

# Economic sustainability of biogas production from animal manure: a regional circular economy model

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## Abstract

**Purpose** – This paper aims to understand the implementation of a circular economic business where animal manure is used to produce biogas and alternative fertilizer in a regional network of manure suppliers and biogas producers and to reveal the impacts of five variables (manure quantity, transportation distance, manure dry content, manure price and manure discharge price) on the economic sustainability of manure-based biogas supply chains.

**Design/methodology/approach** – An enterprise input-output approach is used to model physical and monetary flows of the manure-based biogas supply chain. Computational experiments are performed on all variables to identify under which conditions the cooperation is beneficial for all actors.

**Findings** – The cooperation is profitable for a large-scale farm (>20,000 t/year) if biogas producer ( $b$ ) pays farmer ( $f$ ) to receive its manure (5 €/t) or if  $f$  sells manure for free and manure disposal costs are >10 €/t. Cooperation is always profitable for  $b$  if  $f$  pays  $b$  to supply its manure (5€/t). If  $b$  receives manure for free, benefits are always positive if  $b$  is a medium-large-scale plant (>20,000 t/year). For a small-scale plant, benefits are positive if manure dry content (MDC) is  $\geq 12$  per cent and transportation distance is  $\leq 10$  km.

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**Originality/value** – The paper adds value to the biogas production research, as it makes holistic analysis of five variables which might change under different policy and geographical conditions. The investors in biogas production, suppliers and transportation companies can find correspondence to empirical findings for their own site-specific cases.

**Keywords** Supply chain, Circular economy, Manure, Business ethics and sustainability, Input-output model, Biogas production, Circular business models, Sustainable bioenergy

**Paper type** Research paper

## Introduction

Since the industrial revolution, the world economy has followed a “take-make-consume and dispose” pattern of growth, a linear model based on the assumption that resources are abundantly available, easy to source and cheap to dispose of (European Commission, 2015). Such a model causes large environmental pressure on the planetary boundaries, because it is characterized by high consumption of raw materials, relatively high waste during production and waste discharge after production (Bruckner *et al.*, 2012; Giljum *et al.*, 2015; Wiedmann *et al.*, 2015). Therefore, such models are not sustainable from the environmental point of view. In particular, the increasing awareness that natural resources are limited pushes toward the development and the implementation of new circular economy models, able to manage existing resources in a continuous cycle, hence providing an effective use of these resources (Bocken *et al.*, 2016; Fraccascia *et al.*, 2016). In this regard, the European Commission claims that circular economy may be able to provide economic benefits for firms, in addition to environmental benefits, and widely recommends their adoption (European Commission, 2015).

Within this framework, an important issue concerns the energy production. As about 60 per cent of the total electric energy is produced from fossil fuels (International Energy Agency, 2014), energy generation is one of the main reasons of greenhouse gas emissions (Soytas *et al.*, 2007). Such emissions are widely recognized as the main driver of climate change (IPCC, 2014). With the aim to mitigate this problem, alternative technologies have been developed to produce energy from renewable resources. A well-known example is the production of energy from second-generation biomass (McKendry, 2002; Albino *et al.*, 2015). While first-generation biomass refers to organic products that principally were used to produce food, whose use generated a large ethical debate, second-generation biomass refers to organic secondary outputs, e.g. solid and liquid municipal wastes, manure, lumber and pulp mill wastes and forest and agricultural residues (Hall and House, 1994; Miyamoto, 1997). Therefore, the use of second-generation biomass is widely promoted in bioenergy production (International Energy Agency, 2008; Ellen Macarthur Foundation, 2013).

In particular, the use of manure for energy production may offer remarkable opportunities at places where intensive livestock farming is practiced (Massaro *et al.*, 2015). Technologically speaking, manure-based bioenergy can be produced in two different ways:

- (1) producing biogas by anaerobic digestion (AD); and
- (2) producing biochar, bio-oil and gases through pyrolysis (P) (Beardmore, 2011; Guo *et al.*, 2013).

In both cases, the resulting products can be used as fuel to generate electric energy. Currently, AD ensures the highest performance from both an environmental and an economic point of view (Appels *et al.*, 2011; Miller and Moyle, 2014).

As in The Netherlands, intensive livestock farming is practiced, the amount of manure produced is considerable and its exploitation for bioenergy production may have a

remarkable potential. However, the possibility to produce manure-based energy is actually not fully exploited because of some obstacles in the cooperation among manure producers and biogas producers (De Korte, 2012). Therefore, designing and organizing biogas supply chains (BGSCs) becomes more difficult. As a consequence, the potential environmental and economic benefits cannot be achieved.

This paper analyzes the manure-based BGSC, i.e. biogas production from manure by AD. Through a case example, this paper aims at identifying the main variables affecting the cooperation dynamics among manure producers and biogas producers. To this end, we model the manure-based BGSC through the enterprise input-output (EIO) approach, modeling physical and monetary flows into the supply chain and assessing the environmental and economic benefits generated. Then, we use numerical analysis via computational experiments to assess the impacts of five variables (manure quantity, transportation distance, manure dry content, manure price and manure discharge price) on the supplier–buyer relationships in the local markets to foster cooperation and to stimulate the production of renewable energy. Besides, our work provides practical and managerial contributions aimed at enhancing the development of circular economy models on a local level.

The remainder of the paper is organized as follows. The next section presents the generic EIO model for supply chains, followed by addressing EIO model application in a case example. Then, the circular business model is presented, and a scenario analysis is proposed to reveal the role of uncertainty on cooperation decisions. Results of the computational experiments are presented and discussed. Finally, the paper ends with conclusions.

### Enterprise input-output model for supply chains

In this section, we use a physical EIO model to quantify the material/energy/waste flows of the BGSC and integrate it into the monetary EIO model to calculate the economic performance of the BGSC. The generic EIO model for supply chains is adopted from a paper by Yazan *et al.* (2011).

