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Improving the Sustainability of Farming Practices through the Use of a Symbiotic Approach for Anaerobic Digestion and Digestate Processing

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Abstract: The dairy sector in the Netherlands aims for a 30% increase in efficiency and 30% carbon dioxide emission reduction compared to the reference year of 1990, and a 20% share of renewable energy, all by the year 2020. Anaerobic Digestion (AD) can play a substantial role in achieving these aims. However, results from this study indicate that the AD system is not fully optimized in combination with farming practices regarding sustainability. Therefore, the Industrial Symbiosis concept, combined with energy and environmental system analysis, Life Cycle Analysis and modeling is used to optimize a farm-scale AD system on four indicators of sustainability (i.e., energy efficiency, carbon footprint, environmental impacts and costs). Implemented in a theoretical case, where a cooperation of farms share biomass feedstocks, a symbiotic AD system can significantly lower external energy consumption by 72 to 92%, carbon footprint by 71 to 91%, environmental impacts by 68 to 89%, and yearly expenditures by 56 to 66% compared to a reference cooperation. The largest reductions and economic gains can be achieved when a surplus of manure is available for upgrading into organic fertilizer to replace fossil fertilizers. Applying the aforementioned symbiotic concept to the Dutch farming sector can help to achieve the stated goals indicated by the Dutch agricultural sector for the year 2020.

Keywords: green gas; biogas; biomass; industrial symbolism; energy and environmental system analysis; MEFA; LCA

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1. Introduction

Within the European Union, sustainable agriculture could play an important role in achieving the renewable goals set for 2020 [1], and the renewable vision set for 2050 [2]. Research in the domain of agriculture widely recognizes the importance of sustainable agriculture production systems [3]. However, while modern agriculture is very productive, its negative effects on the environment have become increasingly visible [4]. Current practices aim at reducing per-unit costs of production, which results in increased intensity, more specialised production, and increased emissions of substances (e.g., global warming potential) with negative effects on the surrounding ecosystems and the overall climate [3–5] (e.g., environmental impact). Within the context above, and in accordance with the Dutch goals for energy efficiency and renewable energy production [6], the Dutch agricultural sector has formulated goals for sustainable farming. Among others, these goals include: less use of fossil resources and with it lowering anthropogenic emissions; lowering the use of fossil fertilizers; increasing renewability and sustainability of agriculture as a whole; and connecting and integrating agriculture into society [7]. Furthermore, an agreement signed between the dairy sector and the Dutch government aims at 30% increase in efficiency, 30% carbon dioxide emission reductions compared to the reference year of 1990, and 20% share of renewable energy in the year 2020 [6,8].

Among others, Anaerobic Digestion (AD) has been suggested as a potential renewable energy source for use in the farming sector. The AD process has been successfully implemented in the treatment of several biomass feedstocks, AD is already established as a reliable technology in Europe [9], and can extract energy from biomass in the shape of biogas, which is a flexible and storable energy carrier [10]. However, the choice of feedstocks, technologies, and the operational values of AD systems have a substantial influence on environmental impacts of the AD process [11–17]. The use of intensively cultivated energy crops, long transport distances, and the use of energy intensive processes can negatively affect the environmental impact of AD systems [10,13,17]. Business cases for farm scale AD systems within the Netherlands are often unfeasible due to high investment, feedstock, and operational costs [18–21] and the lack of stable and consistent subsidy [8]. Also, focus within the agricultural sector is often placed on single-issue regulation and/or single improvement options (e.g., renewable production, emission reduction, or waste reduction). Within a complex system like agriculture there is a good chance that "single factor" manipulation could result in a cumulative negative overall gain [4].

Within the aforementioned context, implementing the Industrial Symbiosis concept focusing on optimizing the AD system could potentially lower the environmental impact and cost of farm scale AD systems. Industrial Symbiosis, a key concept of industrial ecology, studies the physical flows of materials and energy in local industrial systems using a systems approach [22]. Industrial Symbiosis engages separate industries in a collective approach to create a competitive advantage involving the exchange of materials, energy and services [23]. In an ideal symbiotic system, waste material and energy are utilized between/among the actors of the system and the consumption of virgin raw material and energy inputs as well as the generation of wastes and emissions are thereby reduced [23]. The Industrial Symbiosis concept can help avoid the single factor manipulation by making the AD system an integral part of farming activities. In particular, waste resulting from a generic production process can substitute primary inputs in another process [24]. For instance, by creating a circular symbiotic system where bio-waste is used for energy and fertilizer production which can be reused for the production of new biomass [25–30], if reuse of waste as fertilizer satisfies the requirements for a negligible concentration of plant harmful elements. Furthermore, the use of local waste products also avoids intensive farming processes [31], long distance transport, and the widespread debate regarding the use of food-quality biomass for energy production [32], while organic fertilizer use avoids the production, import, and use of fossil fertilizers [17]. To achieve the aforementioned, the AD process will need technical adaption and optimization through the use of several improvement options operating symbiotically. This can give the opportunity to gain collective benefits significantly larger than the sum of the individual benefits [23,33].

However, to the authors' knowledge, no literature discusses the integration and optimization of an AD system within local farming practices using the Industrial Symbiosis concept; which could indicate, among others, that the AD system has not been fully optimized. Therefore, within this article a farm scale AD system, utilizing locally available biomass waste streams, is analyzed and optimized on four indicators of sustainability (i.e., energy efficiency, carbon footprint, environmental impacts, and costs), through the use of the Industrial Symbiosis concept, combined with energy and environmental system analysis, Life Cycle Analysis, and modeling. Exploring the aforementioned, combinations could lead to environmental and economic improvements on current AD systems and lead to the integration of circular symbiotic AD systems within future farming practices to reduce the overall environmental impact and cost of the farming process.

2. Methods

In the following section the methods used during the formation of the results are described.

2.1. The Biogas Simulator

The assessment is performed by modeling the complete AD system. The excel model used [34,35] is based on the industrial metabolism concept. To gain insight into the energy use, carbon footprint, environmental impacts, and costs of the AD system, the model combines Material and Energy Flow Analysis (MEFA) [36], Energy and Environmental System Analysis [10], Attributed Life Cycle Analysis (aLCA), and Net Present Value (NPV) [37]. The model was extensively validated before being used [35]. The overall sustainability is defined within this article as "strong sustainability", wherein environmental quality precedes social prosperity and then economic prosperity [38,39]. The LCA analysis is undertaken in accordance with European guidance and DIN EN ISO 14040 to 14044: 2006 [40]. The environmental impacts were obtained through the use of the SimaPro v8.0 (2013) utilizing the Eco Invent database v3.0 (2013) as endpoints.

2.2. System Boundary

Dutch regulation states that at least 50% of the feedstock used in an AD system must consist of manure (e.g., cow, pig, chicken manure). The remaining 50% can comprise of other biomass (e.g., harvest remains, catch crops, roadside grass, or maize). The ratio of manure and feedstock and the type of feedstocks used must comply with Dutch regulation in order for the digestate to be used as fertilizer [41]. Energy and material flows and their impacts are taken into account when they are in service of the AD system (e.g., production, processing, and transport), (Figure 1) [31]. The embodied energy (required energy for the production) of the installations is also incorporated. Within this research, mitigation regarding the replacement of current waste treatment chains (e.g., current manure storage and waste crop management) with an AD system, and of fossil fertilizer with organic fertilizers, is taken into account. Regarding the processing of digestate (Figure 1) only the economic cost are incorporated [17]. Emissions from the soil are not included. Internal energy use is included where external sources of energy can be replaced with the energy gained from the AD system (Figure 1). Additional economic costs or revenues saved or lost through the use of improvement options are taken into account as cash flows within the NPV. The current energy and fertilizer use (e.g., manure, fossil fertilizers) of farms are included in a theoretical reference case, for determining the effectiveness of a cooperatively owned circular symbiotic AD system. The costs and revenues of the AD system are based on prices and subsidies within the Netherlands [42].

