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The circular economy in action: the case of digestate markets.

Authors

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Abstract

Anaerobic digestion (AD) has been much promoted in the European Union (EU) in the last two decades. It is considered as a model of circular economy that produces both energy from renewable sources and recycles nutrients in the form of digestates. The EU is experiencing an important growth of AD and therefore an increasing production of digestates. However, very little is known on digestate markets while controversies and oppositions to their growth emerge. Our paper is a preliminary study that explores the dynamics of these markets, based on a literature review and empirically supported evidence. We identify three co-existing and overlapping models of development of digestate markets, that correspond to different understandings of circular economy. We present six main groups of factors that influence the evolution of these models. We show that competing visions of circular economy have a strong influence on the structure of markets. Also, circular economy is quite always presented as an answer *per se* to environmental issues. We find that the impacts of digestate markets are much more complex than this idealized vision of circularity. Digestate markets are not spared by environmental and health-related controversies, and problems are often displaced along the circular flows of biomass and nutrients, instead of being solved.

Keywords

Digestate; wastes; anaerobic digestion; circular economy; uncertainty.

1. Introduction

Anaerobic digestion has experienced an important growth in the EU in the last two decades. The use of AD technology has been highly encouraged by European energy policies to contribute to renewable energy targets and to the decarbonization of the economy (Scarlat et al., 2015; 2018). The total number of AD plants has grown from 14 572 in 2013 (Torrijos, 2016) to nearly 19 000 in 2019 (EBA, 2020). Germany is by far the leader of the sector (Trombin et al., 2017; Theuerl et al., 2019) with approximately 10 000 plants now operating in the country while there were only a thousand in 2000 (Thrän et al., 2020; German Biogas Association, 2020). A similar trend is unfolding in other EU countries. For instance, less than 200 plants were recorded in 2013 in France (ADEME, 2016) while 900 plants were operating in 2020 (ATEE, 2021). This fast growth is expected to continue with a forecast of 1 700 operating plants by 2023 (ADEME, 2016). While the desired outcome of AD is the production of biogas from organic matter (Figure 1), up to 90% of the AD substrates are transformed into a by-product called digestates. The growing number of AD plants naturally leads to an increasing production of digestates (WRAP, 2013; Plana & Noche, 2016; Dahlin et al., 2017). In 2018, nearly 130 million tons of digestates were produced in the EU (Wilken et al., 2018), Germany being again the largest producer of digestates, with 85 million tons produced annually (Damiano et al., 2015).

The use of digestates as cheap fertilizers in agriculture is greatly encouraged as it should contribute to recycling biomass and nutrients in a circular economy (CE) perspective (Infometha, n.d.; Inrae, 2021). CE has gained a prominent place in EU sustainability policies since 2015 (Leipold, 2021) and bringing “digestates back to agricultural soils” is a key element in the promotion of AD as a model of CE (Infometha, n.d.). However, there is still a lack of scientific consensus on CE (Geissdoerfer et al., 2017; Korhonen et al., 2018; Millar et al., 2019). The literature that focuses on the specificities of circular markets remains scarce (Tura et al., 2019). So far, most scientific efforts have been devoted to

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the conceptualization of the ideal of circularity introduced by Boulding (1966). Only a few papers explore the functioning of circular markets and often without any empirical basis of a particular economic sector (Geng and Doberstein, 2008; Rizos et al., 2015; De Jesus & Mendonça, 2018; Govindan & Hasanagic, 2018; Kirchherr et al., 2018; Tura et al., 2019). Moreover, these articles mainly focus on the *implementation* of circular markets and not on their *actual functioning*. The current expansion of digestate markets represents an interesting opportunity to study the functioning, the evolution and the specificities of an alleged model of circular economy. We here understand the concept of “market” as following the definition selected by Lupton (2005; 2011) to characterize waste markets. These markets are considered as dynamic systems that evolve under the influence of multiple factors such as the anticipations of economic agents and the evolution of scientific knowledge. They are not stable, new institutions emerge over time and coordination is complex (Lupton, 2005; 2011).

In addition, the fast growth of digestate markets is a source of increasing environmental, health and social concerns and controversies (Koszel & Lorencowicz, 2015; Monlau et al., 2015; Theuerl et al., 2019). As demonstrated by Lupton (2002) for sewage sludge spreading markets in Switzerland, controversies can lead to the collapse of markets. Therefore, if AD aims at pursuing its expansion in Europe, more attention must be paid to digestate markets. Until recently, the political and scientific agenda mainly revolved around biogas issues (Inrae, 2021). The literature on digestate markets is very sparse and addresses specific issues, such as logistical issues (WRAP, 2013; Plana & Noche, 2016), marketing and willingness to pay (Dahlin et al., 2015; 2017; Pappalardo et al., 2018) or the estimation of theoretical economic values of digestates (Czekala et al., 2020).

This article is a preliminary study to bridge the knowledge gap on digestate markets. Its originality lies in the identification of detailed factors that shape the development of markets. It aims at answering the following questions. How are digestate markets structured? What are the factors driving their evolution? What can we learn on CE markets from the example of digestate markets?

We analyze the functioning of digestate markets in the EU with a specific attention on the French and German markets. France is quite representative of the average development of AD in Europe, and therefore, of the current state of digestate markets. As for Germany, digestate markets have been growing for more than a decade. The market is more mature and gives an insight into the potential long-term evolution of digestate markets.

The first section of our paper consists in the present introduction. Section 2 details our research method. Section 3 presents our results. We analyze the structure of digestate markets and we detail the factors that influence their dynamics. Section 4 discusses the specificities of the functioning of circular markets based on our observations on digestate markets. Finally, section 5 provides the reader with concluding remarks and suggestions for further research.

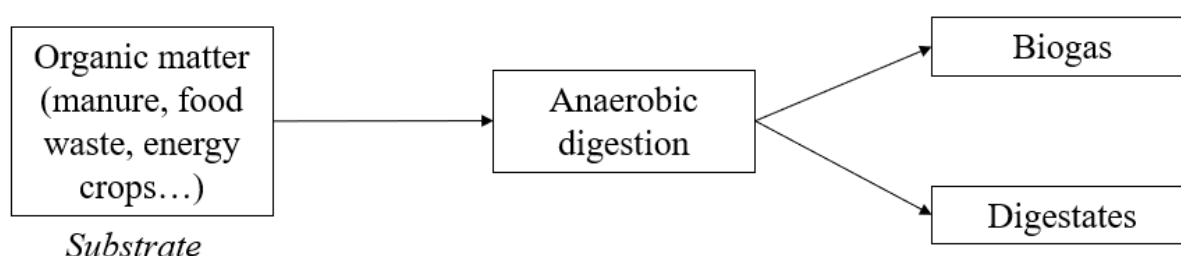


Figure 1: the methanation process. Source: author, 2021.

