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Ecological and economic evaluation of biogas from intercrops

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Abstract

Background: Biogas made from main crops (e.g., corn) is commonly used for producing electricity and heat. Nevertheless, the production of energy from monocultures is highly unsustainable and not truly renewable. Since neither monocultures nor food competition are desirable, intercrops can be used to increase the yield per hectare instead of leaving agricultural fields unplanted for soil regeneration. The extra biomass can be used for biogas production. In a case study, the economic as well as the ecological feasibility of biogas production using intercrops, cattle manure, grass and corn silage as feedstocks for fermenters was analyzed.

Methods: The set-up for the case study included different feedstock combinations as well as spatial distributions of substrate supply and heat demand for modeling and optimization. Using the process network synthesis, an optimum structure was generated representing the most economical technology constellation which included transport of substrates, heat and biogas (when applicable). The ecological evaluation was carried out by using the sustainable process index method.

Results: The application of both methodologies to different scenarios allowed a constellation to be found which is economically feasible while entailing low ecological pressure. It is demonstrated that the production of intercrops for producing biogas has so far not been regarded as a viable option by the farmers due to a variety of barriers. Sensitization is needed to emphasize that planting intercrops holds many advantages like positive effects on soil regeneration and raised nitrogen fixation, as well as increased biomass output per hectare and, last but not least, it allows the production of energy without conflicts between food and energy production.

Conclusions: Using intercrops for the production of biogas has the potential to decrease the ecological footprint decisively while still offering opportunities in the lucrative biogas market. The transfer of know how regarding this option should be taken up by agricultural training.

Keywords: Decentralized networks, Biogas, Intercrops, Crop rotation, Process network synthesis, PNS, Sustainable process index, SPI, Ecological footprint

Background

Intercrops are planted in fields between the main crop periods of e.g., wheat, corn or triticale. A typical crop rotation could be a winter type of main crops (e.g., wheat, rape etc.) followed by intercrops during the regeneration period. After the intercrop has been harvested, the main crop period starts anew. In this study, different grass species (e.g., Sudan grass, ryegrass, cocksfoot), types of grains (e.g., rye, sorghum, buckwheat, triticale, oat), legumes (e.g., pea species, vetch, horse bean, crimson

clover, red clover, lucerne) and different oil seeds (e.g., sunflower, fodder radish, turnip rape) were used as examples for intercrops in corn fields [1].

The basic idea of using intercrops for energy production is twofold: using a biogenous feedstock which is strictly not in competition with the production of food, while at the same time using the nitrogen fixation potential of intercrops (via recycling biogas manure as well as by subsurface nitrogen fixation) to reduce the input of mineral fertilizer, to increase the yield per hectare, as well as to improve soil quality by humus rebuilding. Using less mineral fertilizer and achieving a higher overall yield per hectare (including the energy yield from

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intercrops) will result in lower overall ecological pressure of agricultural activities [2].

The case study, Bad Zell - a spa town in Upper Austria - forms the background for setting up the key parameters of a supply and demand chain of substrates and energy needed for biogas technologies. An important issue in this case is the inclusion of decentralized biogas production sites, a central heat demand (in the spa town) and a feed-in to the national electricity grid. This can be achieved using different structures, featuring e.g., several separated decentralized digesters that are linked by biogas pipelines to a central combined heat and power plant (CHP), using decentralized digesters serving their own CHP and providing a heat transmission to the site of heat demand or any combination of these. Additionally, some digesters may be especially equipped to utilize particular substrates or substrate combinations, leading to a necessity to transport substrates from the site of their generation to suitable digesters, which may be located further away.

This case study is the first one which tries to examine all effects of intercrops on sustainable energy production. It is part of a project called 'Syn-Energy I', in which intercrops were analyzed in detail. Field tests of different kinds of intercrops from this project were used to determine the dry mass yields for this paper. The project also included an analysis of the effects of intercrops on ground water, soil, nutrient management, as well as laboratory-scale biogas digester experiments for the estimation of the biogas potential of intercrops. The results concerning intercrop yields, biogas yields from these intercrops and the ecological impact of intercrop cultivation were applied to the case study of Bad Zell; the results also were used as database for the optimization the paper deals with [3].

Methods

Process network synthesis (PNS)

The setup for this case study included different feedstock combinations as well as spatial distributions of substrate supply and heat demand for modeling and optimization. Using the Process network synthesis (PNS), an optimum structure should be the outcome of the analysis. In a first step, a technology network is generated using the PNS [4-6]. This method uses the p-graph method and works through energy and material flows [7]. The available raw materials are turned into feasible products and services, while the inputs and outputs are unequivocally given by each implemented technology. Time dependency such as resource availability as well as product or service demand (e.g., the varying heat demand for district heating over the year) is part of the optimization. This method has already been applied to various renewable resource utilization cases, including

the optimal technology constellations for green biorefineries [8], the sugar industry [9] and animal residue utilization [10], to name a few.