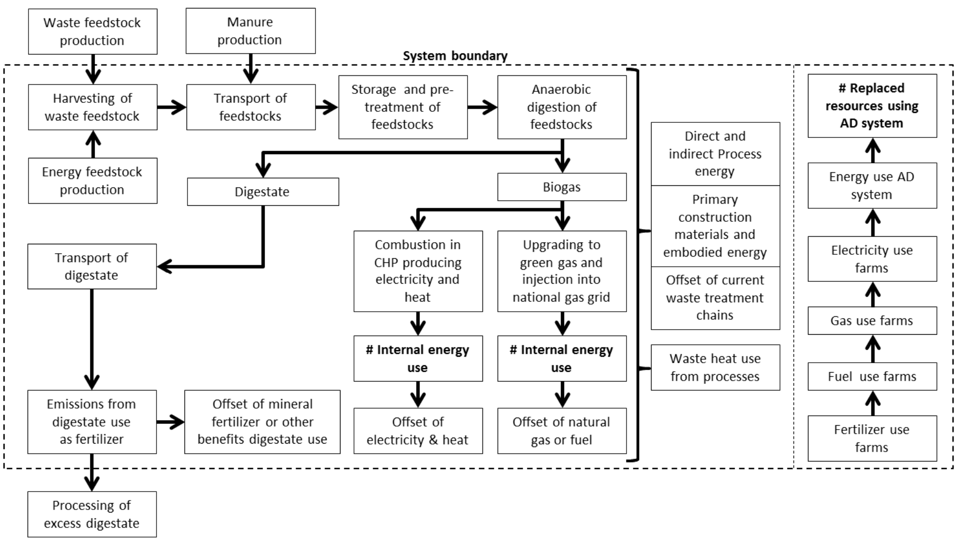


Figure 1. System boundaries of biogas production and utilization, included aLCA. Using the circular symbiotic AD system in the theoretical case will replace current energy and fertilizer flows used on the farm.

2.3. Sustainable Impact Indicators (SI Indicators)

The energy efficiency, carbon footprint, and the sustainability of green gas production are expressed in three indicators: First, (Process) Energy Returned on Energy Invested or (P)EROI, defined as the ratio between the energy obtained from a resource to the energy expended in the production and processing of a resource [43]; Second, the carbon footprint, expressed in carbon dioxide equivalents (CO_2eq) using the relevant 100-year global warming potential scale or GWP (100), [44]; And finally, the overall impact on the environment, expressed in the ReCiPe 2008 Eco indicator, used by the SimaPro model [45,46]. The specific choice for the above-named indicators and a clear description thereof are discussed in Pierie et al. [47]. The financial feasibility is expressed in Net Present Value (NPV) over 25 years [37]. The NPV method was selected as it is a commonly used indicator for economic feasibility and indicates the overall returns of the investment [37]. The general rule of thumb is if the NPV is positive, "invest", and if it is negative, "don't invest". The NPV rule recognizes that the value of money today is worth more than the value of money tomorrow, because the money can be invested today to start earning interest immediately. NPV depends solely on the forecasted cash flows of the project and the opportunity cost of capital. Since the present values are all measured in today's value, they can be added [37]. The aforementioned SI indicators will be the measure of sustainability within this article.

3. The Location and Biomass Feedstocks

The AD system is located on a dairy farm in the middle of the biomass collection area, represented as a circle (biomass circle). The distribution of biomass, dairy farms, and agricultural farms, averaged for the Netherlands, are retrieved from Pierie et al. [47]. In addition, catch crops (e.g., flower rich margins or buffer strips) are also used as feedstock for the AD system. During the cultivation of catch crops the use of machinery and fossil fuel is taken into account for seeding and harvesting, no fossil fertilizers are used directly. Average biogas and methane yield values are selected resulting from several combinations of catch crops [48]. The radius of the biomass circle is determined by the feedstock needs of the AD system: Therefore, the mix of feedstocks is determined from the availability of biomass in the biomass circle (Table 1). With the average radius of the biomass circle known, the average transport distances can be determined [31]. Additionally, a tortuosity factor is included, which represents inefficiencies in transport (e.g., winding roads, multiple pickup locations) [31,49] (Table 1). A clear description of the aforementioned can be found in Pierie et al. [47]. For biomass waste flows, only transport cost are included (Table 1), except for manure from external sources where negative prices are used within the Netherlands, due to its over-abundance [50], and for roadside grass where harvesting costs from road embankments are included [51].

All scenarios will use the same AD plant setup as a starting point (normal scenario), (Figure 2). The AD system, with a feedstock throughput of 20,000 Mg/a (Table 1), is stirred and heated to maintain mesophilic temperature. When required, feedstocks are mechanically pre-treated, screened for foreign debris (e.g., plastics, stones), and/or pasteurized. Transport of biomass is conducted by truck, loading and unloading is incorporated (Table 1). Part of the produced biogas is used in a small boiler to produce the needed heat for the digestion process. The remaining biogas is upgraded to green gas through the use of a highly selective membrane upgrader system [52]. The green gas is injected in the national gas grid (Figure 2). A gas pipe of one kilometer is used to transport the green gas from the production site to the injection station. The electricity use for the AD system is imported from the national electricity grid. The digestate is used on site as fertilizer on the pastures (Figure 2). The NPV of the business case, over a technical lifetime of 25 years and an economic write off period of 15 years, is based on economic factors within the Netherlands (e.g., energy prices, CAPEX, OPEX) [20,50,53]. Subsidies for green gas or electricity production are given per kWh of energy injected into the grid [42], (Appendix B).

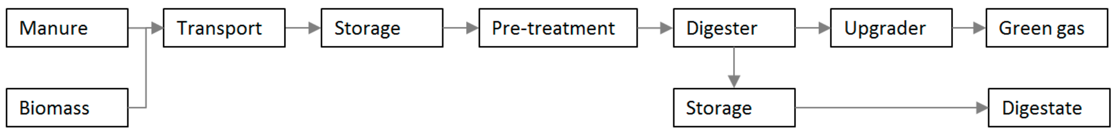


Figure 2. Main green gas production pathway of the normal scenario.

Table 1. Feedstocks used including costs and transport retrieved from Pierie et al. [17,31].

	Feedstock (Mg/a)	Costs (€/Mg)	Tortuosity (Factor)	Transport (km)	Biogas Potential (Nm^3/Mg.oDM [a])	Methane Potential (Nm^3/Mg.oDM [a])
Manure farm/cooperation	1820	0	1	0.1 [d]	350	180
Manure source	8000	−10 [b]	1.5	1.5	350	180
Chicken manure	475	0	1.5	3	416	212
Natural/roadside grasses	6000	10 [c]	5	15	560	297
Tops from sugar beets	1100	0	1.5	3	550	302
Tops from potatoes	2300	0	1.5	3	550	302
Straw from grains	500	0	1.5	3	341	174
Catch crops	1100	0	1.5	3	640	329
Digestate	-	-	-	-	47 [f]	19 [f]
Energy Maize (Reference)	10,000	35 [e]	1	50	606	322

[a] Biogas and methane production per Mg of organic Dry Matter; [b] Price of manure from external sources derived from Kwin, 2013 [50]; [c] Price of retrieving grass from road embankments and natural areas [51]; [d] Transport by pipeline on farm; [e] Costs of maize feedstocks derived from Kwin, 2013 [50]; [f] Biogas and methane potential of the digestate retrieved from [54].

4. Scenarios

To come to a more sustainable farming concept, first, the effect of the individual improvement components on the SI indicators, applied to the AD system, is analyzed (Appendix A). Second, multiple individual improvements are combined in a symbiotic design with maximum positive impact on all the SI indicators (Figure 3). Finally, the theoretical lessons learned from the symbiotic systems are applied in a theoretical case based on a cooperation of dairy and agricultural farms including average consumption of farming practices, which includes energy, fuel and fertilizer use (Figure 3).