2. Method

2.1. Research method

Our research is based on a literature review and empirically supported evidence. We collected and analysed information from a combination of various sources. We started our research with a review of the scientific literature. We collected and reviewed articles in English and in French. We used the citation search method to find more articles. Secondly, in order to complete the limited research, and to have a field perspective on the topic, we reviewed the grey literature. We collected documents and reports in French and in English from official bodies, companies, professional organisations, NGOs, media and social networks. To deepen our analysis of the field situation, we conducted interviews and mail exchanges with stakeholders in France, in Germany and in Brussels. We contacted ten stakeholders that represent various components of digestate markets¹. In addition, we attended five webinars and conferences held by researchers and stakeholders². Thanks to this *modus operandi*, we were able to collect both scientific and field knowledge, and we could apprehend the diversity of stakeholders' perspectives. We believe that these direct interactions with stakeholders are a powerful means of developing a comprehensive understanding of the dynamics of a growing market.

2.2. Technical boundaries of our study

AD is not a new technology since it has been used for years in some wastewater treatment plants or at a small scale in the food industry. But what draws our attention is the current fast development of digestate markets, as described in the introduction. These growing markets are not linked with these two types of plants, but with the rapid development of two other types of AD plants. The first type refers to agricultural plants. These plants mainly produce digestates from agricultural residues and can also use industrial and municipal wastes in smaller quantities (ADEME, 2015). They are always entirely or partly managed by farmers. They can be very small (one plant for one farm) or bigger if run by a group of farmers. The second type refers to centralized / urban plants. They use industrial and/or municipal wastes as substrates and sometimes accept agricultural residues (Guilayn et al., 2020). They often consist of large units and are managed by energy or waste management companies.

3. Results

Our analysis of the structure of digestate markets reveals that they can be classified into **three models of development**, one being predominantly developed and the two others being minor. But these three models have porous and moving frontiers and are not strictly differentiated. We also identify **six main groups of factors** that influence the evolution of digestate markets towards one or another model: political factors, legal factors, economic factors, social and cultural factors, technological factors, and environmental and agronomic factors.

3.1. Three models of development

3.1.1. *The traditional low-value recycling*

This development trajectory is the most common model for digestate management in many countries, including France and Germany (WRAP, 2013; Monlau et al., 2015; Plana & Noche, 2016; Logan & Visvanathan, 2019; Theuerl et al., 2019; Guilayn et al., 2020). It is also the most favored model

¹ Four representatives of digestate producers' unions in France, in Germany and in Brussels; a French producer and user digestates; a representative of a French bank that funds AD projects; three representatives of German and French companies that develop technologies to transform digestates; and a French AD consultancy.

² « La méthanisation, état des lieux et nouvelles opportunités » - 18/01/2021 ; « Microalgues, eaux usées & digestats de méthanisation » ; 28/01/2021 « Digestate valorisation under the EU Fertilising Products Regulation » - 28/04/2021 ; « Waiting for COP26 : the Circular Economy in Italy from research to industry » - 08/07/2021 ; « Circular bioeconomy : production of recycling-derived fertilizers and algal biomass » -09/09/2021

by stakeholders. Figure 2 illustrates this model. Digestates are directly applied on agricultural soils as raw digestates or following a solid-liquid separation. Solid-liquid separation is a widespread technology as it allows better nutrient management, cheaper transport costs, and a better storage while being quite affordable (Hjort-Gregersen, 2015; Trombin et al., 2017; Fruhner-Weiß, 2018). According to stakeholders, 66% of digestates produced in France are managed this way. This system pursues two main objectives: to minimize costs of digestate management and to partially replace mineral fertilizers (Koszel & Lorencowicz, 2015; Dahlin et al., 2017; Pappalardo et al., 2018).

The markets for exchanging raw digestates or solid-liquid fractions are highly localized and are much similar to manure markets described by Lupton (2017). Selling prices, if positive, are often very low, and can even be null or negative. The exchanges follow two main schemes. The first scheme consists of a contract between waste producers, such as farmers, and an AD plant. The waste producers bring their wastes, residues and by-products to the plant that integrates them as substrates. Later, the AD plant gives digestates to farmers. Land application costs are more or less shared between farmers and the AD plant depending on their agreement. The second exchange scheme comprises an AD plant selling or giving digestates to farmers without receiving their wastes. Exchanges of wastes and digestates are sometimes not valued in terms of prices, but in terms of nutrient content and fertilizing value. It is characterized by a local nutrient barter centred on the fertilizing needs of farmers.

This model does not offer a new perspective on traditional waste management in agriculture. As highlighted by Bianchi et al. (2020), closing nutrients loops through an increased valorization of wastes contributes to a more circular agriculture but this practice has been widely implemented for centuries in traditional agricultural systems. Indeed, the current development of this model relies on existing structures specialized in manure storage, transportation and land application, such as the CUMA and ETA³ in France. The use of agricultural residues as substrates for biogas production is also criticized. Some consider that a true circular agriculture directly reuses these residues as fertilizers to maximize the amount of material and embedded energy returned to the natural capital (CSNM, 2019; Nature et Progrès, 2021). Contrariwise, a recent scientific and political trend considers that CE should now go beyond this traditional low-value recycling. As highlighted by Korhonen et al. (2018), recycling is now considered as one of the last preferable options in the waste hierarchy. A true CE should not only close material loops but it should also keep products and materials at their highest economic value (Webster, 2015; Korhonen et al., 2018). In this perspective, this model does not valorise digestates enough. These opposite views show that the debate on how CE should be implemented is far from being closed.