The functional unit of the supply chain is modeled as a process that transforms inputs into outputs and produces wastes from such a transformation. The process may require two kinds of inputs:

- (1) primary inputs, which are purchased from outside the supply chain; and
- (2) main inputs, which come from other processes belonging to the supply chain (outputs produced by other processes).

Each process can require more than one input and generate more than one waste. However, for the sake of simplicity, we suppose that each process can produce only one output (which means that the term “output” in the sequel may refer both to the main product and the process producing that product). Figure 1 displays a simple representation of a supply chain process from an input-output perspective.

Let us consider a supply chain composed of  $n$  processes. We define  $Z_0$  as the matrix of domestic intermediate deliveries between processes,  $f_0$  as the vector of final demands and  $x_0$  as the vector of gross outputs. The matrix  $Z_0$  is of size  $n \times n$ , and both vectors  $f_0$  and  $x_0$  are of size  $n \times 1$ . The intermediate coefficients matrix  $A$  is defined as follows:

$$A = Z_0 \hat{x}_0^{-1} \quad (1)$$

Here,  $\hat{x}_0$  denotes the diagonal matrix so that  $\hat{x}_{0_{ii}} = x_{0_i} \forall i$  and all the other elements are equal to zero. The generic element of the intermediate coefficients matrix  $A_{ij}$  denotes the

necessary quantity of input  $i$  to produce one unit of output  $j$ . Therefore, we have (note that the spectral radius of the non-negative matrix  $A$  is smaller than one):

$$x_0 = Ax_0 + f_0 = (I - A)^{-1}f_0 \tag{2}$$

Besides, there are  $s$  primary inputs purchased from outside the supply chain, and  $m$  by-products and wastes are produced as secondary outputs within the supply chain. Let  $r_0$  be the primary input vector (size  $s \times 1$ ) and  $w_0$  be the by-product/waste vector ( $m \times 1$ ). Let  $R$  be the  $s \times n$  matrix of primary input coefficients, with the element  $R_{kj}$  denoting the use of primary input  $k$  ( $1, \dots, s$ ) per unit of output of process  $j$ , and let  $W$  be the  $m \times n$  matrix of waste and by-product coefficients, with the element  $W_{lj}$  denoting the output of by-product or waste type  $l$  ( $1, \dots, m$ ) per unit of output of process  $j$ . It results:

$$r_0 = Rx_0 \tag{3}$$

$$w_0 = Wx_0 \tag{4}$$

To describe the monetary EIO model, we first introduce the unitary cost and price vectors;  $p_0$  is the vector ( $n \times 1$ ) of the prices, with the element  $p_{0i}$  indicating the unitary price of the main product of process  $i$ . Therefore, using the vector of gross outputs  $x_0$ , we can calculate the vector  $y_0$  ( $n \times 1$ ), representing the total revenues associated with each gross output as follows:

$$y_0 = \hat{x}_0 p_0 \tag{5}$$

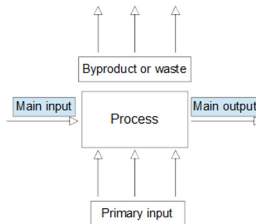
Furthermore, we can determine the monetary coefficients matrix  $B$  ( $n \times n$ ), with the generic element  $B_{ij}$  expressed as:

$$B_{ij} = A_{ij} \frac{p_{0i}}{p_{0j}} \tag{6}$$

Then, we can determine  $b_0$  as follows:

$$b_0 = By_0 + \hat{f}_0 p_0 = (I - B)^{-1} \hat{f}_0 p_0 \tag{7}$$

Here,  $\hat{f}_0$  denotes the diagonal matrix so that  $\hat{f}_{0_{ii}} = f_{0_i} \forall i$  and all the other elements are equal to zero. Moreover, we define the vector of prices (or costs)  $p_0^w$  ( $m \times 1$ ), where the generic element  $p_{0_i}^w$  represents the unitary price (or cost) associated with the by-products (or



**Figure 1.**  
A supply chain  
process from an  
input-output  
perspective

wastes) in all processes (i.e. by-products represent economic gains and waste represents treatment costs). Hence, using the matrix  $W$ , we can identify the vector  $y_0^w$ , a  $n \times 1$  vector, representing the total revenues associated with all by-products and wastes for each process as follows:

$$y_0^w = \left[ (p_0^w)^T W \hat{x}_0 \right]^T \tag{8}$$

In addition, let  $p_0^r$  ( $s \times 1$ ) be the unitary primary input prices vector. Then, we can compute  $y_0^r$  ( $n \times 1$ ), the vector of the costs associated to each process for the primary inputs purchasing (including workforce).

$$y_0^r = \left[ (p_0^r)^T R \hat{x}_0 \right]^T \tag{9}$$

The vector of intermediate inputs costs  $y_0^z$  ( $n \times 1$ ) is also calculated using  $p_0$  and  $i$  ( $n \times 1$  unit vector, having all elements equal to one).

$$y_0^z = \left[ (i)^T \hat{p}_0 A \hat{x}_0 \right]^T \tag{10}$$

Finally, we introduce  $d_0$ , which is a  $n \times 1$  vector representing the amortization costs. The generic element  $d_{0i}$  represents the annual amortization cost of process  $i$ . Then, the profit of the whole production chain ( $\Pi$ ) can be computed as:

$$\Pi = \sum_{i=1}^n (y_i + y_i^w - y_i^z - y_i^r - d_i) \tag{11}$$

The model serves as a planning and accounting tool for the involved supply chain actors, and its use is demonstrated in the next section for a manure-based BGSC.

