9

Economic and Ecological Potential Assessment for Biogas Production Based on Intercrops

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1. Introduction

Biogas production is discussed controversially, because biogas plants with substantial production capacity and considerable demand for feedstock were built in recent years. As a consequence, in most cases corn becomes the dominating crop in the surrounding and the competition on arable land is intensified. Therefore biogas production is blamed to raise environmental risks (e. g. erosion, nitrate leaching, etc.). Furthermore it is still discussed, that a significant increase of biogas production could threaten the security of food supply. The way out of this dilemma is simply straight forward but also challenging: to use preferably biogenous feedstock for biogas production which is not in competition with food or feed production (e. g. intercrops, manure, feedstock from unused grassland, agro-wastes, etc.). However, the use of intercrops for biogas production is not that attractive since current biogas technology from harvest up to the digestion is optimized for corn. Additionally current reimbursement schemes do neither take the physiological advantages and higher competitiveness of corn into account nor compensate lower yield potentials of intercrops which are growing in late summer or early spring. Higher feed-in tariffs for biogas from intercrop feedstock, as they are provided for the use of manure in smaller biogas systems, would not only be justified, as shown below, but also stimulating. Beyond that, the plant species used as intercrops as well as the agronomic measures and machinery used for their growing seem to provide lots of opportunities for optimization to increase achievable yields. Moreover, adaptations of biogas production systems, as discussed in this chapter, facilitate biogas production from intercrops.

Further advantages of intercrops growing are that they contribute to a better soil quality as well as humus content and reduce the risk of nitrous oxide emissions. Simultaneously intercrops allow a decrease of the amount of chemical fertilizer input, because the risk of nitrate leaching is reduced and if leguminosae are integrated in intercrop-mixtures, atmospheric nitrogen is fixed. This is important, because conventional agriculture for food and feed production utilizes considerable amounts of mineral fertilizers. Due to the fact that the production of mineral nitrogen fertilizers is based on fossil resources, it makes economically and ecologically sense to reduce the fertilizers demand.

In the case study, a spa town in Upper Austria, the set-up of the supply chain is seen as key parameter. An important issue in this case are more decentralized networks for biogas production. This can be achieved e.g. with several separated decentralized biogas fermenters which are linked by biogas pipelines to a centralized combined heat and power plant.

2. Methodologies

Process Network Synthesis (PNS) was used as a tool for economic decisions to get an optimal technology solution for biogas production with particular consideration of feedstock which is not in competition with food or feed production. Ecological evaluation of the resulting optimal PNS solution through footprint calculation was based on the Sustainable Process Index (SPI). These calculations are based on the data, which was gathered in three field tests, and the practical experiences, that were gained in the growing and harvesting of intercrops on more than 50 hectares of arable land. Besides the determination of dry matter yields of different kinds of intercrops and intercrop mixtures the effects on ground water, soil and nutrient management were investigated in the field experiments with time-domain-reflectometry, soil water and mineral nitrogen content measurement. Additionally, the potential biogas production was measured by means of biogas fermenter lab scale experiments.

2.1 Process Network Synthesis (PNS)

Process Network Synthesis (PNS) (Friedler et. al., 1995) uses the p-graph method and works through energy and material flows. Available raw materials are turned into feasible products and services, while in- and outputs are unequivocally given by each implemented technology. Time dependencies like resource availability (e.g. harvesting of renewable resources) as well as product or service demand (e.g. varying heat demand for district heating over the year) are part of the optimization.

The necessary input for this optimization includes mass and energy balances, investment and operating costs for the technologies considered, costs for resources and utilities, prices for products and services as well as constraints regarding resource supply and product/service demand. For the case study all data were provided from project partners and are specific for the considered region. First the so called maximum structure is generated linking resources with demands. From this starting point the optimization is carried out resulting in an optimum solution structure representing the most economical network.

2.2 Sustainable Process Index (SPI)

Sustainable Process Index (SPI) was developed by Krotscheck and Narodoslawsky in the year 1995 and is part of the ecological footprint family. The SPI represents as a result the area which is required to embed all human activities needed to supply products or services into the ecosphere, following strict sustainability criteria. Based on life cycle input (LCI) data from a life cycle assessment (LCA) study, SPI can be used to cover the life cycle impact assessment (LCIA) part. LCA studies are standardized and described by the ISO norm 14040 (ISO, 2006). Within the methodology there are seven impact categories defined which are indicated by different colors:

- Area for area
- Area for non-renewable resources
- Area for renewable resources
- Area for fossil carbon
- Area for emissions to water
- Area for emissions to soil
- Area for emissions to air

A high footprint is equal to a high environmental impact!

