generation from biogas (2018) | 12.6 GW, representing 68% of global biogas electricity capacity | Global capacity: 18.1 GW<br>China: 0.6 GW (≈3%)<br>USA: 2.4 GW (≈13%) |
| Biogas energy use (2018) | 88.5% of European biogas is used for electricity and heat generation via combined heat and power (CHP) systems | USA: 40% for electricity, 60% for other uses (heat generation and biomethane production) |
| Ongoing market trends | Shift towards agricultural waste utilization and biomethane production | USA: Market dominated by municipal solid waste valorization<br>China: Rapid development of both household-scale (cooking, lighting) and industrial biogas plants |
| Projected biomethane potential for 2050 | 64.2 billion $m^3$/year (≈4.8% of UE-28 energy consumption) | Global potential estimate: ≈200 billion $m^3$/year |
| Share of agricultural feedstocks in biogas production | Over 70% (crops, livestock manure, agricultural residues) | USA: 25–30%<br>China: 40% (remainder from biowaste and wastewater treatment plants) |

### *1.2. Study Goals*

In the context of European leadership, this review precisely investigates the dynamics and implications of the deployment of a sector around a possible "European model" for agricultural anaerobic digestion. Existing reviews have tended to delineate a divide between the so-called developed and developing countries, with a divide also pertaining to the types of plants and of biogas uses, which can be roughly summarized as agricultural and industrial vs. agricultural and domestic [8] (p. 9) [9]. This makes a comprehensive focus on the European level both coherent and far-reaching, at a scale between global approaches and national cases studies.

For this purpose, we built parallel corpora of French- and English-language studies following a systematic protocol, drawing on sixteen databases. In total, 64 research papers were selected and synthesized (Section 2). These show that the development in this field was initially driven by farmers and public support. This model has been challenged by a range of interconnected trends: a shift from cogeneration to an increasing use of injection (on these concepts, see Table S1 in the Supplementary Materials), with consequences for the interactions between agricultural actors and industrial stakeholders, as well as a shift in relationships to public policies, materializing in subsidy dependence (Section 3). As a result, the sustainability of anaerobic digestion is uncertain for agricultural adopters and for local rural development (Section 4). Ultimately, key dividing lines are identified that will have structural implications on future choices and on how to devise scenarios (Section 5), and possible avenues of research are discussed in the Conclusion (Section 6).

## 2. Materials and Methods

Two corpora of publications in French and English were assembled and discussed; papers were selected following a single protocol. The goal was to obtain solidly grounded findings regarding overarching themes and structuring debates. The process was broken down into three methodological steps.

### *2.1. Literature Search*

The first step consisted of assembling the two French- and English-language corpora. Between 23 February and 6 March 2024, we used the portal of the French National Center for Scientific Research BibCNRS SHS (https://bib.cnrs.fr/, accessed on 6 March 2024), which offers access to many national and international databases. For the purposes of a systematic literature review, we chose not to limit ourselves to one or a few select databases, as has been generally performed in reviews on this subject.

For instance, Alan and Köker have examined the implications of the valorization of agricultural waste in a circular economy based on a bibliometric review of the past twenty years using the Web of Science database [6]. For the purposes of their review on barriers to biogas adoption in 32 European, American, African and Asian countries, Nevzorova and Kutcherov used the Scopus database [8]. Mancini and Raggi reviewed the socio-cultural factors informing the acceptability of biogas projects on the global level, using the systematic PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), but drawing on two databases: Scopus and Web of Science, and focusing on Life Cycle Analyses—which will not be discussed here [9]. Lastly, Brémond et al. devised their scenario for the development of the European biogas sector for 2020–2030 and beyond by focusing on five European countries and four databases: Google, Web of Science, Google Scholar and ScienceDirect [7].

For this review, we searched sixteen databases to ensure a broad overview of the social science approaches to agricultural anaerobic digestion in two languages. These are the following six French-language and ten English-language databases, respectively:

Cairn, Érudit, Gallica, HAL, OpenEdition and Persée; Jstor, Sage, ScienceDirect, SocIndex, SpringerLink, Web of Science, Wiley, Ebsco, Edp Science and Nature. In terms of methodological robustness, this ensured a diverse corpus, as the contents of databases depend on their scope and editorial policy.

In each of these databases, we performed a keyword search for terms associated with "méthanisation agricole" in French-language databases, and with "agricultural biogas" and "agricultural anaerobic digestion" in the English-language databases. We immediately introduced two restrictions by searching specifically for (i) articles (excluding other types of publications: books, PhD theses, research reports, etc.); and (ii) available in a full-text version through BibCNRS SHS, excluding abstract-only pages (to be able to perform a qualitative analysis by reading the entire text). Results were shown sorted by relevance—we selected all hits for databases offering under 100 references, and otherwise the first 100.

The searches generally yielded abundant results despite the two initial filters, ranging from hundreds to thousands of articles. To address this, we added two more restrictions to the protocol for some broad databases, requiring the keywords to be featured in the abstract as well as in the full text (in Jstor, Sage and Wiley), and for the article to be filed under humanities or social sciences (in ScienceDirect, SpringerLink, Ebsco, Edp Sciences, Web of Science and Wiley). This selection process allowed us to automatically exclude 27,905 results ("identification" phase, see Figure 1 below).

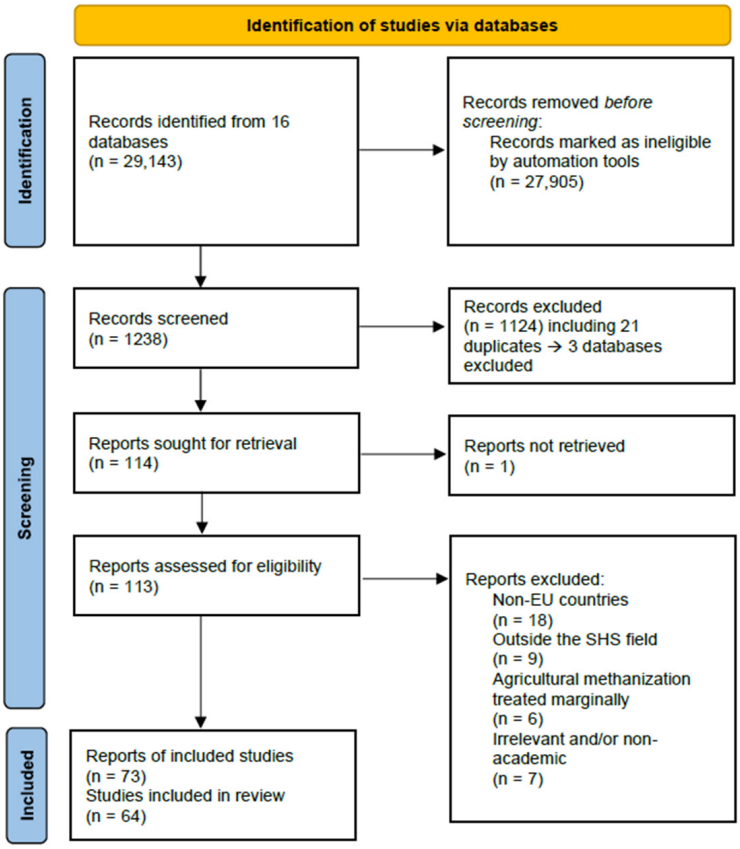


**Figure 1.** PRISMA flow chart of the literature study (© Philippe Hamman and Aude Dziebowski. Source: PRISMA 2020 flow diagram [10]. This work is licensed under CC BY 4.0.).

### *2.2. Literature Assessment*

The second phase of the protocol ("screening phase", see Figure 1) consisted of determining and applying additional selection modalities for the 1238 articles resulting from the first automated search.

Each result was examined in successive steps. We started by checking that it did come from a scientific journal, and then read the abstract to assess whether the article seemed relevant in terms of (i) study topic and (ii) disciplinary affiliation.

Following these steps, we excluded three databases—Ebsco, Edp Science and Nature—for which the keyword search did not yield relevant results after screening. The in-depth work was ultimately conducted on thirteen databases. We only counted articles that came up in multiple databases once (thus excluding 21 duplicates). Out of these thirteen databases, we were left with 114 articles, including 64 in English and 50 in French.

We then performed the final selection phase by reading these 114 articles in full. This resulted in the following choices:

- We focused on articles primarily dealing with European contexts (for instance, removing cases of comparisons between countries from different continents and global literature reviews), removing eighteen articles from the corpus;
- A few articles (nine more) were too far removed from the social sciences;
- Some (six more) turned out to only briefly broach anaerobic digestion. Others (seven more) were more akin to reports from actors outside the academic field.

We thus obtained a total of 73 articles. Among those, we removed nine that did not directly address the sector-building process which is the focus of this review, leaving us with a final tally of 64 articles (33 in English and 31 in French).

All of these steps are summarized on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) flow chart of Figure 1.

### *2.3. Literature Synthesis*

The years of publication of the papers selected in the second phase show that agricultural anaerobic digestion is a renewable energy process that, until recently, remained little-studied in the social sciences (Figure 2); hence, this is the topical interest of this review now that papers are multiplying.