The input necessary for this comparative modeling and optimization includes the mass and energy balances, the investment and operating costs for the considered technologies, the costs for resources and utilities, the cost of products and services, as well as the constraints regarding resource supply and product/service demand. The investment costs will be statically depreciated over a period of 15 years.

First, the so-called maximum structure is generated, linking resources with the demands (e.g., for heat) and the marketable products (e.g., electricity) via all feasible technological structures, including transport. From this starting point, the optimization is carried out resulting in an optimum structure representing the most economic constellation of technologies and logistical pathways linking the given resources with demands and market opportunities.

A discussion with regional decision makers pointed to three decentralized locations which were suitable for biogas production. In the spa town itself, it was impossible to implement a central location for digesters as it would infringe with touristic activity there. The heat needed in the town could be either generated by a centrally placed CHP with biogas transported via pipelines [11] from decentralized digesters or by decentralized CHPs used for digester heating and/or transported via transmission lines to the town. For the optimization, three digester sizes (with capacities serving 80 to 250 kW_{el} CHP) were available for biogas production. Four combined heat and power plant capacities (from 80 to 500 kW_{el}) were implemented in the maximum structure. The digesters could be heated by decentralized CHPs or by a biomass furnace on site [12]. In this case, the biogas could be transported to a central CHP.

The fermentation was modeled to use different substrate feeds. The available substrates for biogas production were cattle manure, corn silage, grass silage and intercrops. Dependent on the feedstock digester sizes, the costs and digestion times differed. Seven different feedstock combinations (and hence types of digesters) were part of the maximum structure to find the most lucrative method for a substrate input strategy. These feedstock combinations are shown in Table 1.

The availability of resources was held constant within an amount of 18% grass silage, 16% corn silage and 34% intercrops (referring to fresh weight (FW)) of the available cattle manure in the region being available. Farmers in the considered region were allocated to eight provider groups regarding their spatial situation. The substrate costs were assumed to be the same within each group. The provider groups differ in the amount of available

Table 1 Substrate feeds for fermentation

Feed (%)	Cattle manure	Corn silage	Intercrops	Grass silage
1	100	-	-	-
2	50	50	-	-
3	75	25	-	-
4	75	15	10	-
5	50	30	10	10
6	50	20	20	10
7	75	-	15	10

Seven different digesters were part of the PNS to find the most lucrative way of using the substrates. The feeds are shown in the above table.

resources as well as in the distance to each possible digester location, which directly correlates with the transport costs. Table 2 shows the total available amount of cattle manure in the region and the distances of each group to the three feasible biogas production locations.

PNS: maximum structure

In Table 3, the substrate parameters are described. The optimization was based on two different cost assumptions (maximum and minimum) concerning substrate supply.

Figure 1 shows the maximum structure for the PNS optimization, which includes all input and output materials, as well as the energy and material flows with their economic parameters such as the investment or operating costs and prices.

The transport costs included the fixed costs for loading and unloading and the variable costs which are dependent on the distance (including the unloaded runs). For solid substrates, fixed costs of 2 €/t fresh weight were assumed. Similarly, the conversion was carried out for the variable costs, which were assumed to be 0.49 €/km. Fixed transport costs for cattle manure with 20 €/t dry mass as well as variable costs of 5 €/t dry mass per kilometer were defined.

Transportation of heat and biogas could be achieved via pipeline networks. Grid operation energy demands as well as losses caused by transporting were taken into account for the heat and biogas lines. Regarding heat, it was assumed that the total produced heat amount could be used for district heating. As location 1 and 3 are in line with the spa town, one biogas pipeline could be used for both locations to transport biogas to a central CHP. Therefore, there would not be any additional costs for a biogas pipeline from location 1 to the town, as long as location 3, which is further away, supplied the center with biogas.

For silo management 150,000 € was allocated which can be seen as a value that is strongly dependent on the location (e.g., ground conditions, silo system used, etc.). Therefore, this number is variable and might differ from case to case.

The biomass furnaces to provide digester heating (in case biogas is transported to the central CHP units) were not implemented as a separate technology in maximum structure, but a price of 5 ct/kWh heat was assumed for heating. Electricity is fed into the national grid, thus benefiting from the feed-in tariffs according to the Austrian Eco-Electricity Act [13].