**The manure-based biogas supply chain: a case example**

In this section, we assess the manure-based BGSC by adopting the EIO approach. The main production processes within the manure-based BGSC are presented in Figure 2. Manure is collected from farms, loaded into trucks and transported to the biogas plant. Then, manure is mixed with other types of biomass to increase biogas yield in later stages. In this paper, we assume the use of corn silage for the mixing process. The obtained blend is converted into biogas and digestate (a nutrient-rich material remaining after AD) by means of AD, where microorganisms break down the biodegradable material in the absence of oxygen.

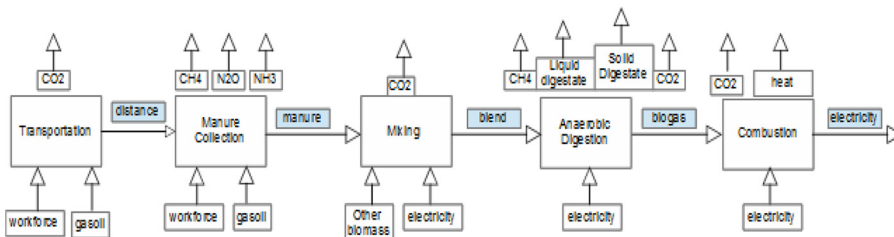


Figure 2. Manure-based BGSC flowchart

Afterwards, biogas is used for combined heat and power generation for the production of electricity and heat (American Biogas Council, 2014).

Accordingly, five main processes are considered: manure collection (P1), transportation (P2), mixing (P3), AD (P4) and combustion (P5). Each process receives a main input and produces a main output. All these outputs are physical products, except for the output of the transportation process, which is the distance covered between the manure producer and the biogas producer. There are also four primary inputs (gasoil, workforce, electricity and other biomass), four wastes ( $\text{CO}_2$ ,  $\text{N}_2\text{O}$ ,  $\text{CH}_4$  and  $\text{NH}_3$ ) and three by-products sold as a value-added (solid digestate, liquid digestate and heat).

In this section, we apply the EIO model to a numerical case example by assuming fix costs and prices for a small-scale biogas plant, i.e. a plant able to receive in input up to 5,000 t of manure per year. All values are referred to a time range of one year. The computations of this section are the basis of the next section, where we describe the circular business model scenario and apply computational experiments to reveal the role of the above-mentioned five variables on chains' economic performance.

In the base scenario, we assume 5,000 t/year of cattle manure and an average transportation distance of 3 km between the farm and the small-scale biogas plant. Values of technical parameters are extracted from some previous studies in the literature (Navaratnasamy *et al.*, 2008; Amon *et al.*, 2007; El-Mashad and Zhang, 2010). In particular, we assume that the manure is characterized by 12 per cent of dry content and 85 per cent of organic content, and we assume a mixture rate of 98 per cent manure and 2 per cent corn silage. The volatile solid content of dry matter of manure has an average value of 80 per cent, while the percentage of volatile solid in the whole manure is 16 per cent (Al Seadi *et al.*, 2013). Furthermore, we assume that 0.8 t of digestate can be produced by 1 t of manure (Berglund and Borjesson, 2006). Finally, we assume that the cogeneration process can produce 1.7 kWh of electricity and 7.7 MJ of heat from the exploitation of 1 m<sup>3</sup> of biogas (Navaratnasamy *et al.*, 2008). Methane production from manure processing is 0.2 m<sup>3</sup>/kg of volatile solid content (Al Seadi *et al.*, 2013).

In cogeneration, biogas passes through a gasometer and after the heat exchanger process, heat and exhaust gas are emitted. In the meanwhile, electricity is produced and also reused within the cogeneration plant. Figures 3 and 4 present the physical and monetary input-output tables, respectively. Physical input-output table (Figure 3) shows final output production, primary input consumption and waste generation by each process depicted in Figure 2, as well as the physical exchanges among processes. Figure 4, on the other hand, displays the costs and benefits associated with physical flows of the manure-based BGSC. We assume that the electricity generation unit uses four-stroke engine with an electrical efficiency of 35-40 per cent (Deublein and Steinhauser, 2008).

Figure 3 shows that in the base scenario, the plant produces 192 t of  $\text{CO}_2$ , 612 t of solid digestate, 3,468 t of liquid digestate, 315,783 kWh of heat and 251,090 kWh of electricity per year. We apply 10 per cent mark-up for the final products of the bio-energy plant, while the manure, gasoil and corn silage prices are considered fixed on 2 €/t, 1.2 €/liter and 40 €/t respectively. As the literature shows that economic value of digestate ranges from 0.5 to 3.2 €/t (Lantz, 2012), we assume an average price of 1.85 €/t digestate. According to Navaratnasamy *et al.* (2008), the capital cost of a small-sized biogas plant is 6,510 €/KWh, and the running cost is 0.019 €/KWh. Furthermore, government incentives for renewable energy production are 0.056 €/KWh in The Netherlands (International Energy Agency, 2014). From Figure 4, it can be seen that the chain produces a total annual value-added of 84 K€ with a loss of 58 K€ and employment of 142 K€ in the base scenario, where value-added is measured as the sum of profit and wages. The loss is due to the difference between

	Processes		Collection	Transportation	Mixing	Anaerobic digestion	Combustion	Final Demand	Total Main Outputs
P1	Collection	ton of manure	0	0	5,000	0	0	0	5,000
P2	Transportation	km	2,143	0	0	0	0	0	2,143
P3	Mixing	ton of blend	0	0	0	5,100	0	0	5,100
P4	Anaerobic digestion	m3 of biogas	0	0	0	0	147,700	0	147,700
P5	Combustion	Kwh of electricity	0	0	0	0	0	251,090	251,090
	Primary inputs							Total primary input use	
r1	gasoil	liter	700	3,500	0	0	0	4,200	
r2	workforce	person.hour	4,000	667	1,600	1,600	1,600	9,467	
r3	other biomass	ton	0	0	100	0	0	100	
r4	electricity	KWh	0	0	4,781	125,545	125,545	255,871	
	By-products and wastes							Total by-products and wastes	
w1	CO2	ton	1.80	9	2	55	124	191.80	
w2	CH4	ton	19.59	0	0	0.01	0	19.60	
w3	N2O	ton	0.05	0	0	0	0	0.05	
w4	NH3	ton	1.40	0	0	0	0	1.40	
w5	solid digestate	ton	0	0	0	612	0	612	
w6	liquid digestate	ton	0	0	0	3,468	0	3,468	
w7	heat	kWh	0	0	0	0	315,783	315,783	