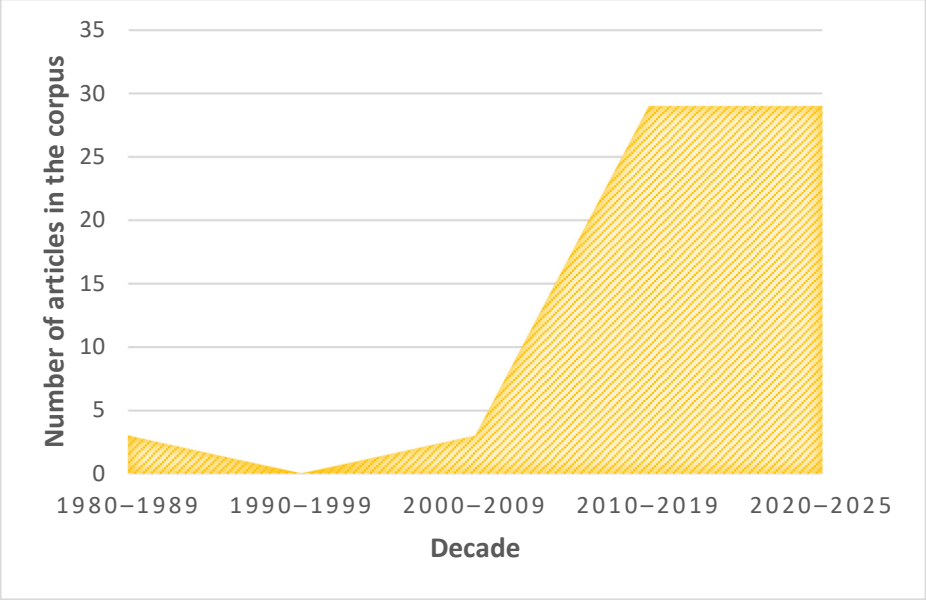


**Figure 2.** Temporal distribution of selected articles in the corpus by decade of publication. The distribution within the corpus indicates that social science research papers on anaerobic digestion have only been emerging since 1980 (see [11]), with a limited number of publications before 2010 (6, none during the 1990s). A notable increase can be observed from 2010 onwards (29 papers published during the 2010s), a trend that has continued since 2020 (with 29 articles already published between 2020 and 2024).

To go further, in the third phase, the papers were categorized using a matrix to synthetize the main results and debates, as shown in Table 2. The result is a European-level comparison, based on an overview of local and national situations and/or modeling proposals drawn from the two corpora. These occasionally overlap in terms of geographical areas of study: 8 out of the 31 French-language articles discuss countries other than France, and 3 of the English-language articles discuss France. In that regard, and considering the variety of countries under study (see Table 2), our approach is truly relational rather than based on monographic examples.

**Table 2.** Identification of key contributions from the French- and English-language social science literature on agricultural anaerobic digestion: Matrix of the 64 papers studied (© Philippe Hamman and Aude Dziebowski).

| References | Empirical Paper/Review | Farmer, Farming and Evolutions | Typologies and Business Models | Regulatory Frames and Public Support | Economic Viability of Methanization | Local Rural Develop-ment | Scenarios and Future Studies | Considered Areas/EU Countries |
|---|---|---|---|---|---|---|---|---|
| **French-language corpus** | | | | | | | | |
| Amand et al./2015 [12] | E* | X | X | | X | X | | France |
| Anzalone, Mazaud/2021 [13] | E | X | X | | | X | | France |
| Attarça, Lassalle de Salins/2013 [14] | E | X | X | X | | | | France |
| Béline et al./2012 [15] | E | | | X | | | | France, Germany, Denmark |
| Béline et al./2013 [16] | E | | | X | | | | Germany, Denmark, France, Italy |
| Berthe, Grouiez, Dupuy/2018 [17] | E | X | | | X | | | France |
| Berthe et al./2020 [18] | E | X | X | | X | | X | France |
| Berthe, Grouiez, Fautras/2022 [19] | E | X | X | | X | | X | France |
| Bioteau et al./2013 [20] | E | | | | | X | | France |
| Bolzonella, Fatone, Cecchi/2013 [21] | E | | | X | | | | Italy |
| Bourdin/2020 [22] | E | | | X | | | | France |
| Brühne, Tempel, Deshaies/2015 [23] | E | | | | | X | | Germany |
| Camguilhem/2018 [24] | E | | | | | X | | France |
| Condor/2019 [26] | E | X | X | | | X | | France |
| Couturier/2013 [27] | E | | X | | X | | | France |
| Delhoume, Caroux/2014 [28] | E | X | X | | | | | France |
| Garambois et al./2022 [29] | E | X | | X | X | X | X | France |
| Grouiez/2021 [30] | E | X | X | X | X | X | | France |
| Jayet, Sourie/1983 [31] | E | | | X | X | | X | France |
| Jutteau, Lacque-ment/2019 [32] | E | X | | X | | X | | Germany |
| Laboubée et al./2020 [33] | E | X | X | | | X | X | France |
| Levasseur et al./2011 [34] | E | | | | X | | | France |
| Mazaud, Pierre/2019 [35] | E | X | | | | X | | France |
| Moraine et al./2019 [36] | E | X | X | | | X | | France |
| Raffin, Dormoy/2021 [37] | E | | | | | X | | France |
| Rakotovao, Godard, Sauvée/2021 [38] | E | X | X | | | | | France |

**Table 2.** *Cont.*

| References | Empirical Paper/Review | Farmer, Farming and Evolutions | Typologies and Business Models | Regulatory Frames and Public Support | Economic Viability of Methanization | Local Rural Develop-ment | Scenarios and Future Studies | Considered Areas/EU Countries |
|---|---|---|---|---|---|---|---|---|
| Carrière/1984 [25] | E | | | X | X | | X | France |
| Sánchez Sáez/2005 [39] | E | | | X | | X | | Spain and the EU |
| Sourie/1980 [11] | E | | | X | X | | X | France |
| Vue, Garambois/2017 [40] | E | X | X | X | | X | | Germany |
| Weiland/2013 [41] | E | | | X | | | | Germany |
| **English-language corpus** | | | | | | | | |
| Alan, Köker/2023 [6] | R | X | | | X | X | | Worldwide |
| Bertolino et al./2023 [42] | E | X | | X | | | | Italy, Brazil |
| Bischoff/2012 [43] | E | X | X | | | | | Germany |
| Bluemling, Mol, Tu/2013 [44] | R | X | | | | X | | Worldwide |
| Brémond et al./2021 [7] | R | | | | X | | X | Germany, Denmark, Sweden, France, Italy |
| Burg et al./2021 [45] | E | | | | X | | X | Switzerland |
| Cadiou, Aubert, Meynard/2023 [46] | R | | | | | | X | France |
| Chodkowska-Miszczuk et al./2020 [47] | E | | | X | | X | | Poland, Slovakia, Czech Republic |
| Darnhofer/2005 [48] | E | | | | | X | | Austria |
| Gava et al./2017 [49] | E | X | X | | | | | Italy |
| Horschig et al./2020 [50] | E | X | | X | | | | Germany |
| Igliński et al./2020 [51] | E | | X | X | | | | Poland |
| Karlsson et al./2017 [52] | E | | X | | X | | | Sweden |
| Kriechbaum et al./2023 [53] | E | X | | | X | | X | Austria |
| Lyytimäki et al./2018 [54] | E | X | | X | X | | | Finland |
| Lyytimäki et al./2021 [55] | E | X | | X | X | | | Finland |
| Magnani/2012 [56] | E | X | | | | X | | Italy |
| Mancini, Raggi/2022 [9] | R | | X | | | X | | Worldwide |
| Martinát, Cowell, Navrátil/2020 [4] | E | X | | | | X | | Wales |
| Mateescu, Dima/2020 [57] | E | | | X | X | | | Romania |
| Mol/2013 [5] | E | | X | | | | X | Worldwide (especially EU—Asia) |
| Navrátil et al./2021 [58] | E | X | | | | | | Czech Republic |
| Nevzorova, Kutcherov/2019 [8] | R | X | X | X | X | | | Worldwide (32 countries) |
| Niang, Torre, Bourdin/2022 [59] | E | X | | | | X | | France |
| Panoutsou et al./2022 [60] | E | X | | | | X | | 18 EU countries |
| Pestalozzi et al./2019 [61] | E | X | | | | | | Germany |
| Piwowar/2020 [62] | E | X | | X | | | | Poland |
| Plieninger, Bens, Hüttl/2006 [63] | R | X | | X | | X | X | Germany |
| Puupponen et al./2022 [64] | E | X | | X | X | | | Finland |
| Sheer et al./2024 [3] | R | | X | | | | | Worldwide |

**Table 2.** *Cont.*

| References | Empirical Paper/Review | Farmer, Farming and Evolutions | Typologies and Business Models | Regulatory Frames and Public Support | Economic Viability of Methanization | Local Rural Development | Scenarios and Future Studies | Considered Areas/EU Countries |
|---|---|---|---|---|---|---|---|---|
| Sorda, Sunak, Madlener/2013 [65] | E | | | X | | X | X | Germany |
| Stürmer et al./2021 [66] | E | | | X | | | | Switzerland, Germany, Austria |
| Sutherland, Peter, Zagata/2015 [2] | E | X | | X | | | | Germany, Czech Republic, United Kingdom |

"E" indicates an empirical paper, "R" denotes a review, "X" serves as a checkmark symbol.