The freeware tool SPIonExcel (Sandholzer et. al., 2005) was used to calculate the ecological footprint (Graz University of Technology, n.d.) This offers the possibility to measure not only the economical performance of the PNS scenarios.

To assess the sustainability of biogas production from intercrops it is necessary to consider the whole crop rotation and the effects of intercrop on main crops. A direct comparison of biogas feedstock from main crops (e. g. corn) and intercrops is not possible, because inter crops grow with lower temperatures and less hours of sunshine. Therefore one of the systems compared, was corn as main crop, commonly cultivated with plow, and an intercrop cultivated with conservation tillage and harvested with a chopper for biogas production. It was assumed, that biogas was processed to natural gas quality. In the second system with intercrops corn was cultivated with conservation tillage whereas the intercrop was grown with direct drilling and harvested with a self-loading trailer instead of a chopper. Since a late harvest of a winter intercrop with high yields would reduce corn yields, an early harvest with an average intercrop yield of only 4 tons dry matter was assumed. In the reference system corn was grown without intercrop and the biogas produced in the intercrop systems was substituted by natural gas. The yield of the main crop corn was equal in all systems (15 tons dry matter of the whole plants per hectare for silage).

	common intercrop system		**improved intercrop system**		**reference system without intercrop**
position in crop rotation	main crop	intercrop	main crop	intercrop	main crop
tillage	plow	conservation tillage	conservation tillage	direct drilling	plow
harvest	chopper	chopper	chopper	self-loading trailer	chopper

Table 1. Systems compared with the Sustainable Process Index (SPI)

3. Intercrops

In temperate climate zones, allowing only the cultivation of one main crop per year, intercrops are planted after the harvest of the main crops (e.g. wheat, corn or triticale) or as undersown crops, while the main crop is still growing. Summer intercrops are harvested in

September or October as long as the trafficability of fields is sufficient. Achievable yields of summer intercrops are higher, the earlier main crops are harvested and intercrops are sown. The variety of plant species, suitable for biogas production from summer intercrops is very high and reaches from different kinds of millet, over grainlegumes, clover, sun flowers to cruciferae or other plants, adequate for regional conditions and the specific crop rotation of the fields. If cultivated as undersown crops, the variety of usable plant species (e. g. specific types of clover and grass) is restricted to those, not growing too fast and capable to resist a long period with shadow from the main crops.

Winter intercrops (e. g. feeding rye, triticale, different types of clover or rape) are sown in autumn and reaped before the cultivation of summer main crops (e. g. corn or soybean). The later winter intercrops are harvested, the higher are the achievable intercrop yields but the higher is also the risk of diminishing yields of the main crop. For example, output cuts of corn may be higher than additional yields of the intercrop, if intercrops are harvested in the middle of May or later. Therefore, the harvest of the intercrop at exactly the right moment with immediate subsequent cultivation of the main crop is crucial for the overall outcome of this type of crop rotation.

Dry matter yields, achievable with intercrops, vary to a higher extent than those of main crops, because they grow at the edges of the growing season and have less opportunities to compensate unfavourable conditions for growing. Furthermore, there are only a few farmers with experience and appropriate machinery for cultivation and harvesting of intercrops for biogas production at present.

Dry matter yields of summer intercrops in own field experiments in the years 2009 and 2010 averaged out at about 3 tons per hectare. After early cultivation with adequate machinery yields achieved 5 tons and more in some cases. However, intercrops did not achieve yields worthy for harvest in other cases, because of late harvest of main crops in the middle of august in connection with high precipitation and low temperatures in august and September. Under these conditions undersown summer intercrops (e. g. red clover under wheat and spelt) were advantageous and reached yields of almost 5 tons in the middle of September.