**Figure 3.** Physical input-output table of the manure-based BGSC. Colors highlight different matrices and vectors:  $Z$  is highlighted in red,  $f_0$  in green,  $x_0$  in blue,  $R\hat{x}_0$  in yellow,  $r_0$  in gray,  $W\hat{x}_0$  in sky blue and  $w_0$  in brown

total costs and benefits, while value added is positive, as it is the sum of the (negative) profit and wages. We understand from the base scenario that small-scale cattle manure-based biogas plant is not profitable. We show in section 4 that the medium-big-scale biogas plants can be profitable under certain conditions.

As we can see from Figure 4, there is no economic convenience under the conditions provided for the small-scale biogas plant's supply chain. However, economies of scale and the other variables such as existing manure discharge cost or manure price might provide additional economic benefit to the supply chain's profit. Therefore, in the next section, we apply our model to medium- and large-scale biogas plants.

### Circular business model scenario

By adopting circular economy models, the produced wastes can be exploited as new production inputs instead of being disposed of in the landfill. In such a way, the consumption of natural resources is reduced, in addition to the lower amount of wastes landfilled, and the circularity is achieved.

As bioenergy supplier and buyer networks are characterized by a notable level of uncertainty (Yazan *et al.*, 2012), our next step is associated with revealing the role of variables that influence the chain performance. Accordingly, decisions-to-cooperate of BGSC actors will change. We

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612

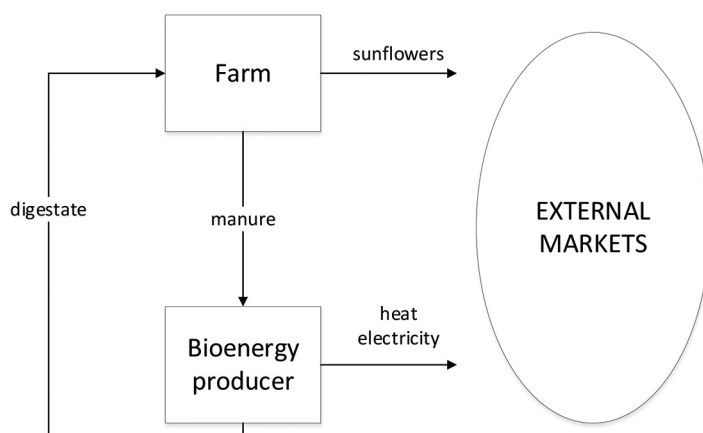
	Processes (€)	Collection	Transportation	Mixing	Anaerobic digestion	Combustion	Final Demand	Total Revenues
P1	Collection	0	0	10,000	0	0	0	10,000
P2	Transportation	2,657	0	0	0	0	0	2,657
P3	Mixing	0	0	0	43,440	0	0	43,440
P4	Anaerobic digestion	0	0	0	0	80,176	0	80,176
P5	Combustion	0	0	0	0	0	131,208	131,208
	<b>Primary inputs</b>						<b>Total primary input use</b>	
r1	gasoil	840	4,200	0	0	0	5,040	
r2	wages	60,000	10,000	24,000	24,000	24,000	142,000	
r3	other biomass	0	0	4,000	0	0	4,000	
r4	electricity	0	0	267	7,031	7,031	14,329	
	<b>By-products and wastes</b>						<b>Total by-products and wastes</b>	
w1	CO2	27	136	31	822	1,842	2,859	
w2	CH4	2,744	0	0	1	0	2,745	
w3	N2O	0	0	0	0	0	0	
w4	NH3	0	0	0	0	0	0	
w5	solid digestate	0	0	0	1,132	0	1,132	
w6	liquid digestate	0	0	0	6,416	0	6,416	
w7	heat	0	0	0	0	1,042	1,042	
	<b>Amortization cost</b>	1,333	10,000	5,141	5,141	5,141		26,757
	<b>Total Costs</b>	67,602	24,336	43,440	72,887	117,147		325,412
	<b>Profit</b>	-57,602	-21,679	0	7,289	14,061		-57,931
	<b>Value-added</b>	2,398	-11,679	24,000	31,289	38,061		84,069

**Figure 4.**  
Monetary input-output table of the manure-based BGSC

consider two actors in the manure-based BGSC: a farmer (*f*) and a bioenergy producer (*b*). As an addition to the base scenario, we assume that the farmer is also a cultivator, meaning that the digestate produced by the bioenergy producer can be used by the farmer in cultivation of sunflowers. Figure 5 displays the simple input/output flows of such a circular business model.

We evaluate two scenarios: non-cooperation and cooperation. In the former, the farmer produces manure which is used as fertilizer for sunflower cultivation, and the biogas plant is not part of the business. In the cooperation scenario, the farmer produces manure which is sent to the biogas plant. The biogas plant produces biogas (used for electricity and heat production) and digestate, which is sold to the farmer. The farmer uses digestate as fertilizer for sunflower production. Therefore, local farmers are confronted with a decision to be involved in energy production.





**Figure 5.**  
Actors involved in  
the manure-based  
BGSC

In traditional production systems, farmers are not involved in energy production because they are mainly concerned with livestock farming. There are other feedstocks that can be used in biogas production instead of manure. Then, what motivates both actors to cooperate?