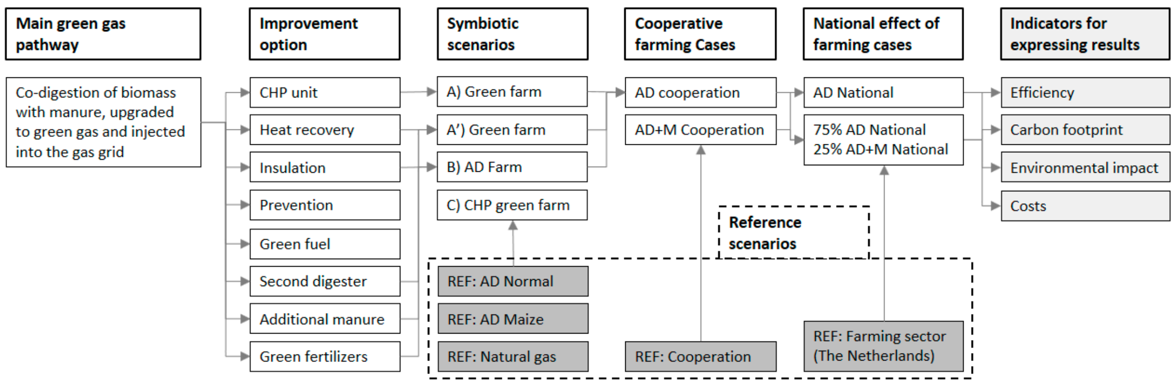


Figure 3. The scenarios and cases used in this article.

4.1. Circular Symbiotic Scenarios

Within the circular symbiotic scenarios the main biogas production and green gas utilization pathway (Figure 2) is expanded with several improvement options (Appendix A) to research possible improvements on the main SI indicators (Section 2.3). The optimum sub-scenarios (Table 2) are determined through empirical modeling of several combinations of individual improvement scenarios. Additional installation properties, investment, and operational costs of improvement options are included (Appendix B).

Table 2. The symbiotic scenarios.

Affiliation	Description of Symbiotic Scenario
Scenario A	Scenario A, describes the symbiotic system which combines: a Combined Heat and Power unit (CHP) for internal energy production, a 2nd digester with additional manure input, green fuel production from green gas, prevention of leakages and emission, heat recovery, and organic fertilizer production which is used in the surrounding farms to replace fossil fertilizers (Appendix A). Additional insulation of the AD system is not used as the required heat is already produced internally.
Scenario A′	Within this scenario one adaption is made to scenario A, namely: the produced organic fertilizers are sold on the market for lower prices and not used within the surrounding farms to replace fossil fertilizers. This only has an economic effect and, therefore, will only be indicated in the NPV results.
Scenario B	Within scenario B, regulations prevent the use of organic fertilizers for replacing fossil fertilizers in the Netherlands by decree of the European Union [55] (although the Dutch government has made some exceptions [56]). Therefore, organic fertilizer production is not included. The scenario combines: a CHP unit for internal energy production, a 2nd digester with additional manure input, green fuel production from green gas, heat recovery from the digestate, prevention of leakages and emissions, and insulation of the digester (20%) for additional heat savings (Appendix A).
Scenario C	Currently, many farm scale AD systems within the Netherlands utilize CHP instead of green gas production; therefore, scenario C describes the possibilities of a circular symbiotic AD system combined with CHP. The scenario includes: internal energy production based on CHP, a 2nd digester with additional manure input, prevention of leakages and emission, heat recovery, insulating the digester, and organic fertilizer production which is used in the surrounding farms to replace fossil fertilizers (Appendix A). Within the scenario the full utilization of the waste heat is assumed.

Reference Scenarios

The results from the symbiotic scenarios are compared to four reference scenarios (Table 3).

Table 3. Reference scenarios used for comparison.

Affiliation	Description of the Symbiotic Reference Scenario
Normal	The basic AD green gas production pathway without any modifications as described in Section 3.
# CHP # Fertilizer # 2nd Digester	The best individual improvement options per SI-Indicator are indicated as a reference scenario for comparison with the circular symbiotic scenarios. The best options are: for (P)EROI the CHP unit; for carbon footprint and Environmental impact the organic fertilizer production option; and for NPV the 2nd digester with added manure option. Full description of individual improvement scenarios can be found in Appendix A.
Ref gas	This fossil reference scenario is based on Groningen natural gas and includes: the production, needed infrastructure for transport and distribution, and combustion of the gas when used [31].
Ref maize	Within the maize reference scenario 50% maize and 50% manure is used as feedstock for green gas production using the same AD system as explained in Section 3, (Table 1). The maize (silage) used as feedstock is specially cultivated for use in the AD system. Therefore, agricultural fieldwork and the use of fossil fertilizers and pesticides during cultivation are incorporated [17]. The maize is transported over a distance of 50 km [10]. Within this scenario, the carbon footprint and environmental impact from normal manure management is also mitigated.

4.2. Cooperative Farming Theoretical Case

The theoretical lessons learned from the individual improvement options and the symbiotic scenarios (Section 4.1) are applied to a theoretical case based on the cooperation of five dairy and seven agricultural farms, which are treated in this article as a single entity called the cooperation. The required amount of farms within the cooperation is determined by the feedstock needs of the AD system (Table 1). The feedstocks acquired within the cooperation (including manure) only include transport costs. Within the theoretical case all manure is retrieved within the cooperation. The cooperation will use biomass from the local government and water board responsible for managing the biomass growth alongside roads, canals, natural areas, and/or parks (Table 4); however, this will include harvesting costs (Table 1). The fields used for roadside grass and natural grasslands do not require fertilization, due to natural inflow of nutrients. Regulation regarding green gas and electricity production using AD within the Netherlands is stable with a guaranteed subsidy for a maximum of 22 years. However, taxes and subsidy schemes for the aforementioned symbiotic systems within the Netherlands are currently undefined, to the authors knowledge; therefore, the effect on the yearly costs is difficult to indicate. For instance, policies and subsidies for green electricity, green gas and green fuel produced and used within the cooperation are currently nonexistent. Within the NPV cost calculation the Dutch low tax rate of 6% is included for the internal energy products produced within the cooperation (e.g., electricity, green gas, green fuel, and organic fertilizers), which is comparable to the current form of subsidy. Additionally, differences in tax rates and their effects on the total cost are discussed in the sensitivity analysis (Section 5.3).

Table 4. Energy and fertilizer requirements cooperation of farms.

	Unit	Dairy Farms	Agricultural Farms	Natural Areas	Total	Source
Average farms needed	farms	5.4	6.9		12.3	
Agricultural land size	ha	270 [a]	276 [b]	275 [c]	821	[17,50]
Diesel use	L/a	35,100	65,688		100,788	[50]
Electricity use	kWh/a	253,800	151,524		405,324	[50]
Natural gas use	Nm^3/a	8640	2898		11,538	[50]
Nitrate cap [d]	Kg/a	71,550	46,920		118,470	[50]
Phosphate cap [d]	Kg/a	25,650	17,940		43,590	[50]
Potassium cap [d]	Kg/a	60,750	62,100		122,850	[50]

[a] Based on average dairy farm with 100 cows and two cows per hectare of land [50]; [b] Based on production of beat tops, Potato tops, Straw, and Catch crops respectively 40, 20, 41, and 18.5 Mg/ha.a [17]; [c] Based on the production of roadside and natural grass of 21.8 Mg/ha.a [17]; [d] Cap means the maximum yearly allowed use of nutrients on a farm.

All three theoretical cases (Table 5) are based on the same energy and fertilizer needs of the cooperation (Table 4). Within the cases the SI indicators are calculated over a period of 25 years and are expressed per year. The SI indicators are expressed in absolute numbers, not including mitigation (and return on investment for NPV), as used in the previous Section. The cases (Table 5) are based on the average land occupation and feedstock availability described in Section 3 and the basic AD system described in Section 4.

Table 5. Main cooperative farming cases.