We singled out six main themes connecting the articles' findings:

- The initial positions of farmers and the industrial evolution;
- The typologies of the business models of farms and biogas plants;
- Contextual and regulatory tools and barriers, with a focus on the role of public subsidies and their evolution;
- The economic viability of biogas and the problem of its limited returns for farmers;
- Its contributions to local rural development;
- The current scenario and future studies.

Combining the themes identified above, we reflect on the possible existence of a European model for agricultural anaerobic digestion. We seek to characterize its main actors, processes and stakes, as well as the levels at which they operate and their commonalities—while also identifying divergent trajectories and national differences, which nonetheless reveal shared framings in the discourse around biogas.

## 3. Results: A European Model Based Primarily on Farmers and Public Subsidies

Agricultural anaerobic digestion is defined by two main characteristics that have informed the sector-building process. First, farmers have been the pioneers of biogas, but their positions within the sector have evolved. The literature debates a shift *in the making* of an agricultural to an industrial model (Section 3.1), corresponding to the emergence of mixed business models relying on various actor configurations (Section 3.2). Second, analyzing the development of biogas plants also requires assessing the conditions of their possibility. The sector appears highly dependent on the different frameworks for regulation and public subsidies in Europe. This evidences a model historically connected to the existence of support schemes, particularly at the national level. Evolution takes place at different speeds depending on the implementation of more or less biogas-friendly policies, to the extent that the question of paradigm shift is now being raised (Section 3.3).

### *3.1. From an Agricultural to an Industrial Model?*

#### 3.1.1. The Role of Local Farming Contexts in the Early Development of Biogas

Farmers and the agricultural sector provided the main initial impetus for the development of anaerobic digestion in Europe, particularly in Germany, a pioneer in the 1990s [50]. The Czech Republic is an interesting borderline case: farmers and farming businesses support biogas because they have been left with underused lands as a result of wide-ranging transformations in agriculture over the past three decades, after the heyday of large collective farms [58].

In France, the development of biogas has been set against the backdrop of a structural transformation of agriculture, characterized by increased specialization and the intensifica-

tion of production systems. This trend has resulted in regional differences. For instance, in Brittany, where intensive livestock farming dominates, biogas has become a tool for farmers to adjust to environmental requirements, such as disposing of excess livestock manure. In the northeastern Grand Est region, dynamics are more heterogeneous. In some areas, like the Aube area of Champagne, with a majority of large farms growing field crops, biogas has been used primarily to diversify outlets for products and improve revenue security by valorizing agricultural byproducts. These examples reflect the influence of local agricultural contexts on the development of biogas since its early days [29].

Therein lies another distinction from other renewable energy sources: biogas is embedded in the social structures and practices of rural areas. Biogas production systems depend largely on inputs—livestock manure and crop residues—that were previously seldom used for energy production and were incorporated into agricultural systems (by spreading manure, burying crop residues to enrich soils, using them as livestock feed, etc.). In that sense, biogas differs from wind, solar and hydraulic energy, where the supply comes directly from the elements (water, wind, sun, etc.). The "social organization" of rural biogas production revolves around farmers, at the intersection of the environmental and social systems [44] (pp. 11–13).

#### 3.1.2. The Integration of Anaerobic Digestion into the Agro-Industrial System

The increasingly clear adoption of the energy transition discourse in biogas production has changed the initial emphasis on farmers and local ties. We are now witnessing closer interactions between farmers and other stakeholders, especially in industry, starting upstream of the process with biomass supply. This was already pointed out by 2006 in the case of Germany, where anaerobic digestion developed earlier and to a greater extent than elsewhere [63] (p. 126). The growing role of financial investors has also been noted there, particularly in large plants [43] (p. 3). A comparison between Germany and the Czech Republic is instructive in this regard: while farmers were biogas innovators in both countries, biogas was anchored into the agriculture regime in the Czech Republic, and in both the agriculture and electricity regimes in Germany [2] (p. 1551).

In Finland, the public debate on biogas is primarily framed by the perspective of energy producers, which reflects the domination of the energy transition discourse [55]. In Poland and Denmark, large, centralized plants have likewise been favored [51]. Multi-actor interactions are expanded, with farms supplying energy industrials for the purposes of biofuel production and the agri-food sector supplying farms for anaerobic digestion. As recovering waste in circular economies has become a mantra, *biomethane* production has been playing an increasingly prominent role in waste processing and recycling processes, starting within the agro-industrial sector: energy production is presented as an economic opportunity [6] (pp. 14–15). An analysis of value chains for industrial crops grown on marginal agricultural lands which was conducted in eighteen European countries yielded similar conclusions: the main goal is to cultivate biomass to support the bioeconomy [60] (p. 1320). The embedding of biogas within the agro-industrial system and the diversity of its applications are clearly evidenced.

Regarding the French case, two main phases can be distinguished: in the 2000s, biogas was essentially the preserve of pioneering livestock farmers who adopted the technology to gain autonomy and valorize manure locally; after 2015, it has been characterized by an increasingly structured sector and the emergence of new intermediaries. This momentum has accelerated with the rise in biomethane, whose injection into gas networks has paved the way for more financialized models. As a result, the ability of farmers to capture some of the added value of biogas becomes more uncertain: this trend might challenge their central

role in the sector—some could be recast as simple suppliers of better capitalized plants rather than full-fledged energy producers [30] (pp. 45–47) [17].

#### 3.1.3. "Energy Farmers" and the Redefinition of the Agricultural Profession

Amid this change, farmers are led to renounce part of what they do to become "energy farmers", i.e., to expand beyond food production to embrace the path of energy diversification [13]. Anzalone and Mazaud call these farmers who are not just managing a biogas plant but adopting entrepreneurial, multi-partner approaches "énergiculteurs". They navigate between multiple social arenas, combining the demands of agriculture and the constraints of industry. Their role goes far beyond the supply of inputs: they have functions pertaining to project management, negotiation and coordination, requiring skills in financing, bureaucracy and territorial communication [13]. On the contrary, to deal with this complex technology, some scientists, industrialists and public officials suggest in Germany that farmers should solely be providers of raw materials and step back from plant operation. For instance, power-to-gas could therefore transform the value chain of the biogas sector by transferring plant management from farmers to industrialists, relying on specialized staff [61] (pp. 9–12).

Concrete dynamics of differentiation appear between the higher-capital farms and those with more limited resources. Biogas thus tends to deepen the fault lines between farmers, illustrating a process of the actualization of productivism in a new guise [12]. Beyond the technological and economic aspects, the modes of appropriation of digestion among farmers also depend on sociological factors and different representations of the job. The professional acceptability of "innovative" renewable energy projects varies widely depending on the farmers' backgrounds, pointing to a divide between conceptions of farming. Some farmers, rooted in an entrepreneurial approach, perceive the energy transition as an economic opportunity, including anaerobic digestion into a broader strategy for modernizing and securing income. Conversely, other farmers who are attached to the local heritage dimension of agriculture may be more reluctant to pursue such changes, highlighting the need to preserve local agricultural identity and food production. This contrast shows that the anaerobic digestion issue reflects the variety of the agricultural world's relationships to the energy transition, depending on their perception of the associated change and risks, their degree of support to innovation dynamics and related discourses on agriculture [28].

### *3.2. Towards Mixed Business Models?*

As we can see, the world of biogas adopters is in no way a monolithic entity. The reality is more complex: Oosterveer and Spaargaren have described "modernized mixtures" characterized by the combination of different technological scales and different organizational and governance forms, yielding a variety of socio-technological systems [67]. These modes of "social organization" of biogas create multiple possible mixtures, depending on several parameters. These include the distinction between the input supply network (involving one or several farms) and the distribution network (either limited to the host farm or extended to outside consumers); the allocation of revenues; the system's social dividing lines (starting with accessibility for local residents); and questions of scale (number of digesters, capacity, degree of integration between suppliers and consumers, etc.) [44] (pp. 12–13).

#### 3.2.1. How Organizational and Territorial Dynamics Shape Business Models

Attempts at classifying biogas plants made by social scientists have often been based on technological, legal or economic criteria, emphasizing the size of installations, the nature of the inputs and the forms of valorization of biogas. As a counterpoint, a few studies have strived to analyze the diversity of business models from the angle of social and organiza-

tional dynamics, looking more specifically into forms of collective entrepreneurship [26] and into the strategic positioning of farmers in the sector [18]. For example, Condor put emphasis on governance challenges, such as diverging interests between members, the coordination costs inherent in group decision-making or the risk of opportunism, as some farmers may temporarily get involved in a collective project and then move on to investing in their own individual project. Collective anaerobic digestion is not just a matter of organization; it is informed by a broader dynamic of shifting power relations in the agricultural world and in the energy sector [26] (pp. 81, 88). In a complementary way, Berthe et al. identify several configurations depending on the identity of the majority shareholders and the degree of autonomy of the farmers. They highlight the increasing heterogeneity of farmers' trajectories in the biogas sector, between continued autonomy in cooperative models and gradual integration into more financialized systems [17,18].