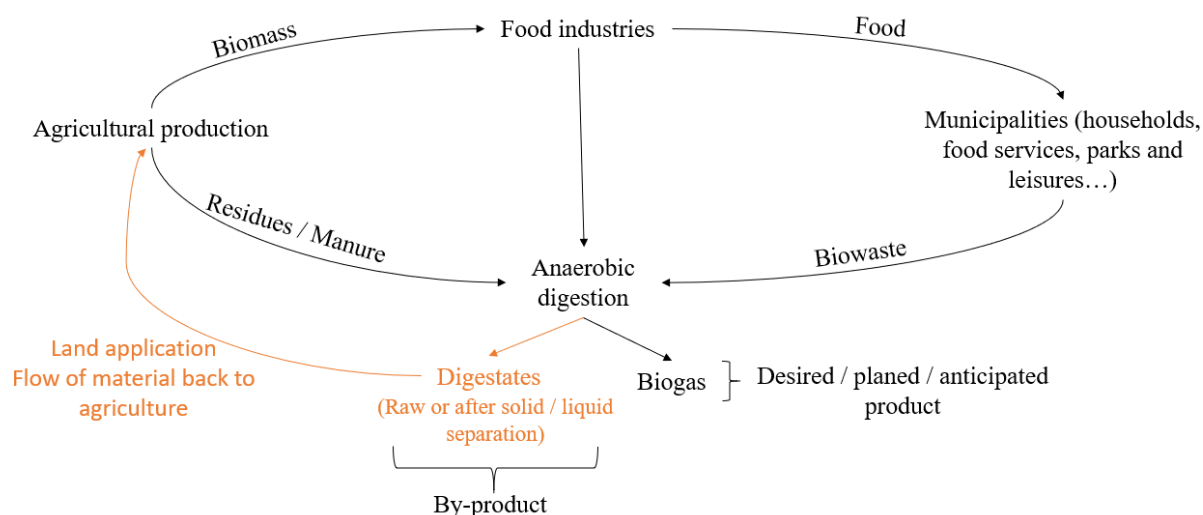


Figure 2: the use of digestates as low-value fertilizers.

³ CUMA = cooperative for the use of agricultural equipment. ETA = agricultural work company.

*Wastes and agricultural residues are collected from farmers, industries and municipalities and are digested. Digestates are sold or given to local farmers.

Source: author, 2021.

3.1.2. *The partial material recovery*

This second model is a slight variation of the low-value recycling model presented before. Its development is minor in France and in Germany⁴. As shown in figure 3, this model is very similar to traditional recycling, but material recovery is incomplete. Some fractions or some categories of digestates are eliminated through landfilling or incineration whereas the other fractions / other categories are applied on agricultural soils as low-value fertilizers. This model is found in several different cases. In Germany, for instance, the Biowaste Ordinance (BioAbfV, 1998) and the RAL quality certification set quality standards for digestates. The Biowaste Ordinance concerns digestates made from municipal wastes whereas the RAL quality label is a voluntary certification for any type of digestates (Dollhofer & Zettl, 2017). They require the separation of the liquid and solid parts of digestates in order to concentrate the impurities, such as plastics, in the solid fraction. The solid fraction is then eliminated through incineration. Only the liquid part, that contains mainly nutrients, is used as a fertilizer. It is therefore accepted, for reasons of quality and reputation, that the material loop cannot be fully closed. As highlighted by Lupton (2002, 2018) for sewage sludge, the outputs of our economic activities often contain elements that were not initially present in natural ecosystems, such as plastics or organic micropollutants, that may harm the environment and human health through the food chain. This is an important limit to the original vision of CE as a complete material cycle where all the outputs of our human activities could be used as inputs for other ecological and economic cycles (Boulding, 1966; Ayres, 1988). In France, the new regulation on fertilizing materials (expected in 2021) may set new agronomic and environmental standards for the use of digestates. The elimination of a whole category of digestates that do not comply with certain quality standards would be compulsory (ATEE, 2020). Negotiations between stakeholders and policy-makers are ongoing to soften this new rule. Biogas producers consider that these new standards are not sufficiently based on sound scientific research. These current negotiations highlight how dynamic digestate markets are. They can evolve rapidly under the influence of a changing regulation that creates confusion among stakeholders.

Although CE is often presented as an answer *per se* to environmental issues (Webster, 2015; Ghisellini et al., 2016; De Jesus & Mendonça, 2018; Millar et al., 2019), this model shows that CE markets are far from being spared by environmental and health concerns. And ironically, the answer to these concerns is to go back to a more linear system by eliminating a significant amount of digestates. It creates hybrid systems that seem to be moving between linearity and circularity though fully benefitting from the current positive aura of CE.

⁴ No official data exist on the share of each model. Our analysis is based on direct observations and stakeholders' opinions.

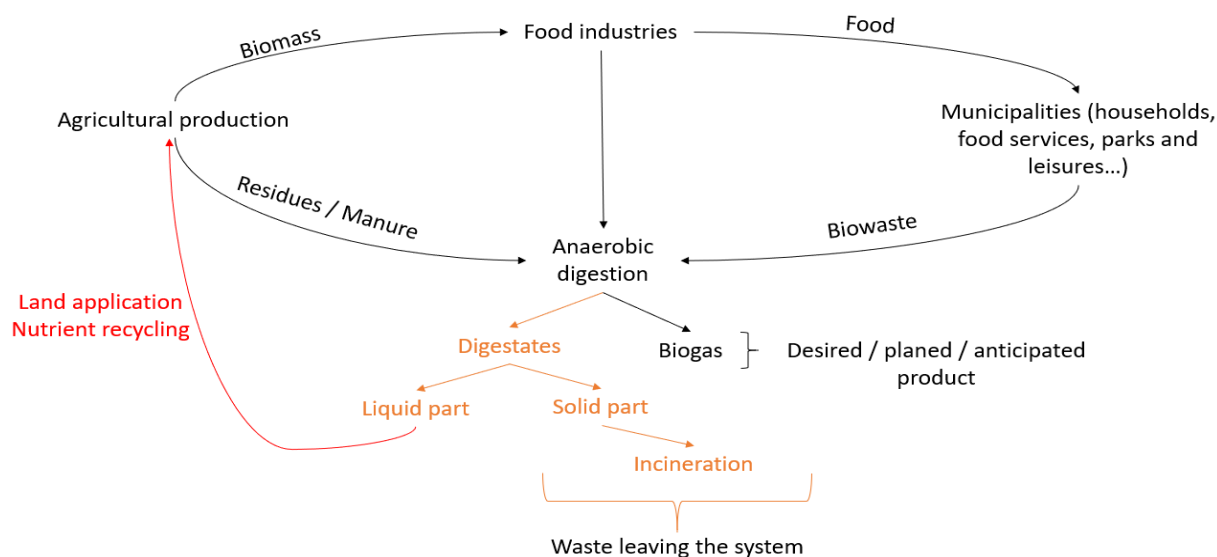


Figure 3: example of the elimination of the solid part of digestates in Germany.