Affiliation	Description of the Sustainable Farming Cooperation Cases
REF (Case)	The reference cooperation (REF): In this case, based on current average farming activities in the Netherlands, the cooperation will import all of their energy and most of their fossil fertilizers. The dairy farms within the cooperation will use their own manure as fertilizer on their fields, whereas agricultural farms will use fossil fertilizer for all their nutrient demands. Additionally, fuel for the machinery, electricity, and natural gas are imported to supply the energy needs of the cooperation (Table 4). The environmental impacts of fertilizer, fuel, electricity, and natural gas production are included. Inflation and increase of prices for energy and fertilizers are taken into account for the upcoming 25 years (Appendix B).
AD (Case)	The AD cooperation (AD): Within this case, the cooperation will operate a circular symbiotic AD system, producing renewable energy and fertilizer from local bio-waste. Dairy farmers within the cooperation use the digestate from the AD system as fertilizer on their fields. Excess digestate is processed into organic fertilizers and used by agricultural farms in the cooperation. Additionally, the fuel for the machinery, electricity, and natural gas is supplied by the AD system (Table 4). The remaining energy or fertilizer requirements are imported. The overall cost of the AD system is based on the NPV calculation (Section 3). Within this case 23% of the total digestate output is upgraded into organic fertilizer to replace fossil fertilizer. The income from selling the remaining green gas is incorporated in the NPV; however, mitigation of carbon footprint and environmental impact by replacing green gas with natural gas is not included, as it does not lower the impacts of farming practices itself.
AD + M (Case)	The AD cooperation using surplus manure (AD + M): The AD + M case is similar to the AD case except that within this case a surplus of 10,000 Mg of manure from surrounding dairy, pig, or chicken farms is available for the production of additional energy and green fertilizer. In some parts of the Netherlands there is a surplus of manure available, often linked to farms with no agricultural land (e.g., pig, chicken farms). For the additional manure feedstock mixture the properties of cow manure are assumed (Table 1). Within this scenario around 50% of the total digestate output is available for upgrading to organic fertilizer, which can be used to replace fossil fertilizer. Excess fertilizer is sold on the market for market prices (Appendix B).

4.3. National Implementation Case

To indicate the possible effect of the theoretical case aforementioned on a national level, results are extrapolated towards full implementation in the Netherlands. Within this case the assumption is made that all farms will participate in cooperatives and that all the local biomass availability is utilized. Also, the available feedstock in the biomass circle described in Section 3 is assumed to be similar for all cooperations (Table 1). Please note however, that in practice biomass circles can differ. Therefore, when actually implemented at national scale, results can vary. The amount of cooperations is determined by dividing the total land availability for farming in the Netherlands by the land required by the farms within a cooperation (Table 6).

Table 6. Possible amount of farming cooperations within The Netherlands.

	Total Land (ha)	Average Farm (ha)	Amount of Farm	Farms Per Cooperation	Amount of Cooperations	AD Cooperations	AD + M Cooperations	Source
Dairy farming	956,000	50	19,120	5.4	3541			[57]
Agricultural farming	995,756	40	24,894	6.9	3608			[57]
Average					3574	2680	894	

Within the national scope case, the total amount of surplus manure available nationally determines how many AD + M cooperations can be set up. According to the Bureau of Statistics of the Netherlands, in the year 2015 there was a nutrient surplus for both nitrogen and Phosphate of around 25% (Appendix C) [57]. Therefore, within the AD + M national case, 25% of the cooperations are based on an AD + M and the rest are based on AD cooperations (Table 6). The results are compared with the total national carbon footprint and the carbon footprint from the farming sector in the Netherlands, for the year 2015 and the reference year of 1990.

5. Results

Within this section first the results of the symbiotic AD system are discussed, followed by the theoretical case and the national case.

5.1. Symbiotic Circular Systems

When implementing the single improvement options individually, improvement on the SI indicators can already be observed (Appendix A). For instance, a substantial gain in (P)EROI can be achieved through the use of a CHP unit (Figure 4a CHP) by avoiding external electricity and heat requirements. Replacing fossil fertilizer with organic fertilizer has a substantial effect on the carbon footprint and environmental impact as fossil fertilizers require high energy investment during production (Figure 4b,c Fertilizer). Installation of a second digester and additional input of manure directly into the second digester can improve the NPV (Figure 4d Manure). The second digester system requires little additional energy and maintenance but still produces additional biogas. However, the reduction achieved by individual improvement options is often significant for only one or two of the four SI indicators (Appendix A). For instance, organic fertilizers production positively affects carbon footprint and environmental impact but negatively affects the (P)EROI and NPV; this is caused by high energy use in the process, substantial initial investment costs, and additional operational costs for energy and maintenance. Within this context, and given the systemic nature of agricultural systems, focusing on single factors does not necessarily lead to optimal results.

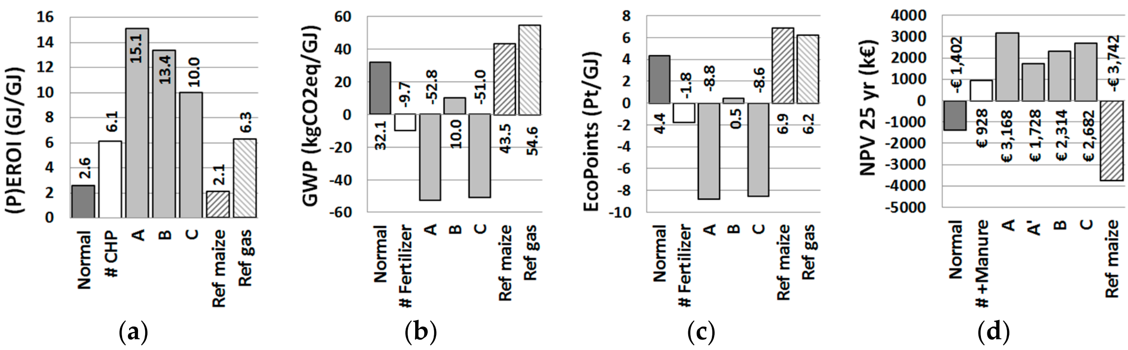


Figure 4. (**a**) Efficiency of the symbiotic system; (**b**) GHG emission of the symbiotic system; (**c**) The environmental impact of the symbiotic system; (**d**) Efficiency Net Present Value of the symbiotic system.

Whereas the impacts of individual improvement options are relatively minor, results from the symbiotic scenarios indicate that a symbiosis of improvement options can substantially improve all SI indicators compared to the reference scenarios, (Figure 4). Internal energy production substantially improve the (P)EROI in all scenarios, with additional improvement in scenario A and C due to the high energy needs of organic fertilizer production (Figure 4a). For both scenarios A and C, the effect of fertilizer replacement is larger than the produced impacts in the biogas pathway, resulting in negative carbon footprint and environmental impacts (Figure 4b,c). In contrast, the actions taken in scenario B reduce the carbon footprint by 69% and environmental impact by 89% (Figure 4b,c), highlighting the effect of fossil fertilizer replacement. Furthermore, scenario C indicates that only operating a CHP unit combined with fertilizer production is sustainable and profitable, suggesting the option for modification of current CHP operated AD systems (Figure 4d). Finally, the NPV for all scenarios are positive, with scenario A being most profitable due to the combination of internal energy production and the production and selling of organic fertilizers (Figure 4d). However, economic success is strongly dependent on possible utilization and added value of digestate: If, for instance, in scenario A, the organic fertilizers cannot be used for replacing fossil fertilizer or sold, the NPV will become negative. Also, if in scenario B more than 65% of the digestate has to be discarded at 10 €/Mg (Average rate in the Netherlands 2010–2016 [19]), the NPV will turn negative.

5.2. The Theoretical Cooperative Farming Cases

Within the theoretical case, focus is placed on combining the circular symbiotic AD system with current farming practices in a cooperative setting. Current farming practices, incorporated in the reference case (REF), include: fossil energy use (e.g., electricity, natural gas) for powering machinery and heating, fossil fuel use (e.g., diesel) for powering machinery, and fossil fertilizer use for nutrient replacement (Figure 5). Results indicate that internal production of energy, transport fuel, and organic fertilizers within a cooperation of farms operating a circular symbiotic AD system can significantly lower energy consumption, environmental impact, and yearly costs (Figure 6).

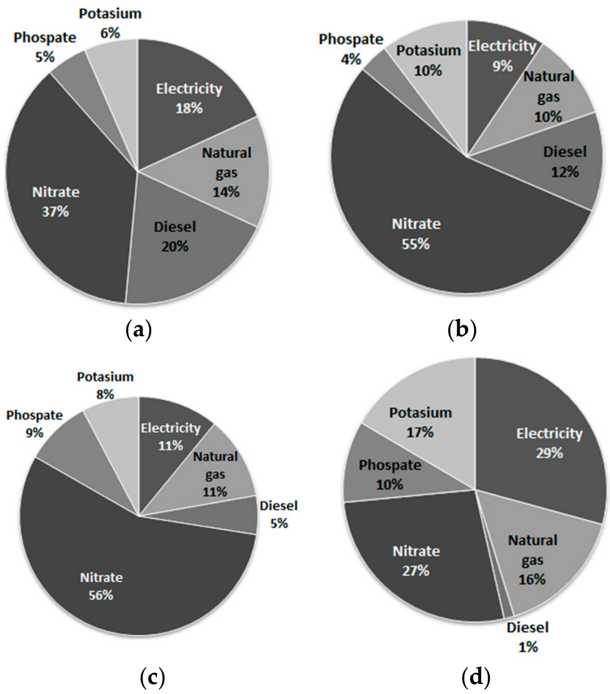


Figure 5. (**a**) Shares within total energy use REF case; (**b**) Shares within total GHG emission REF; (**c**) Shares within total environmental impact REF case; (**d**) Shares within total costs REF case.