More specifically, a 2015 study on biogas adopters in Tuscany singles out two main types of actors: individuals with a background in agricultural training, and energy companies. It also distinguishes three economic models. The first involves multifunctional farms that use biogas to gain market autonomy while maintaining food and feed production. The second includes entrepreneurial farms that adopt biogas as part of a strategy to scale up and maximize profits. The third corresponds to energy companies managing multiple renewable energy installations—now the most widespread model. This first finding is nuanced by a second: while builders and industrialists operating "upstream" of the digestion process are the most influential stakeholders and may contribute to the dissemination of knowledge among adopters, regardless of their environment, self-accessible resources (for instance, visits to plants operated by neighboring farmers) remain the main sources of information at the decision-making stage [49]. This confirms that biogas projects in Europe are territorially anchored [12,19] rather than following a globalized one-size-fits-all model, and it shows the porosity of practical registers.

#### 3.2.2. Multi-Scale Governance and Coordination Challenges

Recent dynamics show that biogas is now embedded in a number of different trajectories, shaped by technological choices, governance models and more complex sets of actors. Berthe et al. identify five business models for agricultural biogas production, according to four criteria: the knowledge mobilized; the technologies used; the networks of actors involved and their institutional environment.

1. The "internalization and symbiosis model" is characterized by a logic of self-reliance and self-sufficiency: the farmers control maintenance costs to the highest possible extent by internalizing them, use their own manure as input and limit external interventions as much as possible. Here innovation relies on an empirical approach—farmers learn by doing and gain expertise as they operate their plant. These units, which are often installed by members of the first generation of adopters (before 2015), have received—at least initially—strong support from public subsidies and favor cogeneration heating.
2. The "small farmers group model" hinges on cooperation between livestock breeders and grain farmers, rethinking their agricultural projects collectively. These units require more sizeable investments and are often monitored by specialized operators. They more often hire employees, and purchase the majority of their inputs (often from cooperatives). Knowledge transmission plays a key role: breeders share their expertise on plant operation, whereas grain farmers bring their knowledge on spreading digestate.
3. The "grain farmer biogas injection model" refers to projects operated by farmers specializing predominantly in grain, either individually or as a small group of farmers.

These units are propped up by high initial investments, often compensated for by contracts with cooperatives and agrobusiness firms to ensure supply and biogas sales. This model is characterized by the hiring of employees from the industrial sector, trained by the manufacturers and the farmers themselves, and by a growing specialization in the plants' administrative and commercial management.

4. The "partial outsourcing and generic technology model" reflects an increased dependence on industrial actors. It is mainly adopted by farmers who invested in biogas after 2015, individually or in small groups, and who operate turnkey plants built by private operators. These units are characterized by a strong dependence on the expertise of manufacturers, the partial outsourcing of management and high investment costs due to the large numbers of actors involved. The researchers stress the challenges faced by these farmers, especially pointing to frequent technical issues (design defects, oversizing, etc.), the high bankruptcy rate and the exposure to the ebbs and flows of public subsidies.
5. The emerging model of "joint projects between agricultural cooperatives and investors" is less widespread but increasingly followed. While it could strike a balance between territorial anchoring and access to financial resources, it also raises the question of governance and of the distribution of added value among the actors [19] (pp. 23–30).

Here we concur with the conclusions of a study conducted on a French "biogas cluster", involving the networking of various local actors in projects in which different groups operate semi-autonomously. The authors highlight the role played by the resources of "organized proximity", sustaining dynamics and creating a sense of belonging through frequent interactions between participants. The correlation between geographical proximity and organized proximity is conducive to both the emergence and the stabilization of projects; in other words, coordination between actors and the involvement of all stakeholders are crucial factors [59] (pp. 345–346). The structuring of a national interest group—the French Association of Biogas Producing Farmers—illustrates the shift from technical innovators to political actors and highlights the skills needed to influence policymaking: conviction, technical expertise and perseverance. It also points to the importance of three key resources for farmers to gain an advantage in the negotiations: information, which allows them to anticipate and adjust their strategy in response to changes in regulation; connections, which are crucial to have influence in institutional talks; and symbolic legitimacy [14].

The former results can be extended in a multi-scale approach: the stabilization and viability of agricultural biogas projects appear to depend on the convergence of territorial anchoring (geographical proximity) and an organized sector-building process that brings together a variety of stakeholders operating at different levels (organized proximity), even as they may pursue different goals. For instance, a typology of success factors in Sweden does mention economic and strategy conditions—i.e., having a long-term perspective on investments and activities and being able to count on a fixed price for the biogas output over several years. But that is not all by any means: the other factors emphasize the practical operation of multi-actor configurations. There is first an organizational dimension, beginning with cooperation between public and private actors and with policymakers. This dimension interacts with factors pertaining to territorial dynamics and interactions between levels, such as the possession of entrepreneurial skills and experience, as well as the role of "influential enthusiasts", i.e., initiators and actors with diverse skillsets, strong communication skills and access to networks of investors/policymakers/industrials, who will persevere to find alternatives whenever challenges arise. We can speak in such cases of mixed business models, in the sense that they allow for lower returns than in

other investments, as long as biogas production and distribution still turn a profit [52] (pp. 2929–2931).

### *3.3. The Dependence on Regulations and Public Subsidies*

#### 3.3.1. A Widespread Reliance on Subsidies

The most consistent finding across the body of literature under study, regardless of the European country, is the correlation between the rise in biogas and the presence of public regulatory frameworks and economic support systems. In 1984, based on the experimental case of a biogas plant in France, Carrière, it was already argued that without massive state support, the economic profitability of biogas production would remain limited and could not compete with fossil energy. Forty years later, this remains a central question for the evolution of the sector, in terms of profitability and institutional structuring [25] (p. 31).

In their overview of barriers to the implementation of biogas worldwide, Nevzorova and Kutcherov immediately note the role of governments through support policies and the establishment of a clear political framework. Conversely, institutional barriers are cited such as the lack of programs designed to promote biogas technologies, shifts in priorities (like the reduction in feed-in tariffs) as well as bureaucratic issues [8] (pp. 6–7). While regulatory frameworks and public support schemes play a key role in the development of biogas, they can also act as barriers when project managers face bureaucratic complexity and uncertainty regarding the availability of funding. For instance, Bourdin pointed out a number of institutional barriers slowing down or outright stopping the implementation of biogas projects in France, citing in particular the lack of adequate subsidies and the burdensome paperwork and consultation process, which considerably lengthen implementation and favor industrial actors with more experience of the regulatory and bureaucratic processes. Additionally, support programs, although necessary, are not always adjusted to the realities of the biogas adopters. Criteria for eligibility for public subsidies are often conceived for standardized models, and do not always consider the specificities of farms involved in biogas production, especially when they favor short supply chains or energy self-sufficiency. This inadequacy contributes to deepening inequalities between farmers, with some enjoying easy access to funding and others struggling to fit into existing programs [22] (pp. 69–72)—an observation that still applies equally at the European level (Table 3).

**Table 3.** Comparative analysis of strategies and performances in the field of anaerobic digestion in eight European countries (based on Gustafsson and Anderberg [68]).

| | Germany | France | UK | Sweden | The Netherlands | Denmark | Austria | Italy |
|---|---|---|---|---|---|---|---|---|
| Biogas output (MWh per inhabitant), 2020–2021 | 1 | 0.1–0.3 | 0.1 | 0.25 | 0.3 | 0.2 | 0.15 | 0.1 |
| Economic instruments at the disposal of farmers | Investment subsidies, feed-in tariffs and green certificates | Investment subsidies, feed-in tariffs, tax bonuses and cuts | Investment subsidies (bidding), feed-in tariffs and green certificates | Investment subsidies, tax cuts | Investment subsidies, feed-in tariffs and tax cuts | Investment subsidies, feed-in tariffs and tax cuts | Investment subsidies (bidding) and green certificates | Investment subsidies, feed-in tariffs |
| Regulatory framework | Stable, favorable policies | Recent but favorable framework | Regulated support framework | Robust regulation | Strong regulation, fiscal challenges | Ambitious regulations | Changing legislation | Less structured legal framework |
| Main challenges | Technological lock-in, production costs | Lack of long-term support, slow adoption | Setting up costs, subsidy dependence | Lack of agricultural substrates, high costs | Bureaucratic complexity, limited market | Rigid regulation | Lack of infrastructure | Weak public support, high costs |
| Medium-term growth potential | Very high, emphasis on innovation | Growth expected, particularly in the use of agricultural byproducts | Moderate growth with targeted support policies | Stable growth, but limited by market size | Moderate growth with fiscal challenges | High potential but bureaucratic challenges | Moderate potential, increased use of agricultural byproducts | Slow growth, but increasing attention to organic waste |

We can multiply these examples. A comparison of the regulations for biogas in Switzerland, Germany and Austria shows the influence of these frameworks on the structure of the sector and on the plants' technical performance indicators. If further development is stalled for legal reasons, power production will decline in the mid-term, as actors in the sector quickly respond to legal changes [66]. Heavy reliance on public subsidies is also reported in Finland [54]; in Italy, too, the importance of political decisions and the need to improve policies to support the growth of renewables are largely cited among the actors in the sector [42].