Sustainable process index

The second step included an ecological evaluation of the optimum PNS structure using the sustainable process index (SPI) [14]. Being an ecological footprint method, the SPI represents the resulting area needed to embed all necessary human activities (to supply products or services) into the ecosphere. The evaluation, itself, is based on comparing the natural flows with the human-induced flows and the natural qualities of the environmental compartments of soil, water (ground) and the atmosphere; the evaluation used solar radiation (driving all natural material cycles as well as providing a sustainable natural income to society) as a reference. The SPI results allow for analyzing ecological impacts

Table 2 Total amount of available cattle manure and provider distances to three locations in kilometers

Group	Available cattle manure (t DM)	Distances from the provider group to the possible fermenter locations (km)		
		Location 1	Location 2	Location 3
1	405.9	1.6	3.4	0
2	99.0	3.3	4.7	4.0
3	188.1	2.7	4.6	1.2
4	168.3	1.9	1.4	3.3
5	79.2	0.3	2.1	2.1
6	99.0	1.5	2.9	3.0
7	158.4	3.1	3.0	2.4
8	198.0	3.8	1.9	3.7

Table 2 includes the total amount of the available cattle manure and the distances of each group to the three locations that would be feasible for biogas production. t, tons; DM, dried mass.

Table 3 Substrate parameters

Parameters	Cattle manure	Corn silage	Intercrops	Grass silage
Dry mass content (%)	9	33	24	30
Substrate costs ^a minimum (€/t DM)	5	65	50	50
Substrate costs ^a maximum (€/t DM)	10	90	80	80
CH ₄ output (m ³ /t DM)	200	340	300	300

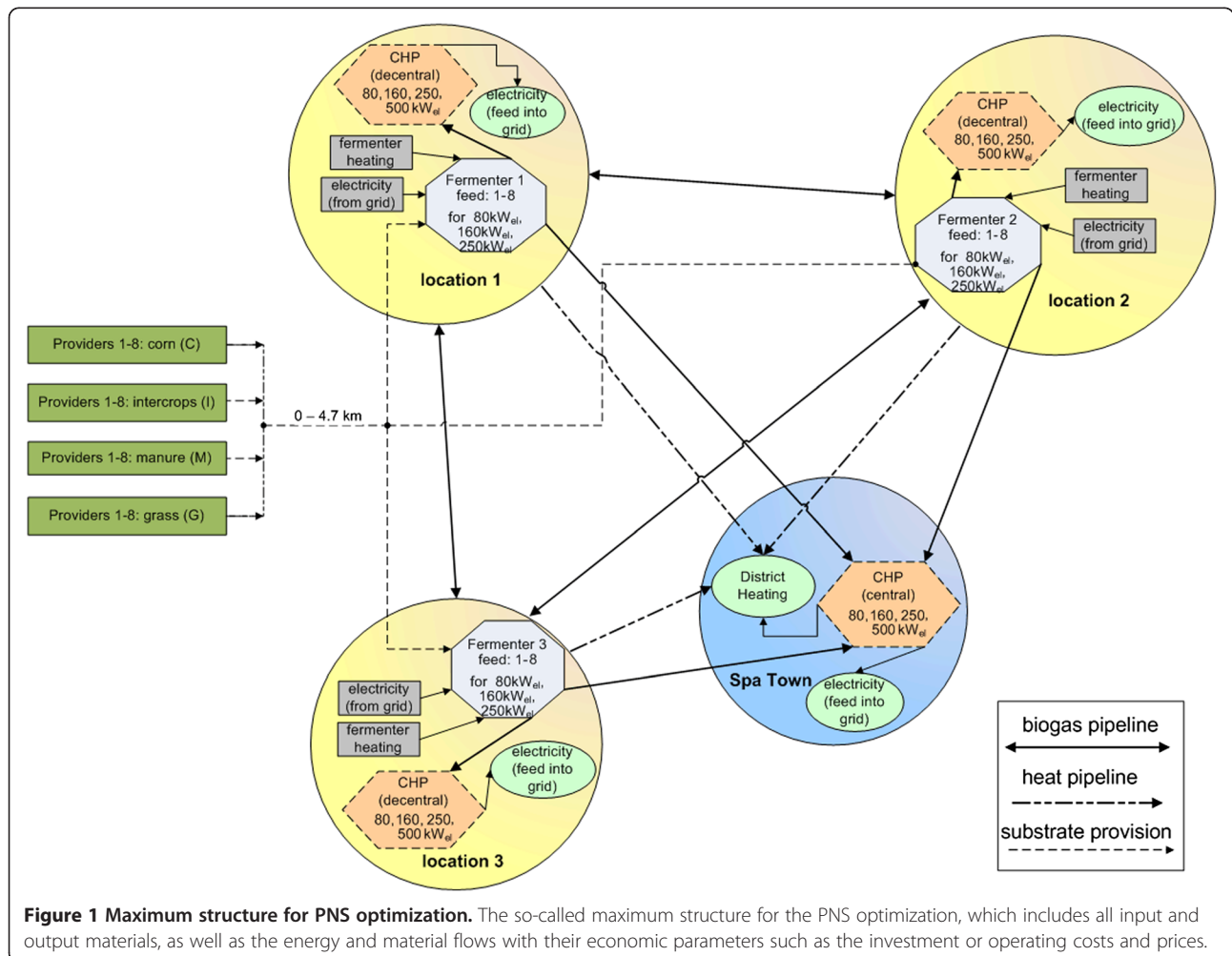
In Table 3, the substrate parameters are described. The optimization is based on two different cost situations (maximum and minimum) for substrate supply.
^aAll costs decided by regional actors. t, tons; DM, dried mass.

according to land use; the supply of renewable, non-renewable and fossil resources; as well as the emissions to water, air and soil.