The yields of winter intercrops depend mainly on the time of harvest and the average temperature in March and April. If harvested at the end of April or the beginning of May, yields of about 4 tons dry matter were achieved with feeding rye or mixtures of rye or triticale with winter pea or rape. Yields of the following corn were equal or at maximum 10 percent lower than corn without preceding intercrop, if the intercrop was sufficiently manured with biogas digestate. A comparison with average yields found by other authors is compiled in Table 2.

	summer intercrops	winter intercrops
	dry matter yields in tons per hectare	
Own experiments	3	4 (without reduction of corn yields)
Neff, 2007	5	
Aigner/Sticksel/Hartmann, 2008	3	4,9 (middle of April)7,5 (5. Mai)
Laurenz, 2009	4,5	6 (with a reduction of corn yield of 2,5)
Koch, 2009	5	

Table 2. Average yields of summer and winter intercrops

Methane yields per hectare, achievable with winter intercrops, average out at about 1100 cubic meter with a methane content per kg organic dry matter of 310 liter. The methane yields of summer intercrops are lower and achieved 800 cubic meter per hectare in average. The methane content amounts in average 290 liter methane per kg organic dry matter. Therefore, between 4 and 6 hectare of intercrops are required to substitute one hectare of corn as biogas feedstock. This may seem little at the first glance. Considering the fact, that only rates of 10 or 20 percent of arable land should be used for biogas production at maximum, if the security of food supply should not be threatened, it becomes a considerable dimension, since intercrops for biogas production may be cultivated on 60 up to 90 percent of the arable land, if crop rotations are designed accordingly. Therefore the overall biogas potential of intercrops is comparable with the potential of corn.

However, the realization of these potentials requires adaptations of farmers' conditions for biogas production, as current reimbursement schemes and common technical equipment for tillage, drilling, harvest and biogas production make the use of intercrops profitable, only if farmers also apply for agro-environmental payments. Since these payments are only available in certain countries and are not guaranteed for the same period as biogas plants have to be operated, the risk for specific investments is considerable. To stimulate biogas production from intercrops, the physiological advantages and higher competitiveness of corn should be taken into account in the design of reimbursement schemes and tariffs should compensate lower yield potentials of intercrops. Higher feed-in tariffs for biogas from intercrop feedstock, as they are already provided for the use of manure in smaller biogas systems, would also encourage the optimization of agronomic practices (e. g. plant species used as intercrops, tillage, drilling) and technical equipment. In this way, the amount and reliability of intercrop yields would be increased additionally.

3.1 Ecological evaluation of intercrops

Based on input data for the production of main crops with and without intercrops several ecological footprints were calculated. Corn silage as main crop has a yield of 15 ton per hectare (dry matter) and 4 t (dry matter) per hectare of intercrop. SPI calculation includes

		common intercrop system	improved intercrops system	common intercrop system	improved intercrops system	conventional
		intercrop	intercrop	main crop	main crop	main crop (no intercrops combination)
	LCI input data	**workings hours per ton (dry matter)**				
machinery input	Tractor (<45 kW), light workload	0.40	0.23	0.04	0.04	0.04
	Tractor (<45 kW), normal workload	0.18	0.18	0.00	0.00	0.00
	Tractor (<70 kW), normal workload	0.88	0.44	0.55	0.52	0.55
	Tractor (<70 kW), heavy workload	0.00	0.00	0.13	0.00	0.13
	Tractor (70-110 kW), light workload	0.24	0.24	0.00	0.00	0.00
	Tractor (70-110 kW), normal workload	0.36	0.24	0.20	0.28	0.20
		kg per ton (dry matter)				
fertilizer	Application of N-Fertiliser	9.33				12.67
	Application of P-Fertiliser	1.57				1.57
	Application of K-Fertilisation	9.29				9.29
	Application of Ca-Fertiliser	8.43				8.43
		g per ton (dry matter)				
pesticides	Herbicide Phenmediapham	0.00	0.00	61.56	61.56	61.56
	Herbicide Terbuthylazin SP	0.00	0.00	108.05	108.05	108.05
	Herbicide Pyridate SP	0.00	0.00	6.91	6.91	6.91

Table 3. LCI data

machinery working hours, fertilizers, pesticides, agricultural area, and nitrogen fixation by leguminosae and seeds. Input data for the footprint calculation is listed in Table 3 which is derived from (KTBL, n.d.).

In terms of nitrogen fertilizer demand the use of leguminosae in intercrop mixtures reduces the demand of mineral nitrogen fertilizer through nitrogen fixation. Based on these data the ecological footprint results are listed in Table 4.