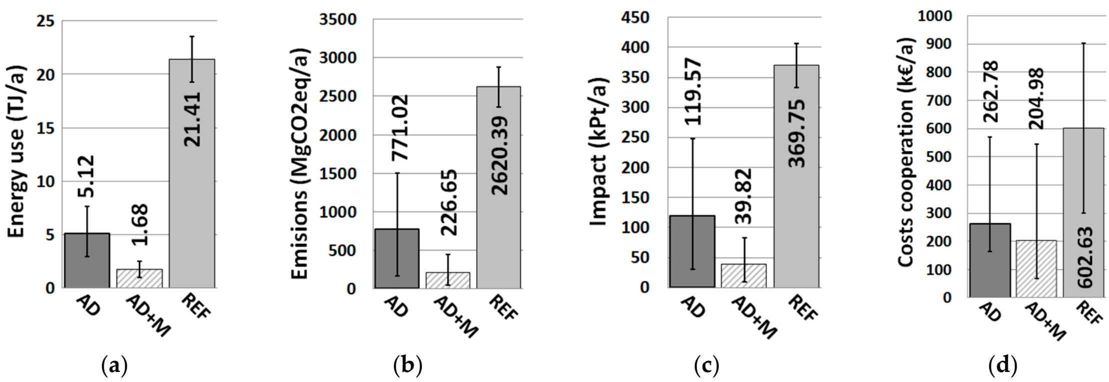
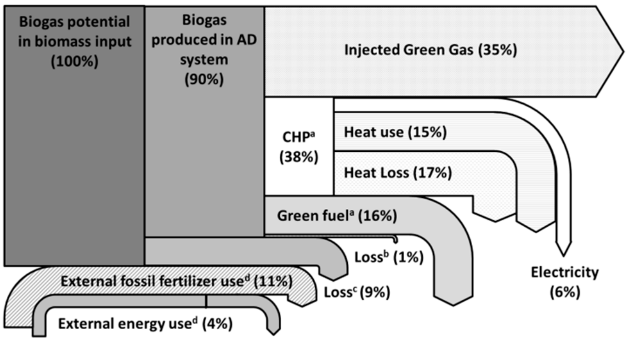
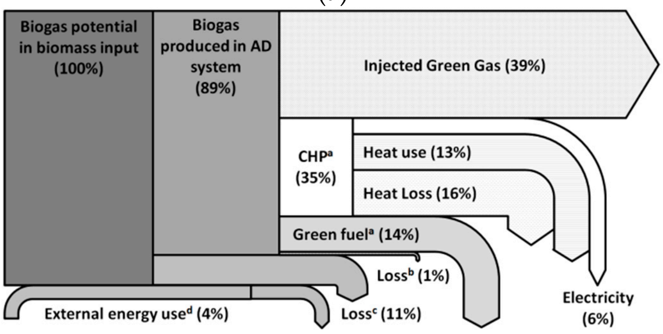


Figure 6. (**a**) Energy use cooperation; (**b**) GHG Carbon footprint cooperation; (**c**) Environmental impact cooperation; (**d**) Yearly costs NPV cooperation.

Energy use in the shape of electricity, diesel, gas and the production of fertilizers can be reduced by 72% in the AD case, and up to 92% in the AD + M case, as compared to the REF case (Figure 6a). The biggest reduction in energy use can be achieved through the replacement of fossil energy sources (e.g., electricity, natural gas, diesel), closely followed by fossil fertilizers that require significant amounts of energy during production (Figure 5a). However, to substitute the fossil energy sources and produce organic fertilizer, around 52% of the produced biogas is used internally within the AD case, and around 49% in the AD + M (Figure 7). The AD + M case produces more biogas due to the added manure in the second digester and, therefore, uses relatively less biogas internally (Figure 7b). Due to internal energy production and fossil energy replacement, external energy demand within both cases is minimal, mostly in the shape of embodied energy (e.g., installations and infrastructure, steel, concrete, etc.), (Figure 7). However, due to insufficient manure availability in the AD case, fossil fertilizers have to be used (Figure 7a).



(a)



(b)

Figure 7. (**a**) Sankey diagram of energy flows for AD scenario; (**b**) Sankey diagram of energy flows for AD + M scenario. [a] All energy produced by the CHP and green fuel systems is used within the cooperation; [b] The leakage loss still occurring from the biogas production and CHP and green gas utilization pathway; [c] Losses during feedstock transport, handling, storage, and leakages of feedstocks; [d] Energy requirement from outside of the system (e.g., energy, materials).

The carbon footprint can be reduced by 71% in the AD case up to and 91% in the AD + M case, while the environmental impacts can be reduced by 68% and 89% respectively, compared to the REF case, (Figure 6b,c). The biggest emission sources in the REF case are the production of fossil fertilizers (Figure 5b,c). Therefore replacing fossil fertilizers with organic fertilizers has a significant effect on the carbon footprint. Within this context, the availability of excess manure feedstock for processing and upgrading into organic fertilizer used for fossil fertilizer replacement has a substantial effect on energy use, carbon footprint, and environmental impact (Figure 6a,c). Therefore, when looking to reduce energy and impact of farming practices, a spatial distribution of dairy, agricultural, and pig and chicken farms in close proximity working closely together within a cooperation could be suggested. Unfortunately, currently the use of organic fertilizers replacing fossil fertilizers is not allowed by the European Union [55]. There are, however, exceptions made within the Netherlands for some companies [56]. Without the replacement of fossil fertilizers the carbon footprint and environmental impact can only be reduced by a maximum of 31% in the AD case and 27% in the AD + M case, compared to the REF case (Figure 5b,c). Additionally, the remaining green gas is injected into the national grid (Figure 7) replacing natural gas and further reducing carbon footprint and environmental impacts indirectly. This effect is not included within the AD or AD + M case as it does not lower the carbon footprint and environmental impact of farming practices. However, the avoided impacts are still significant and can be included on a national scope (Table 7).

Table 7. Possible mitigation of energy, carbon footprint, and environmental impacts per year through replacement of natural gas with green gas.

SI-Indicator	AD	AD + M	Unit	Source
Energy [a]	13.6	17.5	TJ/a	[58,59]
Carbon footprint [a]	642	826	$MgCO_2eq/a$	[58,59]
Impact [a]	73	94	kPt/a	[58,59]

[a] Based on Groningen natural gas including production with 40.6 MJ/Nm^3, 1.92 $kgCO_2eq/Nm^3$, and 0.22 Pt/Nm^3 [58,59].

Yearly costs can be reduced by 56% in the AD case and 66% in the AD + M case compared to the REF scenario (Figure 6d). The biggest reductions and economic gains can be achieved when a surplus of manure feedstock is available for processing and upgrading into organic fertilizer used for fossil fertilizer replacement (Figure 7d). However, the effect of additional manure input has less impact on cost reductions than when looking to the other SI indicators, which can be traced back to the higher initial investment needed in the AD + M case and the higher operational and maintenance costs compared to the AD case. Initial investment costs are substantial ranging from 3.1 million € for the AD case up to 3.9 million € for the AD + M case. Another important cost reduction is the selling of green gas. After internal consumption the remaining green gas (around 35% in the AD case and 39% in the AD + M case) is sold and injected into the gas grid lowering the yearly costs (Figure 6).