#### 3.3.2. The Long-Term Institutionalization of Public Support in National Trajectories

To illustrate disparities in biogas development across Europe depending on public support strategies and regulatory framework changes in each country, Béline et al. proposed a comparative analysis of national trajectories of the sector up to the early 2010s. In short, while some states opted to structure the sector at an early stage and to quickly integrate it into energy policies (Germany, Denmark, Italy), others, like France, adapted more gradually, with a later development of the sector and more complex regulation [16].

In this respect, the case of Germany, often heralded as the leading model for the development of agricultural biogas in Europe for its early, structured support policy, deserves scrutiny. The entry into force of the Renewable Energy Sources Act (*Erneuerbare Energien Gesetz*—EEG) in 2000 marked a key turn for the sector, guaranteeing a stable remuneration for electricity generated from biogas for twenty years. This financial incentive led the sector to quickly expand: as of 2011, Germany had nearly 7100 installations, accounting for 50 percent of Europe's biogas production and 3.1 percent of the country's electricity consumption. Over the years, the regulation changed to reduce some negative externalities, particularly by gradually lowering the share of maize in the plant inputs to promote the diversification of energy crops and prevent an excessive extension of monoculture for biogas [41] (pp. 14–16). An agent-based simulation model applied in 2013 to the German states of North Rhine-Westphalia and Bavaria shows how changes in support schemes, including feed-in tariffs, can impact electricity generation from cogeneration biogas plants, initially the leading type of production in Europe. According to the model, a 25 percent cut in feed-in payments would significantly reduce the installed capacity of new plants by 22 percent in both regions [65] (pp. 54–56).

Italy also stands out as an example of the quick development of biogas, with a strong expansion in the agricultural sector largely propelled by financial incentive schemes. The introduction of a guaranteed feed-in tariff over fifteen years, among the highest in Europe (0.28 EUR/kWh), led to a significant increase in the number of agricultural production units between 2009 and 2011. However, this support scheme caused market distortion effects by favoring the establishment of large biogas plants and incentivizing the use of energy crops (maize and triticale silage) over livestock manure, intensifying competition with traditional agricultural uses and raising environmental concerns. In response to these imbalances, a 2012 decree introduced a reform of the subsidy system, aimed at favoring smaller-size installations (<500 kW) relying primarily on livestock manure. By adjusting its regulatory model after a phase of rapid extension, Italy saw similar trends observed in the other European countries—such as Germany—that revised their support policies to better take into account environmental and agricultural goals [21].

In Finland, a study of newspaper coverage and selected reports on biogas has pointed to the coexistence of two partially conflicting economic narratives. On the one hand, biogas is portrayed as an opportunity to improve farms' economic performance, particularly through savings on energy and fertilizer costs. On the other hand, due to the fairly high investment costs and low returns of biogas production, public subsidies have been a key

factor in implementation [55] (pp. 6–7). For instance, dairy farmers that could have turned to biogas to improve returns and optimize the use of peatlands have reported assessing the risks as being too high for an individual farmer in the absence of public support [64] (pp. 108–110).

Research on the role of incentives has consistently found that biogas revenues are strongly dependent on subsidies and feed-in tariffs, making farmers dependent on public policies. This evidently raises the question of the long-term economic sustainability of agricultural biogas plants as support schemes are being readjusted. The volatility of public policies is a factor of uncertainty for farmers, who must consider possible subsidy adjustments or reallocations of funding to other energy sectors in their strategies [29].

There are many examples of this. An overview of agricultural biogas in Poland, fifteen years after the first plant was built in 2005, shows that development is hampered by a restrictive and frequently changing legal framework. Investors face both legal obstacles (such as the classification of digestate) and economic challenges in the absence of support policies and feed-in tariffs [51]. This situation persists despite the country's high potential: the agricultural sector emits high levels of greenhouse gases—particularly from livestock farming—and 80 percent of energy still comes from non-renewable sources [62] (pp. 1–2). Similar reasons have been proposed for the underdevelopment of the biogas sector in Romania: as of 2020, the installed capacity of biogas projects accounted for around 0.002% of the total installed capacity of renewable-based projects, despite a high potential for biomass and the important place of agriculture in the economy. Cited barriers relate first to the instability of the legal framework (and the lack of specific legislation for biogas as opposed to other renewables) and of the support systems, making banks all the more reluctant to invest [57].

#### 3.3.3. Biogas Futures: Towards a Global Energy Network Model?

Two avenues for the future have been mapped out in connection to this dependence on public support. They both assume that subsidies will decrease, whether the approach is industrial and global or agricultural and local.

First, the increasing harmonization of support policies across Europe can be interpreted as evidence of a move towards more complex and geographically extensive biogas networks, exemplified by the development of cogeneration systems connected to the energy network and by the injection of biomethane in the (inter)national gas network. Mol hypothesizes a "governance paradox" regarding the expected scaling down of state regulation. In the current territorialized model, it is possible to intervene directly in the biogas sector, as projects are mainly developed at a state or regional level. Things will be more complex in the event of a shift towards a globalized model with biomethane, even as the growing role of large industrial actors would warrant more regulation, especially in terms of sustainability [5] (pp. 11, 16).

Second, local actors do recognize that they are dependent on public regulations (legal frameworks and subsidies) that are subject to change. In Western and Central Europe alike, the biogas boom witnessed in some states appears to have receded along with there being a decrease in feed-in tariffs. In the Czech Republic, for instance, biogas reverted to the state of an agricultural niche once public subsidies were terminated [2]. Farmers then face a shift from a model based on direct public incentives to a more self-sufficient economic model, (i) emphasizing cooperation and the involvement of local actors in decision-making, and (ii) based primarily on the valorization of local agricultural residues and household waste for energy—at odds with the industrial model of input and biomethane production [47] (pp. 369, 377).

The future of the biogas sector in the making is uncertain. Changing support frameworks and the rise in large industrial actors challenge the ability of farmers to retain their central role and weigh in on strategic orientations. The diversification of economic models and the growing industrialization of biogas—even in its agricultural version—have led to a redistribution of power between farmers, industrialists and outside investors. As the sector gradually moves away from its agricultural roots to pursue integration into broader energy networks, the question of how to capture added value has become central for farmers [30] (p. 60).

## 4. Discussion: How Viable Are the Biogas Supply Chains in Europe?

The previous results raise the question of whether biogas and biomethane supply chains are viable in Europe for the farmers involved in anaerobic digestion (Section 4.1) and more broadly, whether they contribute to the local development of the rural areas in which anaerobic digestion units are sited (Section 4.2).

### *4.1. How Viable Is Anaerobic Digestion for Farmers?*

#### 4.1.1. Biogas Initially Perceived as an Economic Opportunity by Farmers

While anaerobic digestion is regularly presented as a lever for energy transition and organic resource recovery (see [33], for example), its main appeal for farmers rests on an economic rationale, i.e., the fact that it is a source of additional income or can secure the profitability of their farms. Based on a survey conducted in Western France, Amand et al. argue that farmers primarily consider renewable energy production as an opportunity to increase or stabilize their income through the diversification of their financing sources. According to them, this evolution is in line with the productivist paradigm, since, rather than breaking with this model, anaerobic digestion provides a new niche for capital accumulation, ensuring better economic resilience to face the vagaries of the agricultural market [12].

These motivations are confirmed by a survey conducted in Switzerland in 2019, at a time when farmers still had relatively little engagement in the practice, using a discrete choice experiment and agent-based modeling. The results showed that farmers were mainly motivated by the additional revenue to be derived from the energy produced, and favored small on-farm manure digesters. An increase of 0.10 CHF/kWh in energy revenue (from the price then of 0.45 CHF/kWh) would lead to the construction of 10 additional biogas plants (i.e., +10%) using manure from 4285 more livestock units, while the availability of co-substrates for digestion seemed to have less visible effects [45]. In Poland, digester developers similarly stated that their main motivation was the activity's economic profitability, due to European Union support programs, encouraging prospects for renewable energy development in Poland and favorable global trends [51].

#### 4.1.2. Barriers to Profitability in Practice

In the face of these expectations, several barriers to profitability emerge. First, economically speaking, biogas plants require high investment costs, including the cost of building the digester, buying the necessary equipment, hiring technical staff and transporting the inputs, to which the costs of managing and maintaining the units can be added. Secondly, biogas is more expensive than natural gas, which can dissuade end users concerned about having to pay more [8] (pp. 5–6).

The weak profits to be derived from biogas technologies are regularly pointed out. For instance, in Finland, one consequence is that biogas production has remained very limited compared to other renewable energies. While in 2016, 40% of the energy consumed was from renewable sources, the share of biogas remained very low, at around 0.5% of

all renewable energy produced. Only 0.6% of the biogas, moreover, came from on-farm digesters [54] (pp. 4, 8). Likewise, in Sweden, on-farm anaerobic digestion units are facing profitability issues, leading farmers to redefine their business models: since long-term profitability remains their primary goal, they sometimes find it necessary to engage in private–public partnerships [52] (p. 2925).