Footprint calculations were performed using the free-ware SPIONEXCEL tool [15,16]. For a thorough discussion of the method, the reader is kindly referred to [15-17]. As the natural carbon cycle is included in the evaluation method as a reference flow, the SPI is well suited to compare technologies based on fossil and renewable resources. The SPI has, therefore, been applied to a number of ecological assessment tasks, especially for

evaluating technologies based on renewable resources [18-20].

Using the results of the SPI evaluation, the different options could be compared regarding their environmental impact. The optimum structure obtained by the PNS is not necessarily the technology constellation with the lowest environmental impacts. By comparing the different structures and taking the two parameters (revenue of the solution and ecological footprint) into consideration, a trade-off between the economic and the ecological advantages of different structures may be possible.



Results and discussion

PNS: basic optimum structure

The PNS optimization shows that the technology constellation providing the largest economic benefit only includes location 1 for biogas generation. On this site, biogas is produced using two different substrate feeds (6, 7 in Table 1). Therefore, two digester types are part of the optimum structure. As Table 1 demonstrates, both substrate feeds include intercrops. All provider groups can supply the digesters with at least one substrate. Figure 2 depicts the optimum structure for a situation with maximal substrate costs as listed in Table 3.

Both digesters have a size to supply a 250 kW_{el} CHP. The one with the higher amount of intercrops in the feed (f6) runs at full load, while the other (f7) runs at 96% of capacity. Altogether, around 1,116,300 m³ of methane (CH₄) can be produced. Around one-third of the biogas generated by digester f6 is used in a decentralized 160 kW_{el} CHP (51% capacity) on site, whereas the digester f7 fully supplies biogas via pipelines to a central CHP with a capacity of a 250 kW_{el}. The rest of the biogas produced by digester f6 is sent via pipelines to the center and runs a CHP of 160 kW_{el} in full load mode. In total, around 4,130 MWh heat per year can cover the district heat demand at a price of 2.25 ct/kWh. Both CHP units feed electricity into the national grid (approximately 3,830 MWh/year) at feed-in tariffs of 20.5 ct/kWh (see also Table 4).

Using this technology constellation and a 15-year depreciation period, a total annual profit of nearly 229,000 € can be achieved (interest rates are not included). The total input costs including electricity consumed from the grid add up to 236,000 €/year with an additional 68,170 €/year for transportation. The investment costs for this technology constellation are 2,805,800 €, including the district heating and biogas network as well as the costs

for the digesters, the CHPs and the other infrastructures needed.

The optimization using a minimum cost situation (see Table 3) results in the same optimum network structure as has already been shown in Figure 2. The costs for the substrates are lower (around 163,920 €/year). The profit increases to 301,000 €/year (without taking interest rates into account). Table 4 gives an overview of the monetary input and output parameters for both cost situations.

Scenario generation

Two scenarios were developed both for minimum as well as for maximum substrate cost situations: scenario 1 with a reduced maximum structure does not include corn availability (only feed combinations 1 and 7 are feasible in this scenario); scenario 2 used cattle manure as a substrate only. These scenarios rendered the following results:

Scenario 1

Biogas is produced only at location 1 with a total amount of 751,000 m³ CH₄ per year, using two digesters (both f7). A local 80 kW_{el} CHP covers the heat demand of the biogas digesters. In the town center, a 250 kW_{el} CHP runs with biogas produced at site 1. Figure 3 shows the optimum technology constellation for scenario 1.

The optimum structure of a scenario with a maximum substrate cost constellation provides a yearly profit of 119,460 € (again excluding the interest rates). If the substrate costs are set to minimum, the structure does not change, but the annual profit increases due to the lower material costs up to about 166,000 €/year. Table 5 compares the minimum and maximum substrate cost constellation for scenario 1.