Additionally, within the local setting of this article, the cooperation can become a local handler of organic waste streams and also a supplier of green fuel, green energy (e.g., electricity, gas, heat), and organic fertilizer. For instance, green gas and/or excess heat could be used locally to balance the electricity grid, heat buildings, and help integrate intermittent energy sources (e.g., solar PV, wind). Within this context, heat losses from the CHP unit (Figure 7) could be used in heating surrounding buildings with district heating. When selling heat to external consumers, energy saving options (e.g., insulation, heat recovery) become viable, where now in the AD and AD + M cases there is excess heat. Unfortunately, regulations on green fuel and fertilizer use and subsidies for circular symbiotic systems are currently unclear. Unstable policies combined with a significant investment and operational costs place substantial risks on the business case. Therefore, to support a stable business case over the economic and technical lifetime of the circular symbiotic AD system, focused and stable policies, improved regulation, and strong cooperation must be initiated to achieve the above results.

5.3. National Scope

When applying the concept described in the theoretical case to the agricultural sector in the Netherlands, the targets set by the Dutch agricultural sector can be achieved for the 25% AD + M case (Table 8). Also, the additional production of green gas could supply the whole agricultural sector with electricity and heat. However, part of the energy and emissions saved within the cases are outside of the agricultural sector: For instance, the production of fertilizers and the mitigation of green gas. Also, within the theoretical case, the energy use and carbon footprint from electricity and fuel production are taken into account, where the carbon footprint from the agricultural sector is often only linked to direct use and emissions. Furthermore, within the total carbon footprint of the agricultural sector, the service sector and other agricultural activities are included (e.g., offices, greenhouses), which are not incorporated in the cooperative case. Overall, by fully utilizing the manure and other biomass waste streams, in a circular symbiotic AD system producing energy, green fuel, and organic fertilizer, the energy efficiency, carbon footprint, and environmental impact can be improved upon. Within this context, the circular symbiotic approach can optimize the AD system and help the agricultural sector to become more sustainable and profitable.

Table 8. National possible saved emission and mitigated fossil energy compared to reference years 2015 and 1990.

	Reference Year 2015 [a]		Reference Year 1990 [b]	
	AD	25% AD + M [c]	AD	25% AD + M [c]
Total emission savings	**33.4%**	**37.5%**	**27.1%**	**30.4%**
AD cooperative	24.8%	26.6%	20.1%	21.6%
Sold green gas	8.6%	10.9%	7.0%	8.8%
Total fossil fuel saved	**79.8%**	**98.6%**	**87.3%**	**104.9%**
AD cooperative	43.5%	52.7%	47.0%	55.6%
Sold green gas	36.3%	45.9%	40.3%	49.3%

[a] Carbon footprint and energy use Dutch farming sector 2015, respectively 26.7 Tg and 133.9 PJ [57]; [b] Carbon footprint and energy use Dutch farming sector 1990, respectively 32.9 Tg and 142.9 PJ [57]; [c] MAX national scope case exists of 75% AD case and 25% AD + M case, taking into account manure surplus in the Netherlands.

5.4. Sensitivity Analysis

Using organic material in a biological process and uncertainties surrounding business cases inherently creates variations and sensitivities. When comparing scenarios, similar settings will cancel out sensitivities in the used values. This approach has been applied to the symbiosis scenarios (Sections 4.1 and 5.1). Sensitivities connected to biomass use within the aforementioned scenarios are described in Pierie et al. 2015 [17]. However, in the cooperative scenarios (Sections 4.2 and 5.2) the results will be more prone to sensitivities as compared with a reference farm in more absolute terms; therefore, focus is placed on these results. The most sensitive values regarding the feedstocks (e.g., biogas potential, methane potential, organic dry matter content, and environmental impacts of the collection and/or cultivation process), are retrieved from Pierie et al. 2015 [17] (Appendix B). The results indicate that within the range of the indicators given, even the worst-case improvement scenario has less impact than the reference scenario (Figure 6a,c). Within the economic variables, biogas production, maintenance, and interest are most dominant. When combined, the sensitivity of all SI indicators varies substantially (Appendix B); in this case scenarios may perform better or worse than the reference scenario (Figure 6d). For instance, in the worst case, projected costs for the cooperation exceed the best case of the reference farms, indicating some risks in the business case. However, for this to happen a combination of circumstances working with or against the process is needed (e.g., bad harvest, high energy use harvest, low methane yields of crop, low market prices, and weak regulations).

6. Discussion

Energy production through AD is a promising method for producing a renewable and flexible energy carrier. However, the reference scenario used in this article only indicates a minor reduction in carbon footprint and environmental impacts and a low efficiency with a negative NPV for farm scale AD installations within the Netherlands. Furthermore, results also indicate that the AD system is not fully optimized in combination with farming practices regarding sustainability. Implementation of the single improvement options individually has a positive impact on the SI indicators (i.e., energy use, carbon footprint, environmental impacts, and costs). However, the reduction achieved by individual improvement options is often substantial for only one or two of the four SI indicators. For instance, organic fertilizer production positively affects the carbon footprint and environmental impact but negatively affects the (P)EROI and NPV; this is caused by high energy use in the process, substantial initial investment costs, and additional operational costs in the shape of energy and maintenance. Given the systemic nature of agricultural systems, focusing on single factors does not necessarily lead to optimal solutions. Using a circular symbiotic system of improvement options, however, can substantially improve all SI indicators, making the system profitable over a lifetime of 25 years. Therefore, when implemented within the theoretical cooperative farming case, the symbiotic AD system can significantly lower external energy consumption by 72 to 92%, carbon footprint by 71 to 91%, environmental impacts by 68 to 89%, and yearly expenditures by 56 to 66% compared to a reference cooperation. Sensitivity analysis indicated stable results regarding efficiency, carbon footprint, and environmental impact, but high variation in the economic results. Therefore, the economic assessment requires more research. Economic success and also the reduction of emissions and environmental impacts within the cooperative case are strongly dependent on the availability of manure and making use of the added value from the digestate. Therefore, a spatial distribution of dairy, agricultural, and pig and chicken farms in close proximity working closely together could be suggested. Unfortunately, existing laws prevent the use of organic fertilizers to replace fossil fertilizers in the Netherlands. However, without fertilizer replacement a circular symbiotic system can still be created which produces positive results for all SI indicators. Within the cooperative case, approximately half of the produced energy is used internally; the remaining green gas, electricity, and/or heat can be sold and used locally to replace fossil energy sources and help integrate other intermittent energy sources in the local energy grids. Applying the aforementioned circular symbiotic AD systems can lower the environmental impact of farming by decreasing dependence on fossil-based energy and fertilizers and lowering the carbon footprint from farming, helping the Dutch agricultural sector in achieving their stated environmental goals. However, to achieve the aforementioned goals, focused and stable policies, improved regulation, and strong cooperation must be initiated, as regulations on green fuel and organic fertilizer use and subsidies for circular symbiotic systems are currently unclear within the Netherlands and the European Union.

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Conflicts of Interest: To the authors knowledge there in no conflict of interest steering the results in any way shape or form towards benefits of stakeholder.

Nomenclature

AD	Anaerobic Digestion
CHP	Combined Heat and Power
oDM	Green Dry Matter
PJ	Peta Joule (10^{15} Joule)
GJ	Giga Joule (10^{9} Joule)
MJ	Mega Joule (10^{6} Joule)
Tg	Tera gram (10^{6} Mg)
Mg	Mega gram (equivalent to metric ton)
SI	Sustainable Indicator
GHG	Green House Gasses
(P)EROI	Process Energy Returned On Invested

GWP100	Global Warming Potential 100 year scale
Pt	Environmental impact in EcoPoint
LCA	Life Cycle Analysis
aLCA	Attributed Life Cycle Analysis
kgCO_2eq	Kilograms of Carbon dioxide equivalent
Nm^3	Normal cubic meter (Volume at 1bar 0C)
NPV	Net Present Value

Appendix A. Individual Improvement Options

The individual improvement options and their location within the AD system indicated in Figure A1 and explained Table A1 using corresponding numbers.