First, from an economic perspective, intensive livestock farming results in high quantity of manure, which exceeds the manure-based fertilizer demand (De Korte, 2012). Second, regulatory constraints on manure use as a substitute of fertilizer allows farmers only to use/sell limited amounts of manure (De Korte, 2012). Both situations influence the economic performance of farmers, leading to high manure disposal costs. The bioenergy producer, on the other hand, would have the advantage of producing a by-product to gain higher value-added, i.e. digestate.

From an operational perspective, the ammonia within digestate, differently from nitrogen in raw manure, is immediately absorbed by the soil. In this way, it directly contributes to plant growth. Digestate has three other remarkable advantages for the agricultural practice:

- (1) It does not present the odor nuisance, providing increased land application options.
- (2) It makes weed control easier and more efficient for farmers by destroying unwanted weeds.
- (3) It is more homogeneous, which makes fertilizer spreading more uniform.

Let us present the benefits from cooperation versus non-cooperation. The subscript  $f$  refers to the farm,  $b$  to the bioenergy producer. The superscripts (0) and (1) indicate the scenario of no cooperation and cooperation, respectively.

For the farmer, the benefit from cooperation is given by:

$$B_f = R_f^{(1)} - R_f^{(0)} \quad (12)$$

where:

$B_f$  = farm benefits from cooperation.

$R_f^{(0)}$  = farm revenues in case of no cooperation.

$R_f^{(1)}$  = farm revenues in case of cooperation.

For the bioenergy producer, the benefit is given by:

$$B_b = R_b^{(1)} - R_b^{(0)} \quad (13)$$

where:

$B_b$  = bioenergy producer benefits from cooperation.

$R_b^{(0)}$  = bioenergy producer revenues in case of no cooperation.

$R_b^{(1)}$  = bioenergy producer revenues in case of cooperation.

We assume that the bioenergy producer pays for manure transportation and the farmer pays for digestate transportation. Sunflower price and production costs remain constant in both scenarios. Production costs of the bioenergy producer are attributed to the operating costs (i.e. biogas production costs, digestate production costs, cost of mixing and heat production costs). We introduce  $C^i$ ,  $P^i$ ,  $Q^i$  to denote the unitary cost of production, the unitary market price and the quantity produced of the  $i$ -th element, respectively; and  $E$  and  $H$  indicate the electricity and heat produced from bioenergy producer, respectively. Finally,  $C_d^{discharge}$  is the unitary cost of manure discharge and  $P_d^{government incentive}$  is the incentive provided by government per unit biomass-based electricity production. Then, we can compute  $R_f^{(0)}$  and  $R_f^{(1)}$  as follows:

$$R_f^{(0)} = P_f^{sunflowers} \times Q^{sunflowers(0)} - C_f^{sunflowers} \times Q^{sunflowers(0)} - C_f^{discharge} \times [Q^{produced manure(0)} - Q^{used manure(0)}] \quad (14)$$

$$R_f^{(1)} = P_f^{sunflowers} \times Q^{sunflowers(1)} + P_f^{manure(1)} \times Q^{manure(1)} - P_f^{digestate(1)} \times Q^{digestate(1)} - C^{digestate transportation} \times Q^{digestate(1)} - C_f^{sunflowers} \times Q^{sunflowers(1)} \quad (15)$$

$R_b^{(0)}$  and  $R_b^{(1)}$  can be calculated as:

$$R_b^{(0)} = 0 \quad (16)$$

$$R_b^{(1)} = E^{produced(1)} \times P_b^{electricity} + H^{produced(1)} \times P_b^{heat} + E^{produced(1)} \times P_b^{government incentive} + P_b^{digestate(1)} \times Q^{digestate(1)} - E^{produced(1)} \times C_b^{operating(1)} - P_f^{manure(1)} \times Q^{manure(1)} - C^{transportation} \times Q^{manure(1)} - C^{amortization(1)} - C^{other biomass purchase(1)} \quad (17)$$

To understand how uncertainty affects cooperation among actors, we identify five operational, technical and economic variables (manure quantity, transportation distance, manure dry content, manure price and manure discharge price) and investigate their impact on the implementation of the supplier–buyer relationships in the local manure markets. We use three fixed values for each variable as follows:

- (1) manure quantity (5,000, 20,000 and 100,000 t/year);
- (2) transportation distance between farm and bioenergy plant (2, 10 and 30 km);

- (3) manure dry content (8, 10 and 12 per cent) and organic matter content of manure (80, 82 and 85 per cent);
- (4) manure price (−5, 0 and 5 €/t); and
- (5) manure discharge cost (5, 10 and 15 €/t).

These variables have critical importance for operational efficiency and economic performance of the manure-based BGSC. Manure quantity is decisive on plant scale in the cooperation scenario, as well as on fertilizer use and discharge costs in the non-cooperation scenario. Transportation distance has a significant impact as the manure has a very low value, which is an obstacle for long-distance transportation. Manure dry content and organic matter contents are critical for the biogas and digestate yields. Manure discharge cost is also a critical variable, particularly when the bioenergy producer is a unique alternative to manure discharge. Accordingly, we assume that the biogas producer does not pay more than the discharge cost to the farmer in the cooperation-case. Concerning the manure price, −5 €/t indicates that farmer pays bioenergy producer to supply its manure, 0 €/t means that manure is sent to the bioenergy producer for free and 5 €/t refers to the case in which bioenergy producer pays farmer to receive its manure.