Assessing the economic viability of an anaerobic digestion project precisely requires having a clear business model structure. Couturier, an expert at the consulting firm Solagro, provided a detailed analysis of the cost and revenue structures of anaerobic digestion projects. While grounded in the French context, the business model components and typologies he identified are useful for broader reflection on project viability. Revenues mainly come from the sale of energy (electricity, heat or biomethane), and can be complemented by waste disposal fees or fertilizer savings. On the other hand, expenses include "capital expenditures" (construction and equipment) and "operating expenses" (running costs, plant maintenance, etc.). Collective projects have an even more complex structure, since they involve the collective management of organic matter flows and collective spreading plans. They thus have to meet more logistical and land use constraints, requiring significant investment costs, which can amount to several million euros. They also require specific skills in financial engineering and project management, and financing sources from outside the agricultural sector [27].

#### 4.1.3. A Shift from Cogeneration to Injection

As a consequence, profits are never guaranteed, given the high capital expenditures and operating expenses involved, as well as farmers' dependence on support programs. The figures are telling: in 2018, out of the 250 on-farm digestion plants operating in France, one third reportedly did not make any profit and even generated financial losses, mostly due to higher-than-expected operating costs and uncertainties over the possible use of the energy produced. On top of that, there may also be technical flaws resulting from the imperfect adaptation of imported technologies: anaerobic digestion technologies have often been imported from Germany even though they do not fully match the specificities of agriculture in another country [24] (p. 165).

These concerns about economic profitability can account for the fact that combined heat-and-power units have been losing ground in Europe, while injection into the gas network is becoming the preferred method for energy recovery. The evolution of anaerobic digestion since the 1990s in Germany, where heat-and-power systems initially prevailed, provides a striking illustration of this trend. During the period of strong economic growth between 2000 and 2012, the costs of producing electricity from biogas remained high compared to other renewable energies, such as solar energy, while the heat generated was often incompletely used, especially in rural areas. Regulatory changes were introduced from 2012, resulting in the fact that the production of electricity from biogas in combined heat-and-power units is no longer profitable; upgrading biogas to biomethane has been identified as an alternative [7] (pp. 3–4).

Similar evolutions can be traced in Denmark, a leading country in the development of the biomethane sector in Europe. Italy too passed a decree in March 2018 providing new incentives for biomethane production and for the development of biofuels used in transport [7] (p. 5).

In France, there has been a comparable shift from heat-and-power systems to biomethane injection. The transition was encouraged by revised support schemes: while cogeneration largely prevailed before 2010, incentives to move to biomethane injection were introduced in 2011 and 2014, with guaranteed biomethane feed-in tariffs. From 2016 to 2017, feed-in tariffs for electricity produced in CHP digestion units have been lowered, while

biomethane feed-in tariffs have remained attractive, encouraging new projects. The shift has prompted farmers involved in anerobic digestion projects to redefine their business models, especially those working in larger units with easier access to gas infrastructure. Since 2018, injection has progressively become the dominant model, leading to increased professionalization in the sector and the growing use of external service providers for unit maintenance and operation. Nevertheless, this technological transition has not solved all the difficulties met by farmers: injection requires high connection costs and depends on whether existing gas networks can accommodate the injection of new volumes of biomethane, while the concentration of the sector around large units raises issues of fair access to these new opportunities [30].

As also shown in Austria, this general evolution is linked to the following: (i) a loss of faith in the "energy farmer narrative": there is no longer a real belief in the idea that it is possible to create an alternative market for agricultural products by producing electricity from energy crops; (ii) the evolution of agricultural prices and growing emphasis on the need to reduce carbon emissions and (iii) the promotion of biomethane production by the gas industry, which has become a key player [53] (pp. 7–14).

The biogas sector has had to face a real paradigm shift: while it initially relied on high feed-in tariffs and local electricity production in CHP units, it is now embracing a new model, with biogas being transformed into biomethane to a greater extent [7]. This, in turn, makes it necessary to reconsider the local benefits to be derived from the installation of anaerobic digestion plants.

### *4.2. Does Farm-Fed Anaerobic Digestion Contribute to Local Rural Development?*

#### 4.2.1. Territorial Roots vs. Global Energy Transition

Unlike liquid biofuels, biogas units are strongly place-based, and inseparable from the farmers that operate them. They are rooted in specific territories and can be very different from one place to the other in terms of size, organization, cost structure, operating methods or standards. One question that can be asked is whether such local specificities will endure or whether biogas units will become standardized as a result of the building of a biogas supply chain, as has been the case in other renewable energy sectors. Mol believes the second option is more likely, with a shift from local independent systems to more complex and extensive integrated networks, including larger-scale production units using industrial methods and producing biogas to supply the global energy system [5] (p. 14). Concerns about economic profitability are thus causing the sector to align with energy transition goals rather than to favor local development.

In a centralized energy model, rural areas provide natural resources for large-scale energy infrastructures, while, in a decentralized model, they play a key role in local energy production, with farms becoming involved in a regional energy sufficiency strategy. A study conducted in Germany has shown that changes in the landscape are prompting different types of reactions: some see anaerobic digestion as a lever for local modernization, while others consider that biogas units introduce artificial elements into rural space and result in a loss of identity [23]. These diverging opinions show that the reception of energy installations by residents is inextricably linked to their perceptions of the local landscape and its evolution. We can refer to the notion of "anthropized biodiversity", i.e., the fact that the local environment is invested with sentimental and heritage value, often at odds with the productivist logic that is associated with anaerobic digestion and with the territorial reconfigurations induced by the energy transition [37].

4.2.2. Social Justice and the Unequal Distribution of Biogas Benefits

The problem is that the search for profitability is likely to result in a preference for centralized, larger-scale projects over the existing ones. The failure of such a project in Italy's Trento Valley following protests by small farmers and residents shows that anaerobic digestion projects are not necessarily perceived as compatible with local rural development. Protesters expressed concerns about the potential disruption of local agriculture, the increase in heavy truck traffic and the negative impact it would have on tourism. These negative perceptions came on top of other arguments about the lack of distributive justice [56].

Comparison with the case studied by Camguilhem in the Midi-Pyrénées region (France) suggests that this type of protest is not specific to any particular national context but more generally illustrates the public debates developing around energy transition. The project under study was led by four local business managers from outside the agricultural sector, which in itself was enough to rally opposition against it. Rejection of the project was not only due to technological or environmental concerns (over possible nuisances, input supply, etc.) but also due to doubts expressed as to the legitimacy of the players involved. Local residents expressed their sense of general dissatisfaction with projects that they considered to be imposed from outside [24] (pp. 166–169).

It is worth looking at the role that anaerobic digestion can play in the development of remote rural regions in post-communist European states. In Poland, Slovakia and the Czech Republic, it is expected to bring financial resources (taxes, new sources of income for the commune where the plant is located) but also broader local positive effects, such as stimulating local dynamism, developing infrastructure, creating new jobs, providing support for cultural and sports initiatives and supplying energy, especially heat produced in CHP units. In this respect, residents' perceptions of energy providers play a key role in bringing them to support a project or not, based on their views of the costs and benefits to be derived. There can be significant differences depending on the local situation. In Slovakia, very negative criticisms were aimed at a project considered to only benefit homeowners [47] (pp. 374–377).

The broader issue is how to ensure that the energy transition will be "fair". A study conducted in Italy, based on 114 biogas projects, provides food for thought regarding perceived fairness. While concerns were raised about environmental impacts (on air, water or soil quality), health risks, policy uncertainty, economic disruption and limited technological and scientific knowledge, the most salient issue was social. What was considered essentially "unfair" was the marginal involvement of small- and medium-scale farmers, especially in comparison to corporate actors. In Italy, indeed, policies promoting biogas production mainly benefited the larger-scale plants located in the north of the country, causing significant regional disparities [42].

In France, Mazaud and Pierre also investigate under what conditions the energy transition can provide opportunities for rural residents to develop local initiatives and reclaim local resources. They focus on a "positive energy area", where local farmers, elected officials and residents are engaged in collective solar energy, wind energy and anaerobic digestion projects. The study reveals that there are internal power struggles conditioning the parties' access to the benefits. Most of the economic revenue falls into the hands of a restricted group of operators, with enough resources to invest and organize. They often hold local union or political positions, so that they have power to influence regional energy policies and steer decisions in their interest. The local case shows that it is necessary to pay attention both to the distribution of profits and to the modes of governance giving access to collective resources and decision-making power [35].

#### 4.2.3. Land Use Conflicts in the Context of Biogas Development

A bone of contention lies in the necessarily limited nature of resources: the large-scale use of bioenergy has intensified competition over land use as well as over the available biomass. There have been several social science studies on the matter from the early era of anaerobic digestion. In 2005, a study conducted in Spain dealt with the risk of land being primarily devoted to energy crop production rather than to food production [39].

In Germany, bioenergy seems to go hand in hand with rural development and job creation: up to 29,000 people were employed in the sector in 2004. Yet, the growth of the sector has been fueled by intensive energy crop production, or a "maizification of the landscape". The intensive production of maize, which covered up to 2.1 million ha in the 2000s, has had significant negative impacts, such as soil degradation, use of pesticides, biodiversity loss, higher water consumption, etc. [7] (p. 3). In concrete terms, Vue and Garambois observed in Baden-Württemberg a growing differentiation between farms that have maintained dairy farming activity by combining anaerobic digestion and cattle breeding, and others that have given up dairy farming to specialize in energy crop production. The territorial structure has been significantly transformed in the process, with the following observed:

1. Increased land pressure, accentuated by competition between food production and energy crop production;
2. Changes in crop rotation, with fewer crops intended for human and animal consumption, and more maize and cereals harvested for anaerobic digestion;
3. Social impacts, with a widening gap between farmers who have been able to invest in anaerobic digestion and others who have had no access to such economic opportunities, causing new forms of rural poverty [40].