* Only the nutrients contained in the liquid part are reused.

Source: author, 2021.

3.1.3. The upgrading initiatives

This third model is an attempt to go beyond the low-value recycling of digestates. It encompasses a wide variety of initiatives to transform, stabilize and process digestates, and to manufacture digestate-based products. These transformations are supposed to increase the value and the marketability of digestates (Logan & Visvanathan, 2019; Guilayn et al., 2020). This trajectory mainly concerns large AD plants with no sufficient access to local agricultural lands (Trombin et al., 2017) or plants that want to increase their profitability. Only a few AD plants have engaged in this trajectory so far, with initiatives such as the NADU and the Gartenglück products in Germany (Gartenglück, n.d.; NADU, n.d.). These initiatives come close to the “upcycling entrepreneurship” described by Donner et al. (2020) as an “innovative way to convert low-value by-products into high-value materials”. It leads to the exploration of new markets, including niche markets, and often involves the exportation of digestate-based products far from their production area. Figure 4 presents these upgrading initiatives. Their level of development is very heterogeneous. For instance, composting, drying and pelletizing are already quite popular (Trombin et al., 2017). Other options are still at lab or pilot-scale, such as the production of substrates for alga production, or are only theoretical, such as the production of biochemicals (Guilayn et al., 2020). The two dotted frames on the graph represent two different destinations for these upgraded products. The large dotted frame corresponds to products that are still used to grow biomass. Agriculture remains the major target of these products, in the form of refined fertilizing products such as ammonium sulphate and ammonium nitrate (Wilken et al., 2018; Guilayn et al., 2020). More specific agricultural markets are also under scrutiny, such as winegrowing and horticulture (Dahlin et al., 2017; Fruhner-Weiß, 2018; Wilken et al., 2018), as well as niche markets including substrates for mushroom and alga production, aquaculture and vermiculture (Monlau et al., 2015; Logan & Visvanathan, 2019; Theuerl et al., 2019; Guilayn et al., 2020). Other sectors, such as landscaping and private gardening, are also targeted through products such as potting soils, growing media and litter (Monlau et al., 2015; Plana & Noche, 2016; Dahlin et al., 2017; Trombin et al., 2017; Fruhner-Weiß, 2018; Logan & Visvanathan, 2019). In this case, digestate-based products leave the agricultural sector, strictly speaking, but are still involved in biomass production. The circularity of this system is therefore dependent on the boundaries considered regarding the flows of material. The small frame corresponds to products targeting economic sectors that are not directly linked to biomass production or to the regeneration of the natural capital. Several opportunities are explored in the textile

and in the building industry (Plana & Noche, 2016; Theuerl et al., 2019), and in energy applications such as biofuel production or thermal conversion (Monlau et al., 2015; Logan & Visvanathan, 2019). In this case, there is no guarantee that these sectors will eventually provide outputs that could be used as inputs to produce biomass and close the material loop.

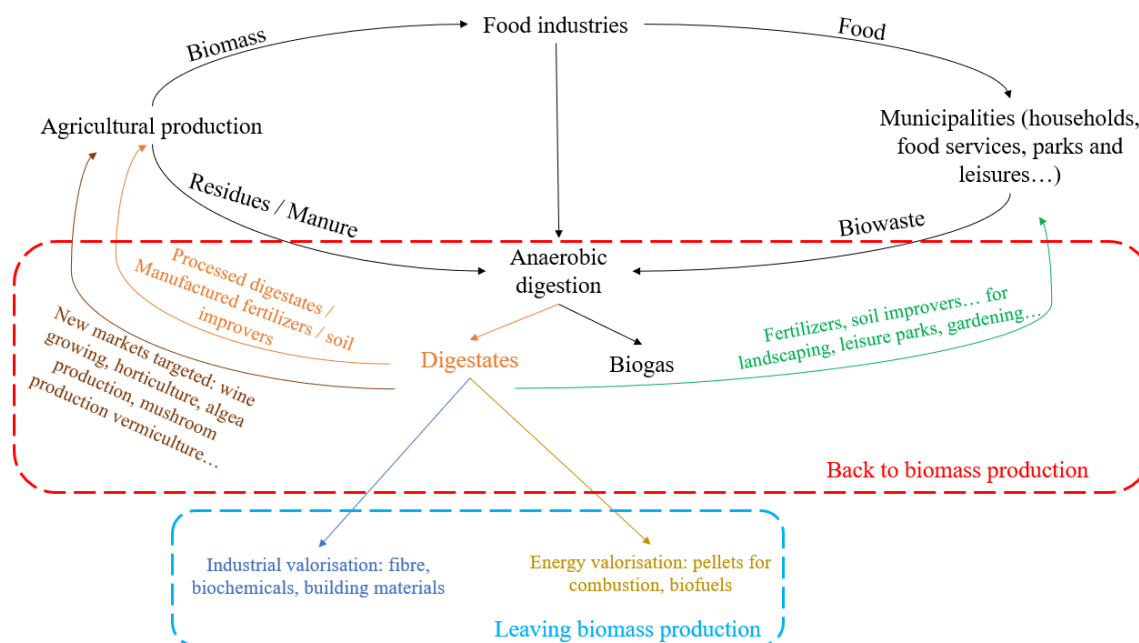


Figure 4: the different upgrading options for digestates. Source: author.

3.2. Overlapping models and porous frontiers

Digestate markets are dynamic systems and their functioning is not stuck into one or another particular model previously described. They constantly evolve and move towards the different models under the influence of factors that we present in the next section. The models can also overlap. Large AD plants can sometimes be part of two or three models. For instance, the AD plant of Kastellin, in the West of France, sends part of its digestates to be used as low-value fertilizers by farmers, while another part is upgraded and the third part is sent back to a wastewater treatment plant (SET Environnement, 2018). Figure 5 represents these dynamics. The development of the models results more or less from three different economic models symbolized by the apexes of the triangle. The bottom left corner (linear model) represents the dominant model in our society, which is the linear throughput of material flows from nature to our economic activities (Webster, 2015). The bottom-right corner represents the initial understanding of the CE as the cyclical flows of materials in the closed planetary system. Circularity should allow all outputs from our economic activities to be turned into inputs for other economic activities and to maintain the natural capital (Boulding, 1966; Ayres, 1988). The top corner corresponds to the new ideal-type of CE promoted by the EU. It involves processing, upgrading and upcycling wastes and by-products thanks to innovative businesses and technologies (Webster, 2015; Stahel, 2016; Korhonen et al., 2018). The overlapping circles symbolise the models of development of digestate markets. The arrows represent the factors influencing the evolution of digestate markets.