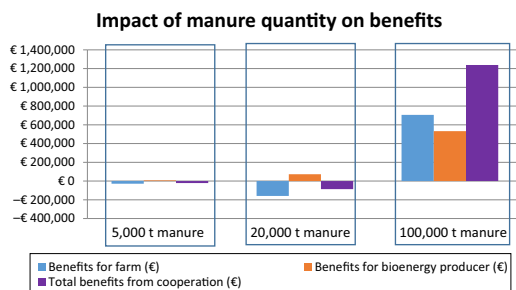
The amount of other biomass, i.e. corn silage, mixed with manure (2 per cent of the blend), the available cultivation land (1,000 ha) and manure application rate (10 t/ha) are assumed constant. Considering that biogas production from cattle manure was not profitable in our base scenario analysis (Figure 4), and swine manure has a higher biogas yield; we use swine manure data for our computational experiments.

## Results and discussion

We apply computational experiments based on what-if scenarios. Considering three values for each variable, in total we obtain  $3^5 = 243$  different combinations. These combinations represent the effects of uncertainty characterizing cooperation dynamics. In this section, we show the most relevant results, some of which display combined effects of the variables.

### *Impact of manure quantity*

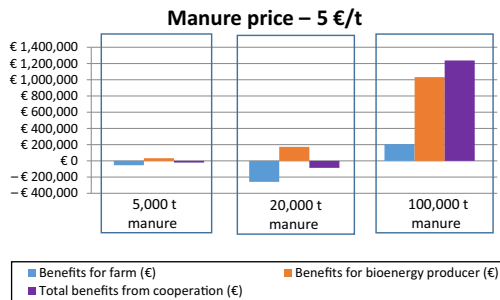
According to Figure 6, manure quantity notably affects cooperation benefits. For a small- and medium-size farm ( $\leq 20,000$  t/year of manure), the benefits are negative. For the bioenergy producer, the higher the scale, the higher the benefits from the cooperation will be, *ceteris paribus*.



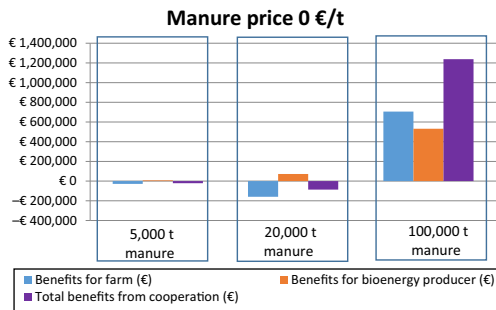
**Figure 6.** Impact of manure quantity on benefits (with a fixed manure price [0 €/t], manure dry content [12 per cent], organic matter content [85 per cent], transportation distance [2 km] and manure discharge cost [15 €/t])

*Impact of manure price and manure quantity*

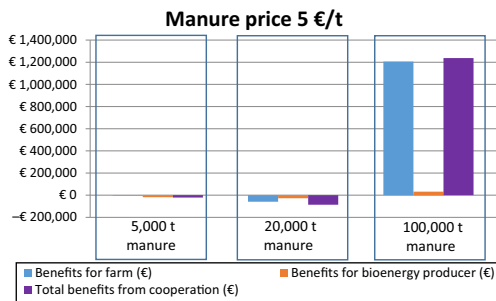
Figure 7 shows the impact of manure price and quantity on actors' benefits. When the farmer pays the bioenergy producer to supply its manure (manure price = -5 €/t), farm benefits are negative in case of small-medium scale ( $\leq 20,000$  t/year of manure). In such a case, the benefits for the large-scale bioenergy producer are the highest. When the bioenergy producer pays the farmer for the manure (manure price = 5 €/t), the benefits for the bioenergy producer are negative in case of small-medium-size plant. The large-scale farmer benefits the most.



(a)



(b)



(c)

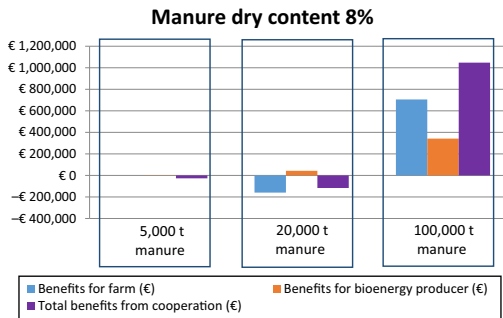
**Figure 7.** Impact of manure price and manure quantity on benefits (with a fixed manure dry content [12 per cent], organic matter content [85 per cent], transportation distance [2 km] and manure discharge cost [15 €/t])

*Impact of manure dry content and manure quantity*

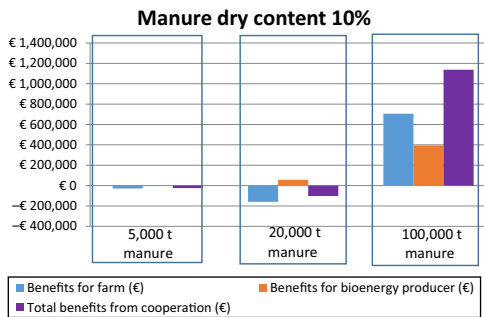
Figure 8 displays the impact of manure dry content (and organic content) on cooperation dynamics. Expectedly, if manure dry content is high, cooperation benefits increase.

*Impact of transportation distance and manure quantity*

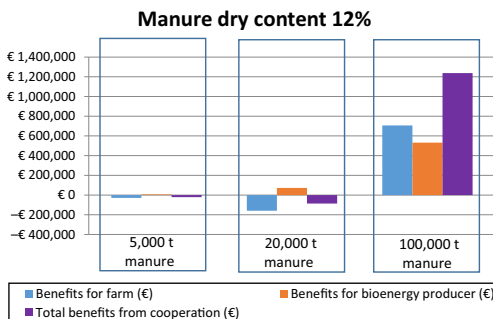
According to Figure 9, the shorter the transportation distance, the greater the benefits arising from cooperation. The impact increases with increasing farm and plant scale.