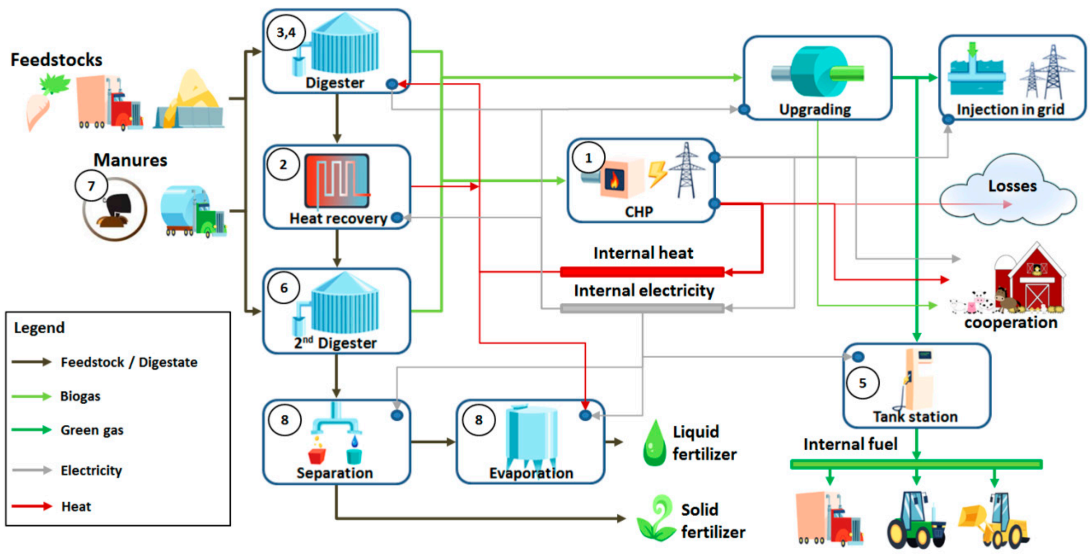

Figure A1. The optimized AD system for use in the sustainable farming concept.

Table A1. Main improvement options.

Nr.	Affiliation	Description of Improvement Option
(1)	CHP	A Combined Heat and Power unit (CHP) is used to produce electricity and heat [17] to fulfill the energy demand of the complete AD system (e.g., digester, green gas production, digestate upgrading). Cables and pipelines are incorporated for transportation to the AD production processes [17]. Additional heat requirement not supplied by the CHP is produced by the biogas boiler. In the case of overproduction electricity is put on the local electricity grid and heat is discarded.
(2)	Recovery	The main digester operates at a mesophilic temperature of around 35 to 48 degrees Celsius; outgoing digestate will be at the same temperature. Therefore, heat energy in the outgoing digestate can be utilized through a heat exchanger to heat up the ingoing feedstocks at ambient temperature fed into the digester. Infrastructure and energy use for heat recovery is taken into account (Appendix B Table A3).
(2)	Heat pump	Additionally, a heat pump can be added to the Heat recovery system aforementioned
(3)	Insulation	Insulation of the main digester will lower the heat loss from the main digestion tank, which operates at mesophilic temperatures. Therefore, biogas can be saved resulting in more green gas finally produced. Insulation will bring with it additional capital expenditure and embodied energy but will also reduce the heat demand of the process. Heat requirement of the main digester is lowered with 20% to simulate the effect of insulation on the SI indicators.

Table A1. *Cont.*

Nr.	Affiliation	Description of Improvement Option
(4)	Prevention	Gas leakages can be prevented through the use of repair and higher greenhouse gas emissions (e.g., methane) can be reduced using catalytic conversion lowering the carbon footprint. Repair focuses on actual leaks in biogas equipment such as the main and second digester, piping, upgrading installations. Catalytic conversion focuses on outputs from upgrading or combustion, which often contain methane or Nitrogen oxides, which are brought back to CO_2 level using catalytic conversion. Within this improvement option, losses and emissions from the main digester and second digester are eliminated and higher greenhouse gas emissions from the green gas utilization pathway and CHP unit are reduced to carbon dioxide level.
(5)	Green fuel	Green gas produced by the AD plant is used as fuel for agricultural machinery ranging from tractors, front loaders, and trucks transporting the biomass, replacing the use of fossil fuels (e.g., diesel). To achieve the aforementioned, infrastructure in the shape of a filling station is needed [60] which compresses the green gas and stores it in large enough quantities to fill several tanks (Appendix B Table A3).
(6)	2nd digester	Processed digestate still contains some biogas potential [52]. However, it is often not efficient and economical to retain this using the main digester, as it is kept at mesophilic temperature and is stirred continuously. Within this context, a second digester (not heated and often stirred) can be used to store the digestate and collect the residual biogas production. The longer retention time in the second digester (up to 5 to 6 months) gives the AD process additional time to break down the last remaining digestible organic material into biogas. Infrastructure and energy use is taken into account (Appendix B Table A4), also including the biogas potential of digestate which is based on an average number, as digestate composition is dependent on the feedstocks use in the digester (Appendix B Table A4).
(7)	+Manure	Due to overabundance and low quality, the available manure is often not fully utilized. Manure can be directly pumped in the second digester to retain the produced biogas to replacing seasonal manure storage during winter or mix it with the digestate for utilization in fertilizer production. This technology can also produce additional environmental benefits, which can be mitigated. A maximum of 10,000 Mg of additional manure is added directly to the second digester. Infrastructure and energy use is taken into account (Appendix B Table A4). For determining the biogas production of the additional manure the biogas potential of manure is used (Table 1).
(8)	Organic fertilizers	Within this improvement option, a large share of the digestate (80%) is separated into a thick and a thin fraction using a manure separator [61]. The thin fraction is rich in nitrogen and contains most of the water, whereas the thick fraction contains most of the phosphates, potassium and organic materials. The thin fraction is processed using reversed osmosis to decrease the water fraction [56,62]. The processed and upgraded thin and thick fractions are used as organic fertilizers on the farm replacing fossil fertilizers (Table 5). The remaining 20% of the digestate is used for replacing manure fertilization on the pasture; however, this will not replace fossil fertilizers. The needed infrastructure and energy use of the installations is taken into account.
(8)	Selling fertilizers	Organic fertilizers can also be sold on the market when own demand is fulfilled, unfortunately for lower prices. Within this improvement option all the organic fertilizer produced is sold on the market (Appendix B Table A3).

In the following figures the impact of the individual improvement options on the SI indicators are indicated, the affiliations used to express the results in the figures will use the description in Appendix A Table A1. The normal scenario in the graphs describes the basic AD green gas production pathway without any modifications as described in Section 4.1.

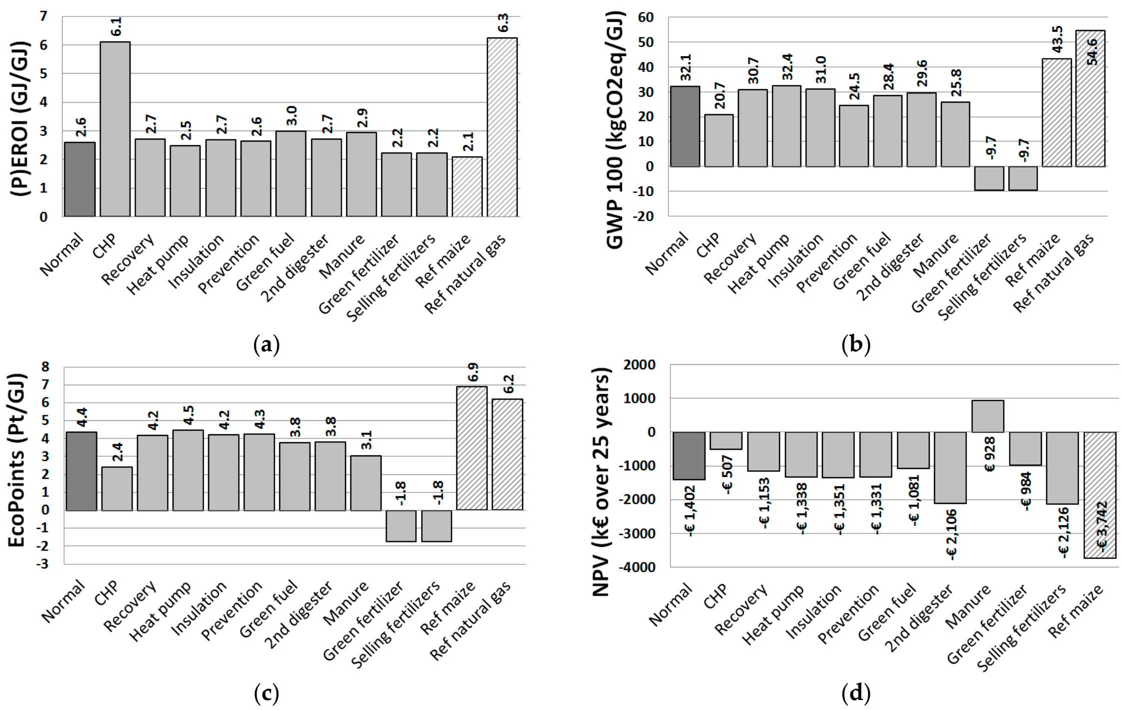

Figure A2. (**a**) The (P)EROI of the improvement scenarios; (**b**) The carbon footprint of the improvement scenarios; (**c**) The environmental impact of the improvement scenarios; (**d**) The NPV of the improvement scenarios.