As early as 2006, Plieninger et al. insisted on the need to differentiate between bioenergy plants depending on their size: small-scale digesters create more added value in agricultural and rural areas than larger-scale ones [63]. Indeed, biofuels are refined in large-scale units, connected to the global market and the needed biomass can be imported from remote sources, so that little added value is created for the rural areas themselves.

#### 4.2.4. The Rural Imaginary vs. The Urban–Industrial Reality of Biogas

At the same time, since farmers have been pioneers in the field, biogas has tended to be associated with rural areas and local development. Yet such social perceptions may today prove misleading. Finland provides a borderline and all the more significant case. Due to its perceived connection with farming and rural life, public opinion has tended to consider biogas as a decentralized energy source. Similarly, the fact that biogas consumption strongly relies on centralized networks and infrastructures and that most of Finland's biogas is produced in relatively large-scale facilities has been obscured. The vision of biogas as a distributed energy resource has been further established by the high visibility given to small-scale, on-farm production. Farmers have been overrepresented as key players, given the very limited share of biogas actually produced in on-farm facilities, i.e., 3% of the total amount of biogas produced. In other words, while in the media or on social networks, biogas has remained associated with rural development and with agri-environmental management, the truth is that in Finland, most of the biogas is produced in an urban and industrial context, as a result of wastewater treatment and urban waste management activities [55].

## 5. Scenario Studies

The social science review we conducted has revealed some prominent elements and debates that can be found in different national and regional contexts. Even though different

answers may be given and different priorities taken over time, it is possible to identify a European model for farm-fed anaerobic digestion, characterized by the following: (i) the primacy given to energy transition goals over objectives related to the agricultural and ecological transition, and (ii) a central tension between the prominence given to farmers and to localized references vs. a process of industrial supply chain building and the rise in a more globalized model. In this context, as summarized in Figure 3, a new field of study has emerged to explore the future of the biogas sector and identify possible scenarios. These studies are centered on four main points.

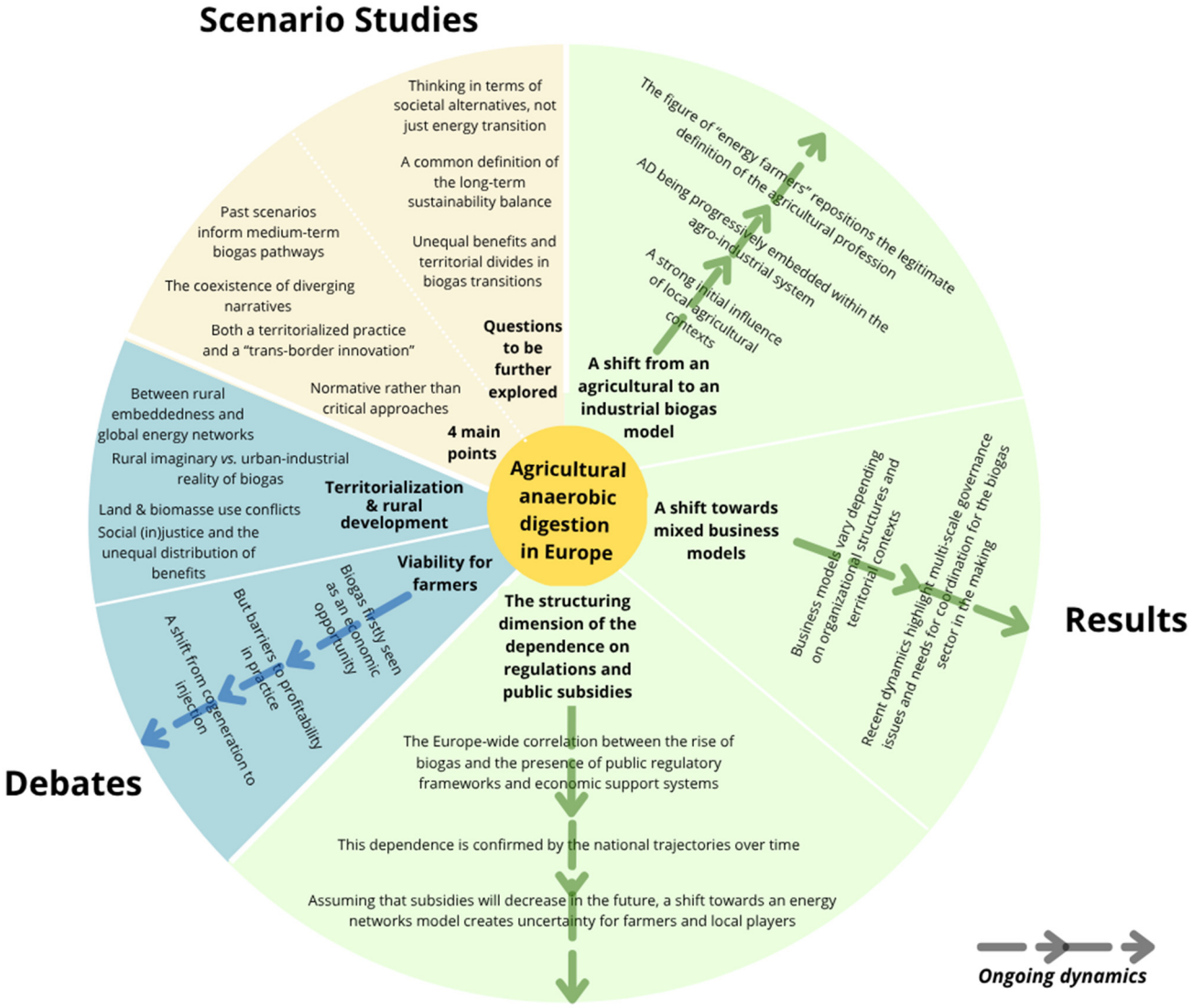


**Figure 3.** Overview: The organization and social challenges of building an agricultural biogas supply chain in Europe as evolving processes (© Philippe Hamman and Aude Dziebowski).

### *5.1. Scenarios as Embedded Action-Research: A Normative Rather than Critical Approach*

As the sector has developed, numerous prospective studies have been devoted to the future of agricultural anaerobic digestion. Rather than viewing it from a critical perspective, most of them focus on the issue of sustainability by embracing a normative vision of the evolution of agriculture. For example, Cadiou et al. compare 16 possible biogas development scenarios in France, exploring the influence of agricultural anaerobic digestion by 2030–2050. The studies use a mostly techno-economic approach, suggesting technological solutions to ensure agri-environmental benefits and avoid risks (14 studies out of 16) and advocate "best management practices" (12 studies out of 16), based on the additional

income anaerobic digestion will bring farmers or on reductions in operating costs [46] (p. 9). As a sign of their focus on energy transition goals, they pay particular attention to greenhouse gas emissions: 11 studies consider anaerobic digestion as a lever for reducing carbon emissions. They argue that it will reduce biomethane emissions from cattle effluents (seven studies), limit emissions of $N_2O$ (four studies) or even decrease the indirect emissions from chemical fertilizer use since farmers will spread digestate instead (one study). Five other studies also point out that there will be fewer greenhouse gas emissions since biogas will substitute fossil fuels.

In addition to this, 12 studies also look at soil carbon sequestration. Seven of them consider that anaerobic digestion will increase carbon storage through the use of energy crops and carbon sequestration in the soil via thatch, roots and digestate. The 13 studies that explore the impact of anaerobic digestion on the nitrogen cycle are also mostly positive. Eight of them argue that the main benefit will result from reductions in the use of mineral fertilizers, due to the fertilizing properties of digestate. At a more detailed level, some differences nevertheless do emerge: while three studies specifically point to anaerobic digestion as a way to reduce $N_2O$ emissions through the use of alternative fertilization methods, three others suggest that there are risks of increasing $N_2O$ emissions, especially if the energy crops used as inputs are fertilized. Finally, water quality issues are addressed in similar ways. Seven studies predict a reduction in nitrate pollution thanks to the use of energy cover crops and digestate fertilization; two argue that the fertilization of energy crops with digestate presents similar risks of water pollution as fertilization with mineral nitrogen and one study points to a higher risk of water contamination linked to an increasing use of inputs for anaerobic digestion [46].

The first observation, then, to be drawn from a social science viewpoint is that a great number of studies appear to be favorable to the development of anaerobic digestion. A more precise analysis reveals a connection between the priorities developed in the studies and the institutions they spring from. The seven studies that dwell the least on the issues of agricultural sustainability come from institutions with links to the energy sector. The scenarios they propose mostly focus on the contribution of biogas to a low-carbon economy, with positive effects expected for the agricultural transition. Yet, they only pay scant attention to the coevolution of technological and social conditions in agriculture, to agri-environmental effects and to the decisions made by farmers. Conversely, the three studies that are the most thorough on agri-environmental sustainability were authored by a non-profit company and a non-governmental organization specialized in agricultural subjects [46] (p. 10).