(a)

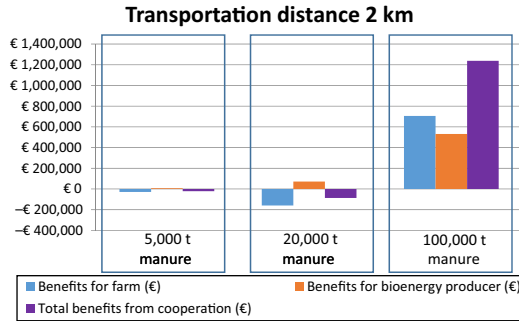


(b)

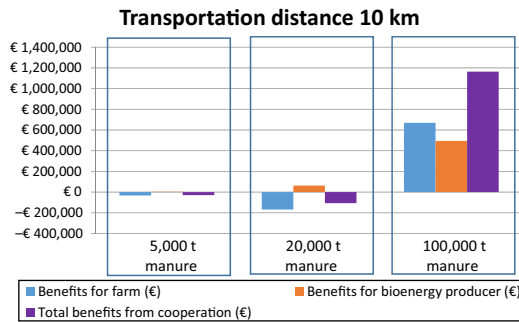


(c)

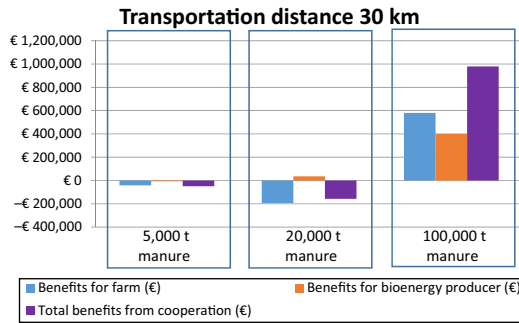
**Figure 8.** Impact of manure dry content and manure quantity on benefits (with a fixed manure price [0 €/t], transportation distance [2 km] and manure discharge cost [15 €/t])



(a)



(b)



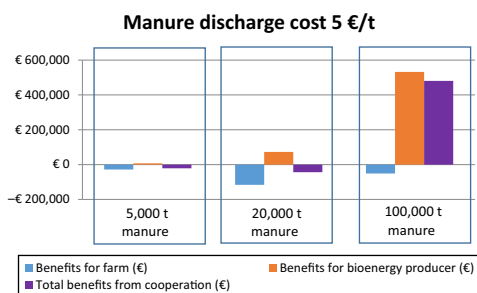
(c)

**Figure 9.** Impact of transportation distance and manure quantity on benefits (with a fixed manure price [0 €/t], manure dry content [12%], organic matter content [85%] and manure discharge cost [15 €/t])

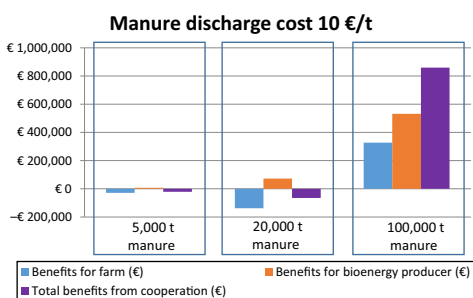
*Impact of manure discharge cost and manure quantity*

Farm benefits are strongly dependent on manure discharge cost (Figure 10). If discharge costs are high, the farm revenues in case of non-cooperation decrease because the remaining amount of manure, not usable as fertilizer, has to be disposed of. On the other hand, the bioenergy producer is not affected by the discharge cost.

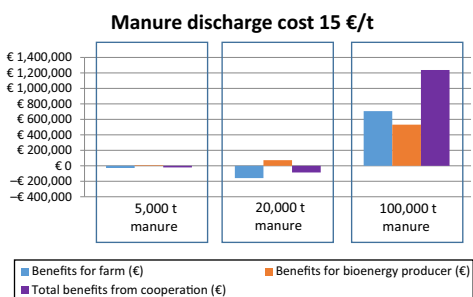
However, depending on the case, manure discharge costs might provide an idea to the bioenergy producer about the manure price to offer to the farmer. Our next analysis is based on the combined effects of manure discharge cost and manure price.



(a)



(b)



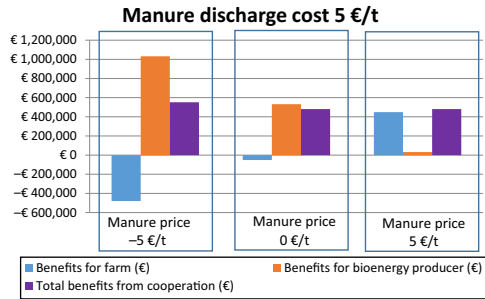
(c)

**Figure 10.** Impact of manure discharge cost and manure quantity on benefits (with a fixed manure price [0 €/t], transportation distance [2 km] and manure dry content [12%], organic matter content [85%])

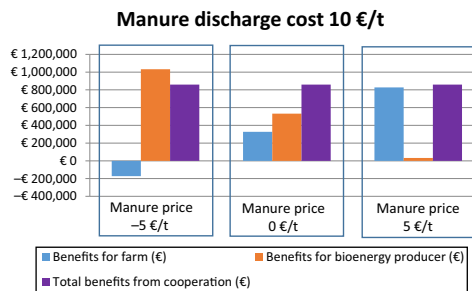
*Impact of manure discharge cost and manure price on benefits*

In Figure 11, we present the combined effect of manure discharge cost and price on cooperation dynamics for a big-scale plant, having revealed in precedent analyses that big-scale cooperation is more advantageous. The farm has the highest benefit when manure discharge cost is 15 €/t and manure price is 5 €/t (bioenergy producer pays farmer to receive its manure). Bioenergy producer’s benefit reaches a peak if manure price is -5 €/t (when he is paid by farmer to receive its manure), regardless of the discharge cost.