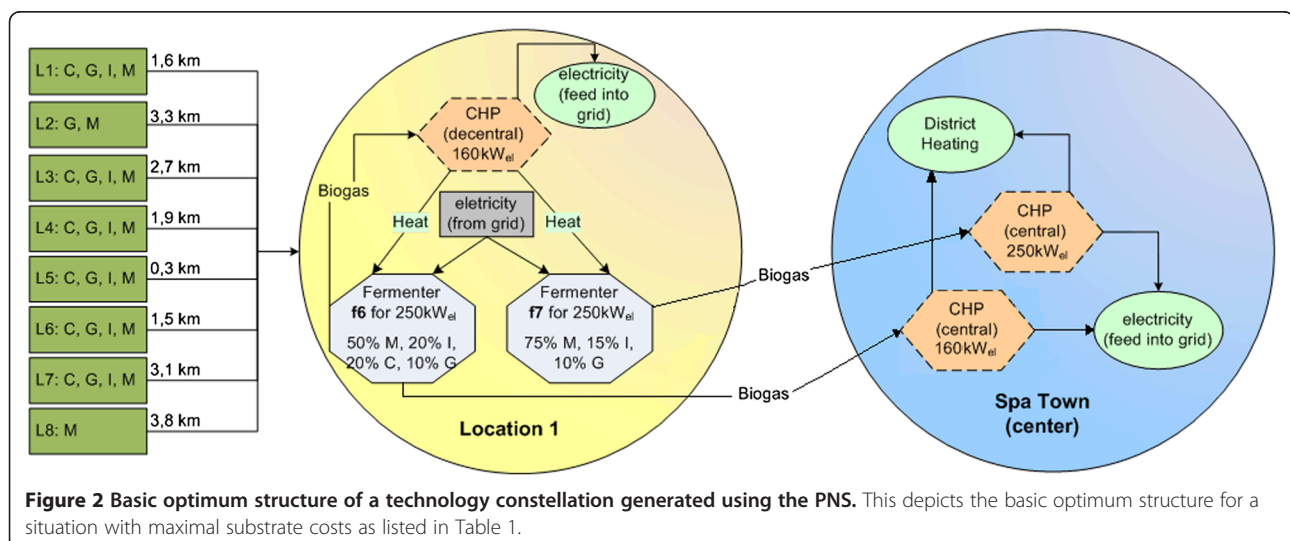


Table 4 Comparison of monetary parameters for minimum and maximum substrate costs

Depreciation period: 15 years	Minimum	Maximum	Capacity (%)
Total investment costs (1,000 €)			
Digester f6 250 kW _{el}	850.9	850.9	100
Digester f7 250 kW _{el}	1,075.6	1,075.6	96
CHP 160 kW _{el} location 1	200	200	51
CHP 160 kW _{el} central	200	200	100
CHP 250 kW _{el} central	250	250	100
Transformer	35	35	-
Silo management	150	150	-
Biogas pipelines	44.3	44.3	-
Total investment costs	2,805.8	2,805.8	-
Yearly depreciation (1,000 €/year)			
Yearly operating costs (1000 €/year)	187.1	187.1	-
Material costs			
Transport costs	129.5	201.6	-
Digester f6 250 kW _{el}	68.2	68.2	-
Digester f7 250 kW _{el}	37.8	37.8	100
CHP 160 kW _{el} location 1	37.8	37.8	96
CHP 160 kW _{el} central	23.3	23.3	51
CHP 250 kW _{el} central	23.3	23.3	100
Silo management	29.2	29.2	100
Electricity from national grid	5.9	5.9	-
Total operating costs (1,000 €/year)	34.4	34.4	-
Yearly profit (1,000 €/year)			
District heat 22.5 € × 4,134 MWh	389.4	461.5	-
Electricity feed in 205 € × 3,827 MWh	93.0	93.0	-
Total profit (1,000 €/year) ^a without depreciation and operating costs	784.4	784.4	-
Total profit (1,000 €/year) ^a	877.4	877.4	-
	300.9	228.9	-

Table 4 gives an overview of monetary input and output parameters for both cost situations (minimum and maximum, see Table 3). ^aWithout interest rates.