Appendix B. Additional Data Used in Article

Table A2. The main economic values used in the calculation of the NPV.

Main Economic Values	Value	Unit	Source
Interest on loan and Required rate of return	5	%	[53]
Inflation	1.8	%	[63]
Increase of electricity and gas price per year [a]	2	%	[64]
Economic write off period	15	Years	
CAPEX Main installation	Value	Unit	Source
AD system	53.64	€/(Mg/a capacity)	[18]
Feedstock pre-treatments systems	3.00	€/(Mg/a capacity)	[65]
Upgrading system	4024.88	€/(Nm^3/hr capacity)	[18]
Green gas injection system	550.00	€/(Nm^3/hr capacity)	[18]
Scrap value installation after 25 years	5%	%/CAPEX	[66]
OPEX	Value	Unit	Source
Operation and maintenance	5	% Investment/a	[18]
Tax on products	6	%/costs resource	[67]
Income tax	25	%/costs resource	[68]
Transport by truck	0.05	€/ton.km	[18]
Electricity from grid	0.19	€/kWh	[57]
Natural gas from grid [c]	0.53	€/Nm^3	[57]
Diesel fuel	1.40	€/L	[50]
INCOME GREEN GAS [b]	Value	Unit	Source
Green gas market price [c]	0.020	€/kWh	[42]
SDE Subsidization (12 years)	0.076	€/kWh	[42]
SDE extended (additional 12 years)	0.067	€/kWh	[42]
Correction fee SDE Subsidization (12 years)	0.022	€/kWh	[42]
Correction fee SDE extended(12 years)	0.022	€/kWh	[42]
INCOME GREEN ELECTRICITY [b]	Value	Unit	Source
Green electricity market price	0.025	€/kWh	[42]
SDE Subsidization (12 years)	0.114	€/kWh	[42]

Table A2. *Cont.*

Main Economic Values	Value	Unit	Source
SDE extended (additional 12 years)	0.101	€/kWh	[42]
Correction fee SDE Subsidization (12 years)	0.032	€/kWh	[42]
Correction fee SDE extended (12 years)	0.033	€/kWh	[42]
CAPEX improvements	Value	Unit	Source
Heat recovery digestate	25	€/kWth	
Heat recovery with heat pump system	200	€/kWth	
Insulation of the AD system	4000	€/% improvement	
Second digester/manure storage	90	€/m^3 (storage capacity)	[50]
CHP unit	946.16	€/kWe	[69]
Digestate separation unit	1.45	€/(m^3 digestate/a)	[61]
Digestate upgrading system (reversed osmosis)	30	€/(Mg/a capacity)	[56]
Fueling station (approx. 4–8 trucks, tractors per day)	75,000	€/(20–40 GGE/day)[d]	[70]

[a] The Increase of electricity and gas price per year is assumed based on [64] as the marked is very volatile and the price dependents on many factors; [b] The subsidy is determined by the SDE subsidies minus the correction fee; [c] Based market price gas of 12.5 €/MWh. Groningen natural gas and green gas have an higher energy content of 35 MJ/Nm^3 or 9.7 kWh/Nm^3; [d] GGE/day = Gallons of Gasoline Equivalent per day.

Table A3. The main values of the added technologies.

Added Technologies	Value	Unit	Source
Efficiency heat exchanger	90	%	
COP value heat pump	5		[71]
Energy requirement second digester	5	MJ/Mg FM	
Energy requirement separator [a]	4.68	MJ/Mg FM	[72]
Energy use reversed osmosis	35	MJ/Mg FM	[56]
Energy use filling station [b]	4.68	MJ/Nm^3	[60]

[a] Based on an electric separator [72]; [b] INTERMECH BBR/FBR/VIP CNG compressors 55–450 kW/75–600 HP [60].

Table A4. Main values for production of fossil fertilizers replaced by upgraded digestate.

Fertilizers Replaced	Nitrogen as N	Phosphate as P_2O_5	Potassium as K_2O	Units	Source
Market price fossil fertilizer	1.10	1.05	0.65	€/kg	[50]
Market price organic fertilizer	0.60	0.51	0.26	€/kg	[73]
Required energy for production	75.90	27.9	12.9	MJ/kg	[58,59]
Emission during production	12.60	2.22	2.30	kgCO_2eq/kg	[58,59]
Environmental impact during production	1.77	0.76	0.24	Pt/kg	[58,59]

Table A5. Scenarios used within the sensitivity analysis of the more sustainable farming cooperation cases.

Variable in Scenario	Worst	Ave	Best	Source
Percentage	%	%	%	
(P)EROI	57.18%	100.00%	149.02%	[17]
Emission	194.16%	100.00%	21.74%	[17]
Impact	207.00%	100.00%	25.51%	[17]
Total investment	120.00%	100.00%	80.00%	
Salvage value	0.00%	5.00%	10.00%	[50,66]
Biogas production	57.18%	100.00%	149.02%	[17]
Interest	6.00%	5.00%	2.00%	
Taxation on internal use	21%	6%	0%	[67]
Discarding digestate	50.00%	0.00%	0.00%	
Fertilizer price	150.00%	100.00%	50.00%	
Maintenances	7.00%	5.00%	3.00%	

Table A6. Energy and fertilizer use average Dutch dairy and agricultural farm.

Energy or Material Flow	Dairy Farm	Agricultural Farm	Natural Areas	Unit	Source
Total land use the Netherlands	956,000	995,756	?	ha	
Diesel use	130	238	-	L/ha.a	[50]
Electricity use	940 [a]	549	-	kWh/ha.a	[50]
Natural gas use	32 [a]	10	-	Nm^3/ha.a	
Water use	80 [a]	10	-	m^3/ha.a	[50]
Nitrate cap	265	170	?	kg/ha.a	[50]
Phosphate cap	95	65	?	kg/ha.a	[50]
Potassium cap	225	225	?	kg/ha.a	[50]

[a] Based on two cows per hectare of land producing 8500 kg of milk per year [50]; [b] Based on average agricultural farm of 40 ha [57] KWIN table p. 57.

Appendix C. Main Calculation Output National Case

Table A7. Carbon footprint and energy reduction of cooperative cases compared to Dutch carbon footprint and energy use in 2015.

Energy or Material Flow	Total NL [a]	Farming [a]	AD + M	AD	Unit
Carbon footprint	193.7	26.7	18.1	20.1	Tg
Carbon footprint green gas			23.8	24.4	Tg
Energy	2206.0	133.9	63.4	75.7	PJ
Energy green gas			72.4	85.3	PJ

[a] Carbon footprint and energy use retrieved from Dutch Central Bureau of Statistics [57].

Table A8. Carbon footprint and energy reduction of cooperative cases compared to Dutch carbon footprint and energy use in 1990.

Energy or Material Flow	Total NL [a]	Farming [a]	AD + M	AD	Unit
Carbon footprint	193.7	26.7	19.6	20.1	$TgCO_2eq$
Mitigation green gas			23.8	24.4	$TgCO_2eq$
Energy	2206.0	133.9	63.4	75.7	PJ
Mitigation green gas			72.4	85.3	PJ

[a] Carbon footprint and energy use retrieved from Dutch Central Bureau of Statistics [57].

Table A9. Carbon footprint and energy reduction of cooperative cases compared to Dutch carbon footprint and energy use in 2015.

Energy or Material Flow	Nitrogen	Phosphate	Source
Total nutrient production	497,500	180,100	[57]
Possible placement of nutrients [a]	377,000	134,300	[57]
Nutrient	120,500	45,800	
Percentage deposit	24.22%	25.43%	

[a] The possible placement of nutrients within the Netherlands is determined by the available land surface [57].

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