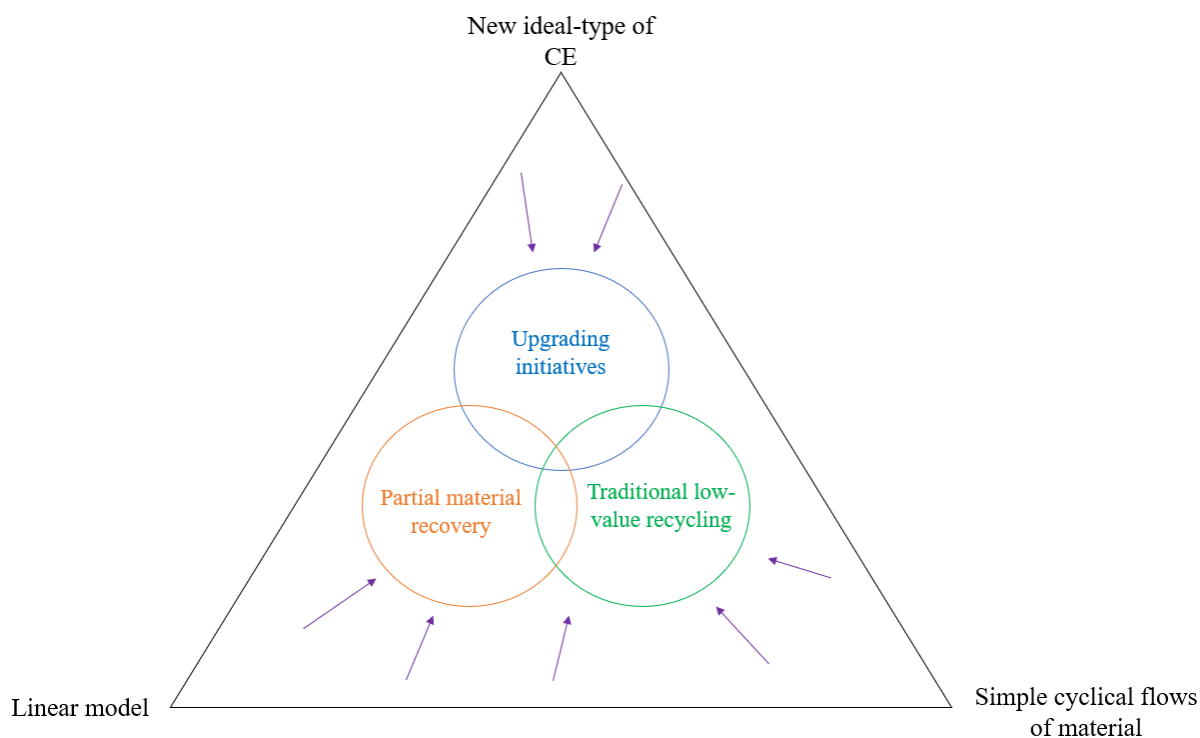


Figure 4: the dynamics of digestate markets. Source: author, 2021.

3.3. The six influencing groups of factors

3.3.1. Political factors

Political factors are often found to be among the main barriers to the development of CE in existing literature (Araujo Galvão et al., 2018) but are often reduced to legal considerations. Our findings go beyond these aspects and emphasize the influence of political **visions** on circular markets, in line with Rizos et al. (2015). Official definitions of circularity and the influence of powerful stakeholders shape CE implementation and favour a certain understanding of the concept (Leipold, 2021). We divided the political factor into three categories: EU policies and visions of CE, national policies and visions of CE, and the local political context / governance. **EU and national policies and visions** provide an official framework for market development. EU renewable energies policies have been promoting the development of AD in agriculture since 2000 (Scarlat et al., 2018) and the partial replacement of mineral fertilizers with digestates. These policies have favoured the predominant development of the traditional low-value recycling of digestates. Contrariwise, the EU bioeconomy and circularity ambitions have been recently promoting the new ideal-type of circularity, that supports the development of upgrading initiatives (Vivien et al., 2019; Leipold, 2021). **National visions** are more or less an adaptation of EU ambitions. In France, the energy transition law (LOI n° 2015-992) and the understanding of CE by public authorities favour the simple recycling of biomass and nutrients (Infometha, n.d.). The **local political context / governance** refers to the acceptance of digestates by the local political forces in a specific territory. The decisions of local officials and the balance of power between different stakeholders, such as local residents or NGOs, can support or hamper the use of digestates and therefore influence the development of these markets.

3.3.2. Legal factors

Legal factors are rarely emphasized in the CE literature although their ambivalent role have been highlighted (De Jesus and Mendonça, 2018; Tura et al., 2019). We find that regulation actually plays a crucial role in the evolution of digestate markets. The legal factor can be divided into four categories: waste / product status, land application limits, complexity of regulation and frequency of

changes of the regulation. **Waste / product status** and **land application limits** play a critical role in market dynamics. The qualification of digestates and digestate-based products as wastes or products has a direct impact on market development. For instance, the new regulation (EU) 2019/1009 on fertilizing materials defines digestates as products under certain conditions, with the possibility to be traded on the EU internal market and used in fertilizers manufacturing. This regulation supports the transition of digestate markets towards the new ideal-type of CE. The **land application limits** set by the Nitrates Directive (91/676/CEE) and the Water Directive (2000/60/EC) also directly restrains the use of digestates as fertilizers in livestock-intensive regions such as Brittany in France, or the north-West of Germany (Trombin et al., 2017). These restrictions encourage producers to upgrade and export digestates. Hence, restrictions to traditional recycling can be a driver to upcycling strategies. The **frequency of changes in the regulation** and the **complexity of the regulation** both create confusion among stakeholders. In France, the waste / product regulation changes every year whereas in Germany, different regulations add up to each other and overlap. The resulting indeterminacy can restrain digestate producers in their will to engage into upgrading projects, while it can also prevent farmers from accepting digestates. This political conundrum is an obstacle to the development of digestate markets.