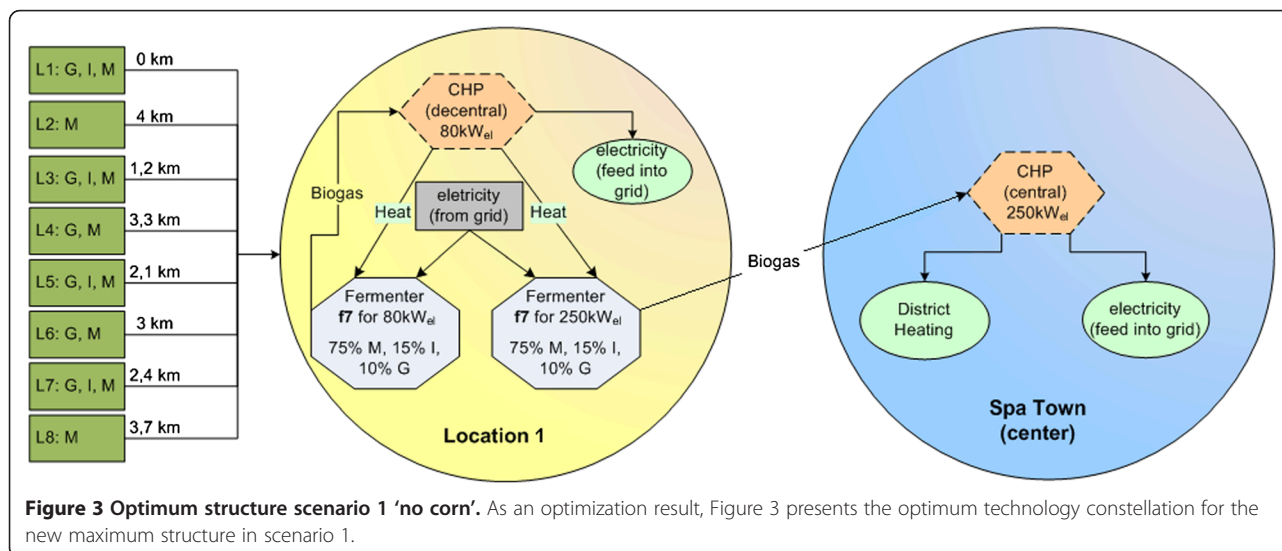


Table 5 Comparison of the results for minimum and maximum substrate costs for scenario 1

Depreciation period: 15 years	Minimum	Maximum	Capacity (%)
Total investment costs (1,000 €)			
Digester f7 80 kW _{el}	474.7	474.7	100
Digester f7 250 kW _{el}	1,075.6	1075.6	100
CHP 80 kW _{el} location 1	110	110	100
CHP 250 kW _{el} central	250	250	100
Transformer	35	35	-
Silo management	150	150	-
Biogas pipelines	44.3	44.3	-
Total investment costs	2,139.6	2139.6	-
Yearly depreciation (1,000 €/year)			
Yearly operating costs (1,000 €/year)	142.6	142.6	-
Yearly operating costs (1,000 €/year)			
Material costs	73.0	119.6	-
Transport costs	56.6	56.6	-
Digester f7 80 kW _{el}	27.1	27.1	100
Digester f7 250 kW _{el}	37.8	37.8	100
CHP 80 kW _{el} location 1	18.9	18.9	100
CHP 250 kW _{el} central	29.2	29.2	100
Silo management	5.9	5.9	-
Electricity from national grid	23.2	23.2	-
Total operating costs (1,000 €/year)	271.7	318.3	-
Yearly profit (1,000 €/year)			
District heat 22.5 € × 2,340 MWh	52.6	52.6	-
Electricity feed in 205 € × 2,574 MWh	527.7	527.7	-
Total profit (1,000 €/year) ^a without depreciation and operating costs	580.3	580.3	-
Total profit (1,000 €/year) ^a	166.0	119.5	

^aWithout interest rates.

Scenario 2

The input materials of the maximum structure (Figure 1) are dramatically changed. In scenario 2, only cattle manure is available as a substrate for biogas fermentation. With that, only feedstock 1 can be used to produce biogas and no silo management is needed.

The optimization shows that just location 1 is feasible for biogas fermentation. Biogas can be produced in a digester of a capacity to supply a 160 kW_{el} CHP (78.7% capacity). The produced biogas with an amount of 286,420 m³ CH₄ is used in a decentralized 160 kW_{el} CHP on site. The heat demand for the digester at location 3 is covered by this CHP. The rest of the heat (about 790 MWh/year) is sent via heat pipelines to the center where it is sold for a price of 22.5 €/MWh.

In this scenario with maximum substrate costs of 9 €/t dry mass, no profit can be gained. The optimum structure for scenario 2 results in a yearly loss of about 6,100 € (not including interest rates). If the substrate costs are set to minimum, the structure does not change but a little profit of about 900 €/year can be achieved.

Ecological evaluation

Any meaningful ecological evaluation requires a precise definition of the system boundaries. In this study, the evaluation of the field crops started at the point of crop sowing. Energy (especially fuel), fertilizer and pesticide input for all steps of cultivation (such as sowing, plowing and fertilizing), as well as the infrastructure of the technical equipment are included. For cattle manure, the system boundary includes the cattle as a manure producer, taking feed (wheat and grass) into account. Cattle are regarded as means to produce meat, milk and manure. An ecological pressure is assigned to these products by price allocation. A low footprint for manure results as the manure price is rather low (approximately 1 €/t FW) compared to the main product of milk (about 288 €/t FW). The intercrop evaluation is based on precise data from actual cultivation experiments during the project. A major part of the ecological footprint is caused by transport. In the structures described before the transport situation, the location for biogas plants is also location 1. But as presented in Table 2, the provider

distances differ depending on the location, whereas the substrate amounts differ depending on the scenarios, leading to considerably different ecological pressures due to transport. Table 6 provides an overview of the main parameters for SPI evaluation [21].