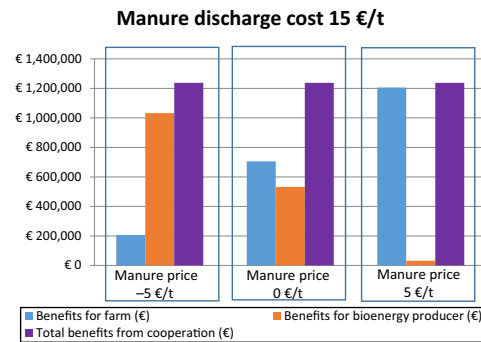
Summarizing (Figures 6 to 11), cooperation is not profitable for a small-medium-scale farm ( $\leq 20,000$  t/year). It is profitable for a large-scale farm if  $b$  pays  $f$  to receive its manure (5 €/t), regardless of the values of other variables; or if  $f$  provides its manure for free and



(a)



(b)



(c)

**Figure 11.** Impact of manure discharge cost and manure discharge price on benefits (with a fixed manure quantity [100,000 t], manure dry content [12 per cent], organic matter content [85 per cent], transportation distance [2 km])

manure discharge costs are high (10-15 €/t); or if *f* pays *b* to supply its manure (5 €/t) and at the same time manure disposal costs are very high (15 €/t).

Cooperation is always profitable for a bioenergy producer if *f* pays *b* to supply its manure (5 €/t). If *b* receives manure for free, benefits from cooperation are always positive if *b* is a medium-large-scale plant (>10,000 t/year). On the other hand, (if manure is free) for a small-scale *b*, benefits are positive only if manure dry content is high (MDC = 12 per cent) and transportation distance is short (≤10 km). If *b* pays *f* to receive its manure (5 €/t), *b* benefits are always negative, except when manure quantity processed is ≥100,000 t/year (large-scale bioenergy plant), MDC = 12 per cent and transportation distance is very short (≤2 km). We



notice that manure quantity and manure price have the strongest impact on cooperation dynamics, because they significantly affect the benefits for both actors.

These results allow us to better understand the potential of cooperation through supply chain actors in the context of developing a local circular economy business model, as it was explained in “Circular business model scenario” section. Indeed, our results show that such a mechanism provides an effective use of existing local resources, particularly when the quantity of supply is high and the bioenergy plant uses the advantage of economies of scale. Small- and medium-size plants can also be advantageous under certain conditions discussed above. Based on the results of our analysis, in some cases, cooperation can be beneficial for one actor while the other one has negative economic return. However, when the total benefit is still positive, then to foster cooperation, benefits could be shared between the two actors. How companies can implement benefit-sharing schemes should be further investigated in future research. Furthermore, the cooperation scenario has other remarkable advantages from technical, environmental and social perspectives. In comparison to untreated manure, AD of manure brings along multiple additional benefits, such as decreasing methane emissions and odor nuisance, as well as increasing the hygienic status and nutrient availability of manure.

## Conclusions

While the production of bioenergy from manure via AD has been largely studied in the literature, few studies have investigated the cooperation dynamics among actors within the manure-based BGSC. Our paper fills this gap to understand under which conditions cooperation can be beneficial or detrimental to actors involved in the supply chain.

The benefits of the cooperation are strongly influenced by several technical, operational and economic variables whose impacts are quantified via scenario analysis. Such variables represent the effect of uncertainty on the supplier–buyer relationships in local manure markets, where waste technical quality, price and quantity vary over time. In particular, we apply computational experiments to reveal the role of such variables aimed at enhancing the development of a circular economy business models on a local level.

Considering that animal farming and cultivation activities are mostly performed in rural areas, our business model provides a closed-loop supply chain to reduce environmental impacts of secondary outputs of such activities in rural areas. The business model can be extended to a case where manure is used for biogas production, digestate is used for fertilization, agricultural residues are used as a blending biomass and the bioenergy produced is used instead of fossil-based energy in animal farming and cultivation activities. This would be a complete circular model in line with the EU’s regional development strategies, particularly when we consider that the sustainable development should be on local level. Implementing sustainability at on a local level involves efficient cooperation of local business actors on efficient use of local resources and the suitable conditions are promoted by regional authorities. Hence, our case can also be considered as a regional development model.

Several assumptions of our paper should be dealt with in future research. Our business model considers a simple case of a one-to-one relationship in which only two actors are involved in the BGSC. However, we should consider that there might be multiple farmers or biogas plants according to the available manure quantity in a region. For example, if there are ten farms producing different amounts of manure under same conditions, then the benefit will be proportionally divided among them, meaning that each farmer gains much less than the bioenergy producer. This also means that different levels of bargaining power and willingness-to-cooperate for each supplier and biogas plant might appear. Hence, total

economic benefits calculated in circular business model scenario section might be distributed among involved actors according to potential contracts or benefit-sharing schemes. Similarly, other actors, such as intermediaries between suppliers and buyers or third-party logistics players or farmer coalitions, might be involved in such a business model, and the network then must be modeled considering multiple actors. In fact, further research should assess the managerial conditions of such supplier-buyer networks where small-, medium- and big-scale farms and plants are located randomly. Hence, simulation techniques such as agent-based modeling can be used to evaluate different cooperation strategies of the multiple actors approach.

Furthermore, we assume that in the cooperation scenario, all of the produced manure is sold to the bioenergy producer, i.e. the demand is equal to supply. So, our model can be used by biogas producers as decision support to invest in biogas production considering a one-on-one relationship. However, the supply-demand match is critical, and if there is a surplus or lack of manure, then the economic benefits might fluctuate, which can also be dealt with simulation techniques. Such a technique is also useful to address the dynamicity of the circular business model, which evolves over time. Further research will aim at extending our study to a more complex scenario in which more suppliers and buyers are involved in a network.

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