3.3.3. *Economic factors*

Economic factors are crucial in the implementation of circular systems (Araujo Galvão et al., 2018; De Jesus and Mendonça, 2018). Regarding digestate markets, these factors can be divided into six categories: demand for nutrients, competition with other materials, cost savings for farmers, transportation costs, path dependency, and subsidies / incentives. The local **demand for nutrients** plays an important role in the development of digestate markets (Logan & Visvanathan, 2019). For example, if the local demand for nutrients is high, digestates will be useful to farmers, (in the sense given by Jevons (1871) to utility⁵). This configuration supports the landspreading of digestates. If demand for nutrients is low, or if the region suffers from an excess of nutrients, digestates will be useless. They will either be eliminated or given (at negative prices), or upgraded and exported to other regions. **Competition with other materials** has an ambivalent influence on the markets. For example, the competition with other efficient fertilizers (WRAP, 2013) can support upgrading initiatives to make digestates more attractive. But digestate-based products suffer a lot from the high competition with well-established products on niche markets, such as in the private gardening sector (Dahlin et al., 2017). This competition can discourage upgrading efforts. **Cost savings** occur when farmers can partially replace mineral fertilizers by digestates (Pappalardo et al, 2018). It favours the local recycling of digestates as low-value fertilizers and it is often used as an argument to promote AD. **Transportation costs** rise when digestates are transported beyond a certain distance⁶. They also play an ambivalent role. To avoid these costs, digestate can be either used very locally, or upgraded into stabilized products that are less costly to transport (Drosg et al., 2015). **Path dependency**⁷ is a strong obstacle to the circular transition (De Jesus and Mendonça, 2018). Potential markets for digestates-based products, such as the textile industry, already rely on established supply chains. The lack of **incentives or subsidies** is also an obstacle to the circular transition (Ranta et al., 2018). Very few subsidies exist to upgrade digestates. The heat bonus in Germany encourages the development of drying technologies (Dahlin et al., 2017) but it has a very limited impact on the development of the markets.

3.3.4. *Social & cultural factors*

Social and cultural factors are mainly considered as a major barrier to implement circularity (Araujo Galvão et al., 2018; Govindan and Hasanagic, 2018; Kirchherr et al., 2018). Concerning digestate markets, these factors can be divided into four categories: acceptance and perception of wastes

⁵ The utility of an object is relative and depends on a specific context. An object is useful when it meets human needs (see Lupton, 2011).

⁶ Around 10 and 15 kms according to stakeholders.

⁷ We understand path dependency in the sense of past decisions and organisations influencing present technological choices (see Åhman and Nilsson, 2008).

and waste-derived products, reputation, level of information, and time requirement. The **acceptance and perception of wastes** have been described in waste economics as a social and cultural construct (Lupton, 2011). Farmers may accept to use these wastes based on personal preferences and perceptions (Lupton, 2017). Currently, digestates and digestate-based products are still perceived as wastes. This leads to a low willingness to pay (Dahlin et al., 2015; Czekala et al., 2020) and little interest for digestate-based products. **Reputation**⁸ is an important driver to the demand of wastes (Lupton, 2002) and the reputation of quality is decisive to sell waste-based products (Govindan and Hasanagic, 2018; Agyemang et al., 2019). Until now, no clear reputation has been made for digestate-based products and this prevents their commercial success (Dahlin et al., 2017). The reputation for digestates is still very local: farmers set up their opinions on direct observations and they are more likely to trust digestate producers they already know. The influence of the **level of information** on digestate markets has only been analysed through information asymmetry (Dahlin et al., 2017; Pappalardo et al., 2018). It is assumed that only farmers and digestate users lack information on digestate properties. This lack of information is held responsible for the rejection of digestates by potential consumers (Dahlin et al., 2017; Pappalardo et al., 2018). This definitely plays a role in slowing down the development of digestate markets. The importance of **time requirement** to develop new products and reach the ideal-type of circular economy has been highlighted by Rizos et al (2015) for SME enterprises. AD plants are mainly small businesses (Appel et al., 2016) whose owners rarely have the time to engage into upgrading strategies. When they built AD plants, they had never planned to upgrade digestates in the first place.

3.3.5. *Technological factors*

Technological factors are also considered as a key element to promote or hamper the transition towards circularity (Geng and Doberstein, 2008; Araujo Galvão et al., 2018; De Jesus & Mendonça, 2018; Govindan & Hasanagic, 2018; Tura et al., 2019; Dieckmann et al., 2020). We found that these factors have a strong influence on the dynamics of digestate markets. We divide them into four categories: material characteristics, technology readiness, technology affordability, and skills requirement. **Material characteristics** refer to the high heterogeneity of digestates whose characteristics depend on many parameters (WRAP, 2013; Monlau et al., 2015; Plana & Noche, 2016). They exert an ambivalent influence on market dynamics. The difficulty to handle digestates can support the development of upgrading processes that aim at standardizing digestates. But they can also favour the use or the elimination of digestates through the simplest processes, i.e. land application and incineration. **Technology readiness** refers to the existence of adequate technology to process and upgrade digestates. As the majority of adequate technologies are not yet mature (Monlau et al., 2015; Guilayn et al., 2020), this factor is currently an obstacle to the upgrading of digestates. **Technology affordability** refers to the capacity of digestate producers to invest in upgrading technologies. The currently available technologies are often very expensive and only a few plants invest in them, such as large AD plants or plants located in regions where the demand for nutrients is low (Trombin et al., 2017). It is widely acknowledged in the CE literature that **skills requirements** are a major barrier to CE implementation (Rizos et al., 2015; De Jesus and Mendonça, 2018; Govindan and Hasanagic, 2018). We found that this is a major obstacle to the development of the upgrading model (Trombin et al., 2017). Digestate producers often lack technical, communication and marketing skills. Most of them are farmers that already have to deal with their farming tasks, as well as with the production of biogas, and they cannot handle a third job.