Table 6 shows that the structure with the largest economic benefit entails the highest ecological pressure. This is a result of the high amount of corn (with its high SPI value of 86,216 m²/t DM) used in this structure. The SPI values are dominated by machinery use (causing fossil fuel consumption and CO₂ emissions) and fertilizer use for growing corn. In scenario 1, the corn input is put to zero. This change decreases the SPI value considerably. Scenario 2 has the lowest SPI value because it uses only manure of a small footprint as the substrate (1,887 m²/t DM). This scenario, however, achieves little or no economic profit.

The amount of product differs widely between the scenarios with the 3,827 MWh/year electricity in the basic optimum structure: in scenario 1, the produced electricity decreases by one-third. In scenario 2, only 978 MWh/year can be fed into the grid. Accordingly, the material input varies and with that the SPI values. Figure 4 indicates the SPI per megawatt hour (MWh) electricity produced dividing each bar into the seven SPI sub-categories. The figure shows that the most important impacts resulting from the input of fossil resources were mainly caused by the fuel for the machinery, the fertilizers and the electricity use. The emissions to air and water are mainly due to the production of electricity based on fossil and nuclear materials.

Compared to the basic optimum structure (Figure 2), the two scenarios have a lower ecological footprint per MWh of electricity. But a disadvantage of scenario 1 and 2 is that more digesters or higher capacities are required to produce the same biogas amount compared to the basic optimum structure where corn silage can be used as the substrate. This does not really affect the ecological footprint, but it is also a reason for the decreased revenue of scenario 1 and 2 as the investment costs change.