### *5.2. Agricultural Anaerobic Digestion as Both a Territorialized Practice and a "Trans-Border Innovation"*

While the energy transition in the agricultural sector is often expected to yield environmental and economic benefits, Garambois et al. underline that it actually comes with paradoxes and limitations that are not sufficiently taken into account. Anaerobic digestion provides a case in point: it is considered as part of the possible strategies for achieving a low-carbon economy but its systemic effects on the evolution of farming practices and territorial organization are rarely seriously documented. According to the authors, the existing studies are biased insofar as they tend to favor a techno-economic approach to anaerobic digestion mostly driven by national schemes and industrial logics, without fully considering its impact on the sustainability of agricultural and food systems. Garambois et al. therefore call for a more localized approach, one in which anaerobic digestion is not only viewed in terms of energy production but also considered as a tool for agricultural and environmental resilience, fully related to the local dynamics of soil, biodiversity and water resource management [29].

Moreover, in the same way that the ecological and energy transitions are inviting us to reconsider our society both from a political and socio-economic perspective and in terms of its relationship to nature, anaerobic digestion needs to be approached as a "trans-border innovation", situated at the junction between questions related to energy production, waste management, agriculture, transport and fuels [2] (p. 1545). Promoting technologies for converting agricultural waste into resources requires a *holistic* approach, bringing technological questions and economic, social and ecological issues together [3]. Lyytimäki et al. precisely point to such intersections when defining ten tension pairs that characterize the development of the biogas sector in Finland: producer vs. consumer, urban vs. rural, local vs. national, domestic vs. foreign, centralized vs. distributed, food vs. energy, environment vs. economy, tradition vs. innovation, long term vs. short term and private vs. public. As a complement to studies that have so far focused on the role of technologies, institutions and the action/lack of action of the involved parties in sustainability transitions, the authors draw attention to the influence of conflicting dualities—also including the influence of social perceptions and images spread by the media—in the way priorities are set on the energy agenda and possibilities for protest and for negotiation, as well as for action or non-action [55] (p. 3).

### *5.3. The Role of Uncertainty in Shaping Biogas Trajectories*

That is not all. Predicting how things will evolve remains difficult, due to the coexistence of several timeframes that do not fully align. First, there is a long-term project timeframe, stretching from inception to implementation and day-to-day management. Second, a shorter political timeframe is shaped by election cycles. Third, a non-linear social timeframe fluctuates depending on the actors involved, the audiences addressed and the local contexts in which anaerobic digestion plants are situated. In this sense, we observe the emergence of three competing narratives about biomethane in Austria:

1. The greening of gas: In this narrative, biomethane is given a key role in the energy transition, and as such, biomethane production needs to be stepped up in large-scale facilities.
2. "The champagne of the energy transition": This narrative expresses doubts as to whether there are enough usable residues available and concerns about the high costs involved. Biomethane production can only be justified, therefore, if there is no other alternative strategy to move to a low-carbon economy, and the use of maize as an energy crop is not encouraged given the competition with food productions for land use.
3. The "energy farmer 2.0", associated with job creation and local economic activity.

The coexistence of these diverging narratives has made it impossible to adopt a stabilized frame for reflection—which should remind us of the ever-changing nature of the socio-technological foundations upon which thought and action are based [53]. Studying anaerobic digestion thus directs us to the depth of the social world, which is why it deserves to be the focus of more comparative and multiscale social science and interdisciplinary studies.

### *5.4. Revisiting Past Scenarios to Inform Medium-Term Biogas Pathways*

Future projections should not dismiss the lessons of the past: the current uncertainties about the role of anaerobic digestion in the transition to sustainable energy were already apparent in the early 1980s. At a time when the oil crises had shown that it was necessary to find alternative sources of energy, Jayet and Sourie were already seeking to assess the potential of the biomass sector and of anaerobic digestion, taking into account the possible economic and technological barriers to its development. They underlined how difficult

it would be to integrate this type of bioenergy into the energy mix due to competition with fossil fuels, the costs of the infrastructure and the logistical challenges of collecting and storing substrates. They had suggested two possible scenarios: (i) a "low" scenario, in which only the most easily accessible resources (wood, straw) would be exploited as biomass and mainly used for local heat recovery; and (ii) a more ambitious, "high" scenario, which considered that technological advances and the rising price of fossil fuels would make the large-scale production of bioenergy, especially biofuels, profitable. Their projections already highlighted the tensions between technological feasibility, economic profitability and the structure of the market [31].

Some forty years later, the prospective scenarios about the evolution of anaerobic digestion still hinge around the same issues: while technological advances have made biomethane development and injection into the gas networks possible, structural challenges remain concerning the availability of substrates and the effects on agricultural and territorial systems. They should be reconsidered today in light of emerging imperatives, i.e., reconciling the objectives of energy transition, food security and ecosystem preservation. The evolution of political frameworks and industrial strategies will play a crucial role in the way such tensions will be solved in the coming decades.

## 6. Outlook

The social science literature has so far provided valuable insights into the rise in agricultural anaerobic digestion and its role in the energy transition in Europe. Yet, some questions still deserve to be further explored.

### *6.1. Accounting for Unequal Benefits and Territorial Divides in Biogas Transitions*

First, little attention has been paid to benefit distribution and territorial inequalities. While many studies have underlined that anaerobic digestion projects tend to widen economic inequalities between farms, few have explored in detail the way profits are distributed at the local level and what profit capture mechanisms come into play. The role of public policy in encouraging the development of anaerobic digestion has been extensively analyzed, but not its differentiated effects on farms and local areas. Which players do actually benefit from public support schemes, and which agricultural or energy models seem to be privileged? The existing studies fail to measure the extent to which public support programs might contribute to making access to the sector even more uneven and to accelerating the concentration of anaerobic digestion units on certain types of farms or in certain geographical areas.

### *6.2. What Are the Long-Term Environmental and Agricultural Trade-Offs?*

Second, it might be worth paying more attention to the long-term effects of anaerobic digestion on land use and on the evolution of agricultural systems. Although the competition between food crops and energy crops has long been identified as a major issue, there has been no study of the long-term impact of anaerobic digestion on crop rotation or on farmers' resilience to climate change. Only a few studies make projections that take into account the possible future development of anaerobic digestion and other land use and agricultural dynamics together.

The link between anaerobic digestion and overall environmental sustainability has also been explored too little. While many studies point to the role of anaerobic digestion in cutting greenhouse gas emissions and recovering energy from cattle effluents, they have not paid the same amount of attention to its potential negative impacts: the increased pressure put on water resources, the intensification of biomass transport and the long-term impact of digestate spreading on soil quality.

### *6.3. From Energy Transition to Societal Alternatives: Broadening the Perspective*

Finally, alternatives to the dominant models for anaerobic digestion have not been fully assessed. The literature has focused on studying how existing models could be improved and on predicting industrial developments, but has not given much thought to alternative scenarios that might provide answers to some of the issues raised—how to find alternative biomass sources, develop more decentralized and self-sufficient models, establish collaborations with other energy sectors, etc.

Further social sciences research is necessary to analyze the changes caused by the development of the biogas/biomethane sector on agricultural systems, on local areas and on regulatory frameworks, while taking into account the resulting tensions and differing impacts on the parties involved. More than just contributing to energy production, anaerobic digestion is part of a broader process of the redefinition of agri-industrial systems and environmental governance. Understanding its relations to ecological, food and social transitions is crucial to be able to anticipate its long-term effects and achieve a balance between the objectives of producing energy, ensuring farmers' resilience and preserving natural resources.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17135806/s1, Table S1: Glossary of key concepts related to agricultural anaerobic digestion and sector-building.

**Author Contributions:** Conceptualization, P.H. and A.D.; methodology, P.H. and A.D.; investigation, P.H. and A.D.; resources, P.H. and A.D.; writing—original draft preparation, P.H. and A.D.; writing—review and editing, P.H. and A.D.; supervision, P.H.; project administration, P.H.; funding acquisition, P.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the French National Centre for Scientific Research (CNRS) under the interdisciplinary programs supported by the Mission for Transversal and Interdisciplinary Initiatives (MITI), as part of the research project 80 | Prime METHATIP "Socio-environmental implications of agricultural anaerobic digestion: Energy transition, professional identities and 'new ruralities'" (2022–2025); and by the interdisciplinary thematic institute Making European Society of the 2021–2028 ITI programme (University of Strasbourg, CNRS, INSERM) as part of the project MéthAEurope "Renewable energies, territories and risks: Actors and comparative implications of agricultural anaerobic digestion in Europe". ITI MAKErS has received financial support for IdEx Unistra (ANR-10-IDEX-0002) and funding from the Future Investment Programme within the framework of the SFRI-STRAT'US projects (ANR-20-SFRI-0012). The APC was funded within the framework of the industrial chair on anaerobic digesters in the Grand Est region (MERGE) led by Emmanuel Guillon at the University of Reims Champagne Ardenne.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** No unpublished data were created in this study. Data sharing is not applicable to this review article.

**Acknowledgments:** We wish to warmly thank Jean-Yves Bart (Maison interuniversitaire des sciences de l'homme—Alsace, France) and Stéphanie Alkofer for translating this article from the original French.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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