3.3.6. *Environmental and agronomic factors*

Environmental factors are either omitted in CE studies, or only considered as drivers to the CE transition (Mont et al., 2017; Govindan and Hasanagic, 2018; Agyemang et al., 2019; Tura et al., 2019). Conversely, our study shows that this factor plays a pivotal role in the dynamics of digestate markets. Its influence is much more complex than being just a simple lubricant to the expansion of digestate

⁸ Reputation can be defined as goodwill value attributed to a firm (Shapiro, 1983, p. 659).

markets. Our understanding of the term “environment” is large and includes human and animal health and biodiversity. We add the “agronomic factor” to the environmental factor as digestate markets are very much linked with agriculture. The **environmental and agronomic factors** are divided into three categories: expected agronomic benefits, environmental and health uncertainties and risk perception. Public authorities and digestate producers insist on the **expected agronomic benefits** of digestates to encourage their local use as fertilizers (ADEME, 2016; German Biogas Association, 2018; Infometha, n.d.). Digestates can partially replace mineral fertilizers and manure as a source of readily available nutrients (Logan & Visvanathan, 2019). Pathogens and odours are said to be reduced compared to manure (Lereau, 2018; Tignon, 2018), as well as leaf burns and leaf contamination (Wilken et al., 2018). These agronomic benefits are therefore a driver to spreading digestates on lands as low-value fertilizers. However, high **environmental and health uncertainties** remain concerning their impacts (Couturier et al., 2019). Biodiversity loss, GHG emissions (Guilayn et al., 2020), water pollution (Trombin et al., 2017) and animal health (Topagrar, 2014) are found to be among the main concerns. The agronomic properties of digestates are also uncertain, such as the effect of digestate use on soil functioning and on yields (Koszel & Lorencowicz, 2015; Wilken et al., 2018; Sadet-Bourgeteau et al., 2020). These uncertainties are used by opponents to the sector to prevent the use of digestates (FNE, 2020). However, supporters of digestates argue that engaging into upgrading can eliminate some uncertainties. The **risk perception** that goes with these uncertainties seems to be influenced by the individuals’ general perception and acceptance of wastes. This factor therefore plays an ambivalent role in the acceptance or rejection of digestate markets. According to the literature, this risk perception can be over-estimated for refurbished and recycled goods (Agyemang et al., 2019).

4. Discussion

4.1. Competing circularity understandings shape digestate markets

Our results show that the circularity of digestate markets is questioned in many ways although AD is being promoted as a model of CE. How circular are digestate markets? The answer to this question may rely on which CE definitions are chosen to analyse the functioning of digestate markets. As there is no scientific or political consensus on circularity, many interpretations exist. These contending interpretations try to establish a certain vision of CE with specific goals and targets (Flynn et al., 2019; Leipold, 2021). They create guidelines and frameworks for market development. At the EU level, active lobbying enforces a definition over alternative ones in order to enhance the development of digestate spreading markets and the development of upgrading initiatives.

If we refer to the primary conception of CE from Boulding (1966), digestate markets should contribute to the development of a closed economic system based on a “continuous material reproduction” that conserves material stocks. This economic system should also rely on renewable sources of energy (Ayres, 1988). According to French public authorities’ vision of CE, AD contributes both to renewable energy targets and to material conservation thanks to the use of digestates. This is why the use of digestates as low-value fertilizers is still the most promoted model. But finding the right balance between energy production and material conservation is controversial. Opponents to AD consider that as AD transforms organic matter to extract biogas, the digestates “brought back to nature” are not as useful and valuable to ecosystems as agricultural residues. They argue that digestates will not efficiently participate to the conservation of natural capital (Agrobiosciences, 2014; JAMAG, 2021; Nature & Progrès, 2021). Moreover, they doubt that carbon emissions from biogas use will be absorbed by the agrosystems that supply AD plants (CNVM, n.d.). They strongly question the closed nature of AD systems. The contribution of AD to a more circular economy may eventually rely on the comparison between its effects on circularity and the effects of other waste management options. For instance, the Waste Hierarchy encourages the AD of municipal wastes over landfilling. The use of municipal waste-based digestates as fertilizers contributes more to the regeneration of material stocks than the incineration of these wastes.

But now, EU ambitions, supported by scientific literature, tend to argue that material conservation and recycling are not sufficient goals for CE. The EU circular economy should aim at

maximizing the value of materials and at keeping them in high-value applications as long as possible (Webster, 2015; Stahel, 2016; Korhonen et al., 2018). EU bioeconomy strategy also supports the development of a bio-based CE to produce high-value products for European industries (Vivien et al., 2019). In this perspective, some scientists call for the transformation of AD plants into biorefineries to improve their profitability (Logan & Visvanathan, 2019; Theuerl et al., 2019). What would circularity mean if the upgrading model was to be generalized? It would first involve an important change in the geographic scale. The distance between the areas of production and of use of digestates could significantly increase. The solely eventual return of digestates to nature would be considered, but no matter *where* it would take place. This could also enlarge loops, with an increased number of intermediaries processing and selling digestates to many different industrial sectors and actors. However, this would go against the advice of narrowing the loops as much as possible (Webster, 2015). If the loops are multiplied, complexified and globalised, how would we know, among all the applications possible for digestates, if their use will eventually directly or indirectly contribute to preserve material stocks? And would this system be fundamentally different from our current economic model? How could these practices be monitored? At the local scale, this model may look like a very linear throughput of material. In Germany for instance, some AD plants have already created a nutrient imbalance between the regions of production of their substrates, and the regions where their digestates are applied (Trombin et al., 2017).

4.2. Environmental and health impacts: a much more complex story

Recycling materials is at the core of CE thinking. It is viewed as a solution to protect the environment and to fight the depletion of natural resources (Ghisellini et al., 2016). But it involves using wastes whose properties are often not fully known. For instance, scientists are increasingly concerned about cocktail effects of different substances that have not been yet fully identified (Lupton, 2017). The use of digestates is supposed to help nutrient recycling and to avoid environmental damages that result from nutrient loss (Wilken et al., 2018). But digestates are also heterogeneous objects that result from a mix of various substances. Whatever the legal status they acquire, they fundamentally remain by-products of biogas production. They are neither desired nor anticipated products of AD, predestined for a market. They therefore clearly lack identified and homogenous physical characteristics (such as nutrient and carbon content or share of impurities) typical of a standardized product. In addition, digestates are wastes originating from other wastes. They are “square wastes”. They often combine their own uncertainties and controversies and those attached to their substrates. One example is the presence of pesticides in both AD substrates and digestates (Fuchs et al., 2008; Monlau et al., 2015). Conversely, AD is also supposed to improve the quality of digestates compared to their substrates, with for instance, the deactivation of certain pathogens (Nkoa, 2014). Digestates are thereby “two-sided” goods: they have the potential to harm the environment, but they can also contribute to its protection. Very polarized positions result from this dual good. Digestate supporters strongly promote their use whereas opponents fiercely reject them (Agrobiosciences, 2014). This strong polarization often compromises peaceful debates and negotiations in places where digestate markets emerge and it threatens their development (Galibert & Kosuth, 2019).