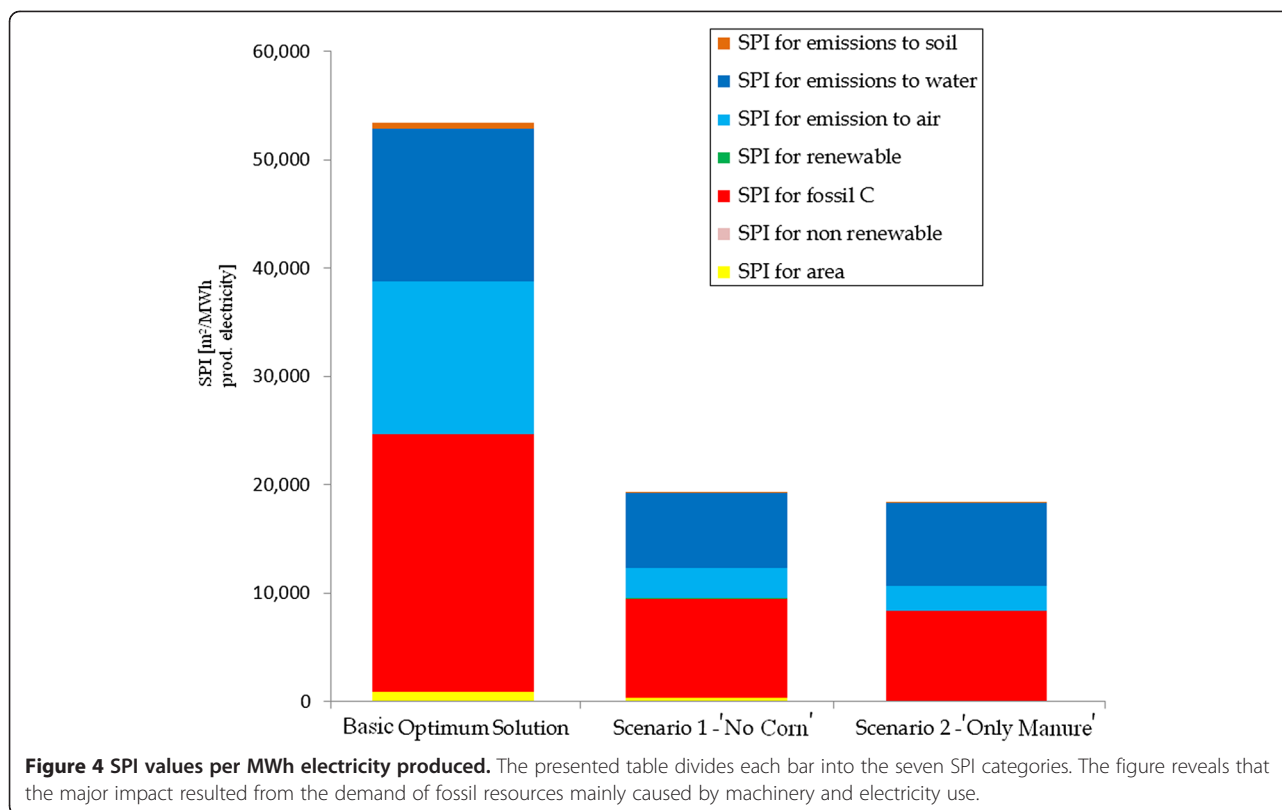
Social aspects

In general, the first reactions from actors regarding the production of intercrops show that the psychological barriers are of high importance: farmers expect low yields (as are common for intercrops) and, therefore, tend to disregard biogas production from intercrops. Because farmers have to put in additional effort and must adhere to strict timing, barriers to using intercrops are raised. Another aspect is that in order to fully benefit from intercrop cultivation via the production of biogas, large investments as well as close economic and operational co-operation between the farmers and other local actors is required. It seems like all these arguments and facts are speaking against implementing complex solutions. Therefore, it is even more important to raise awareness and to offer external incentives (e.g., funding) to convince the farmers of the fact that intercrops may contribute to a higher overall added value as the optimum structure clearly shows.

Table 6 Main parameters for SPI evaluation [21]

Yearly	Optimum	Scenario 1	Scenario 2
Corn silage (t DM/year)	537	0	0
Corn silage SPI (m ² /t DM)	86,216	86,216	86,216
Intercrops (t DM/year)	960	1,351	0
Intercrops SPI (m ² /t DM)	9,250	9,250	9,250
Grass silage (t DM/year)	711	375	0
Grass silage SPI (m ² /t DM)	7,640	7,640	7,640
Cattle manure (t DM/year)	1,393	895	931
Cattle manure SPI (m ² /t DM)	1,887	1,887	931
Electricity from grid (MWh/year)	230	154	37
Produced heat			
Total (MWh/year)	5,038	3,159	1,412
Out of that for district heating (MWh/year)	4,134	2,340	790
Electricity feed (MWh/year)	3,827	2,574	978
CHP capacity (kW _{el})	160; 160; 250	80; 250	160
SPI electricity (m ² /MWh)	53,437	19,305	18,327
SPI heat (m ² /MWh)	5,865	2,119	2,012
SPI total (km ²)	204.5	49.7	17.9

t, tons; DM, dried mass.



Conclusions

Ecological, economic and social sustainability aspects should be considered at the same time when new concepts are introduced to provide energy from bio-resources. Using the PNS to generate optimal constellations for linking resources with demands and the markets via integrated technologies, it has proven to be helpful to generate scenarios and evaluate them ecologically using an encompassing methodology, such as the SPI. The latter provided a clear picture regarding the interplay between ecological and economic factors. In this study, the applied approach highlighted the trade-off between ecology and the economy, best represented in Figure 4 where scenario 1 has been identified as the solution which optimizes economic as well as ecological benefits.

The social aspects will, however, be decisive for implementing innovative energy systems based on renewable resources. It was demonstrated that the production of intercrops for producing biogas so far has not been regarded as a viable option by the farmers due to a variety of barriers. Additional work and a strict time frame to cultivate their fields are the main counter-arguments in the discussion about intercrops, coupled with the necessity to a close cooperation and mutual dependency between farmers as well as between agriculture and other social actors on the local level. A rise in awareness is needed to emphasize that planting intercrops holds

many advantages. Intercrops reduce the ecological footprint decisively. In times of green taxes, a reduction of CO₂ emissions can also decrease production costs. More biogas output per hectare raises income while a reduced need for mineral fertilizer reduces costs. This issue should be taken up by agricultural training courses, where the advantages could be demonstrated on the example of the best practice demonstrative farms.

A crucial logistical aspect would be an intelligent digester set-up and an innovative approach regarding biogas and heat logistics. All this, however, calls for a high level of organization, possibly in the form of a farmer association running the network constellation described before, to lower the investment risk and ensure a continuous operation and stable substrate availability. On the other hand, such an association has the potential to strengthen the community and the social cohesion in the region. On closer examination, it reveals that intercrops can play an important role in a sustainable agriculture of the future when developing and running a socially and ecologically acceptable network constellation still being lucrative for the operators and the region.

Abbreviations

CH₄: methane; CHP: combined heat and power plant; ct: cent; DM: dried mass; FW: fresh weight; kW_{el}: kilowatt electric; kWh: kilowatt hour; MWh: megawatt hour; PNS: process network synthesis; SPI: sustainable process index.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

NN collected the data, carried out the PNS evaluation, as well as its interpretation, and drafted the manuscript. KHK provided the SPI evaluation data and interpretation. Both authors read and approved the final manuscript.

Author's information

NN, born in 1982 in Vienna, Austria, holds a diploma in environmental system sciences. She is currently working in the field of process evaluation at the Institute for Process and Particle Engineering, Graz University of Technology (GUT). Her main research topics are the implementation of sustainable system structures/networks at a regional level and sustainable resource management. GUT is the second technical university in Austria with 104 institutes in six faculties and around 12,000 students in bachelor, master and doctoral programs.

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