The uncertainties and controversies about digestate characteristics are amplified by their relative newness. Many countries such as France are still at the genesis of digestate markets. Environmental damages caused by digestates emerge and create new oppositions to the sector, such as the ammonia pollution of the river Aulne by a leakage of digestates in the West of France (France 3, 2020). Many leakages of digestates have already been recorded in Germany (Trombin et al., 2017). The new upgrading technologies that are supposed to help reduce uncertainties around digestates also face emerging controversies, such as on their contribution to air pollution or their use of chemicals⁹ (Drosg et al., 2015; Trombin et al., 2017). A similar situation of uncertainty was described by Lupton (2002) for the use of sewage sludge in agriculture. The shared lack of certainties and information goes beyond

⁹ For example, the use of flocculants.

information asymmetry and makes digestates fall into the category of "indeterminate goods", i.e. goods for which information about their characteristics is not yet available to any group of agents (Lupton, 2005). Moreover, the emerging controversies resulting from the polarization of opinions transform digestates into "controversial goods", i.e. indeterminate goods generating scientific, social or political controversies (Lupton, 2002). These environmental controversies reveal a much more complex perception of CE initiatives than the ideal one intensely promoted by public authorities and by the CE literature. They strongly impact the local acceptance of digestate markets.

4.3. The displacement of issues along the loop

The CE literature has highlighted that circularity does not automatically equal environmental sustainability (Geissdoerfer et al., 2017; Korhonen et al., 2018; Millar et al., 2019). Our results demonstrate that the majority of digestate markets are very similar to manure or other agricultural by-products markets and have already caused environmental damages. This supports concerns that circular systems could eventually produce the same negative externalities as linear systems and displace problems caused by linear thinking instead of solving them (Korhonen et al., 2018; Millar et al., 2019). Problems displacement already exists around digestate markets. It fuels suspicion that digestate markets may only be "cosmeticizing" the current unsustainable system by surfing the wave of circularity without fundamentally transforming it. Among the problems displaced "along the loop" of AD, an important one is the surplus of nitrogen in intensive livestock farming areas (Trombin et al., 2017). The promises of the benefits of CE have led to a concentration of AD plants in some of these regions (Monlau et al., 2015). Large amounts of manure-based digestates are produced and applied on agricultural parcels located in nitrogen vulnerable zones, such as in the North of Germany (Lereau, 2018; Logan & Visvanathan, 2019). The source of the nitrogen issue, (i.e. intensive livestock farming systems concentrated in certain regions), is perpetuated, and the issue is just displaced from manure to digestates. Moreover, in some cases, digestate markets have even worsened the situation. In some German regions, an increased quantity of nutrients (mainly nitrogen and phosphorous) in groundwater has been attributed to a growing number of AD plants. Concerns about the eutrophication of the sub-catchment of the Baltic Sea are also raising (Plana & Noche, 2016; Trombin et al., 2017). Therefore, if there is too much of an output in a system, making it flow is an unsatisfactory solution.

One of the keys proposed to solve the issue of the excess of digestates is to upgrade and export them to other regions or countries, or to other economic sectors, i.e. to develop the upgrading model. The EU strategy to reduce its importations of nutrients favours the circulation of digestates on the EU single market through its new Regulation (UE) 2019/1009. However, stakeholders and specialized media agree on the absence of demand for importing digestates and digestate-based products (Euractiv, 2019). This issue is common to many waste markets which have been created "ex-post" with the hope of valorising wastes but not to meet an actual demand (Lupton, 2002). Europe has a long tradition of exporting its wastes to less-developed countries, such as nuclear or electronic wastes. Are these trials to export digestates another attempt to get rid of cumbersome wastes or do they really contribute to close material cycles?

Upgrading digestates is also a source of problems displacement. Markets for digestate-based products are submitted to the same factors as digestate markets. They particularly suffer from environmental uncertainties, low acceptance from potential users, and a dizzying regulation (Drosg et al., 2015; Guilayn et al., 2020). In addition, upgrading processes also generate wastes and by-products that often have to be sent to wastewater treatment plants (Wilken et al., 2018) or incinerators. In order to avoid that potential problems exceed expected benefits, Korhonen et al. (2018) suggest that the physical scale of circular systems should be carefully considered. But, as previously mentioned, the choice of the physical scale will depend on the dominant visions on CE. Many questions on the physical¹⁰ scale of digestate markets remain unanswered. Is there a limit to the physical growth of these markets? Can we produce an ever-growing amount of digestates? What is the best scale to trade and use

¹⁰ By « physical » we refer to the amount of digestates produced and used.

digestates? And what governance mechanisms are needed to ensure that the development of digestate markets benefit the largest number of people?

5. Conclusion

Our study aimed at understanding the dynamics of digestate markets with a specific focus on the French and German markets. We identified three different models of functioning. The first model is dominant and consists in the use of digestates as low-value fertilizers in agriculture. Digestate markets are very localized and prices can vary considerably depending on the local context. These markets often rely on intermediaries already specialized in manure and fertilizers management. The second model is minor and consists in the elimination of specific categories of digestates mainly through landfilling or incineration. It is considered as a guarantee of quality for the digestates that are not eliminated. The third model is currently minimal. It involves the transformation of digestates into high value products such as refined fertilizers. It requires the development of new technologies and new business opportunities. If this model was to become dominant, it could complexify and lengthen the supply chains between digestate producers and final users. Digestate markets would not be local anymore and exportations would be common rule. These three models are not strictly separated and can even overlap. Digestate markets are not stabilized and they constantly move from one model to another. We identified six main groups of factors that influence the evolution of these markets: political factors, legal factors, economic factors, social and cultural factors, technological factors, and environmental and agronomic factors. Circumstances are quite similar in France and in Germany although the first and third models are more developed in Germany. The very fast growth and evolution of these markets make it difficult to predict their future development. They could collapse like the sewage sludge market in Switzerland or the balance between the models could change. Several understandings at national and European levels promote the development of one model as the best option. But the best option may have to be decided at the local level, at the scale of the AD plant and its territory. This would involve the co-existence of a variety of development models adapted to the local context. The plasticity of digestate markets shows us how complex it is to characterize circular markets. The diversity of competing scientific and political CE definitions and visions can produce systems that are different from the initial visions of circularity. Our findings also point out that digestate markets are not spared by environmental and health issues and controversies. Strong oppositions to these markets emerge locally. Therefore, the best development model could be the one that locally satisfies the largest number of people and minimizes environmental and health-related threats. Further research should focus on studying the governance mechanisms that allow to find this right balance. It would imply to understand finely the alchemy between local contexts and the positioning of stakeholders, and its influence on market development.

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