	SPI results [m² / t (dry matter)]		
	common intercrop system	**improved intercrops system**	**conventional**
main crop	27,217.8	26,374.6	31,528.6
intercrop	13,988.1	9,250.2	--------

Table 4. LCIA results

These footprints are per ton dry matter of intercrop or main crop. In general the lower machinery input for reduced tillage results in an accordingly lower footprint which points out the advantage of this method. This effect becomes more important as the yield of the crop decreases. The yields of intercrops are inevitably lower than of main crops, because of lower temperatures and less sunshine hours. Therefore, the footprint of intercrops sown with direct drilling and harvested with self-loading trailer is 34 % lower than of intercrops grown with conservation tillage and harvested with chopper. The amount of fertilizer for the main crops can be reduced with leguminosae intercrops. For this reason the footprint of the main crop in the reference system is higher than in the first system with intercrops with common tillage. If the effect of reduced nitrogen leaching or nitrous oxide emissions would be considered in the SPI-calculation, the difference would become even bigger.

For an overall assessment of the three systems, biogas produced in the systems with intercrops was processed to natural gas quality and substituted with natural gas in the system without intercrop. With processing the average methane content of biogas from about 60 % is increased to 96 % CH_4. Of course, biogas from intercrops can also be used in combined heat and power plants (CHP). Its processing is only obligatory for the comparison with natural gas. Although the footprint per ton dry matter of intercrops, even if they are sown with direct drilling, is bigger than the footprint of main crops, it is much smaller than the footprint of natural gas, it may substitute.

Table 5 illustrates this overall balance per hectare of agriculture area. Biogas purification SPI relies on life cycle data from ecoinvent database (Ecoinvent, n.d.). This balance can be seen as a rough estimation of the footprint reduction potential, if not only agriculture but also natural gas consumption is considered.

Table 5 points out an advantage for intercrop cultivation with direct seeding and harvesting with self-loading trailer in comparison with intercrops grown with conservation tillage and harvest with chopper. The footprint of intercrops used for green fertilizing to increase soil quality, was not calculated in detail. Nevertheless it can be assumed that the footprint is worse than the footprints of intercrops for biogas production, because the efforts for drilling are the same and instead of harvesting energy is needed for their incorporation into the soil.

For natural gas the SPI value is 540.4 m²/Nm³. Although further biogas purification is needed the whole balance points out a footprint reduction potential of 39 – 42 %.

	with intercrops		conventional
	common intercrop system	improved intercrops system	
CH_4 yield [m³ / t (dry matter)]	1,200	1,200	
overall purified biogas [m³/ha]	4,800	4,800	
intercrop SPI [m²/ha]	408,266	395,619	472,929
maincrop SPI [m²/ha]	55,952	37,001	0
provision of natural gas [m² /ha]	0	0	648,480
biogas fermentation process (electricity, heat) [m² / ha]	21,074	21,074	
biogas purification [m² / ha]	193,500	193,500	0
SPI [m² / ha]	**678,793**	**647,194**	**1,121,409**

Table 5. Energy balance per hectare

4. PNS optimization

A case study, as part of the so called Syn-Energy[1] project, was carried out in a spa town in Upper Austria wherein the set-up of the supply chain was seen as one of the key parameters. Beside detailed analyses of intercrops (e.g. biogas content, yields) a main focus was to find a network in respect of a higher degree of decentralization for biogas production. This can be achieved e.g. with several separated decentralized fermenters that are linked by biogas pipelines to a single combined heat and power plant. The specific data for intercrops were used to carry out the evaluations. Of note was to show how intercrops can affect networks from an ecological and economical point of view.

4.1 Case study

Figure 1 shows three potential decentralized locations for biogas production. As there is a spa town located in the considered region it was not possible to contemplate a fourth, central location for a fermenter as it would infringe with the touristy activity there. There is already an existing district heating network in town that should be extended. The heat needed could be either generated by a centrally placed CHP with biogas transported via pipelines or heat produced with decentralized CHPs could be used for fermenter heating and/or transported via long –distance heat pipelines to the town. In the first case, with central CHP, fermenter heating is provided by wood chip furnace.

The fermentation could work with different feedstock types to find out the most lucrative way of using intercrops, manure, grass silage and corn silage. Corn as additional feedstock was taken into consideration for economic reasons, because it is favored under current economic conditions. For the optimization it was assumed that proportional to the availability of manure biomass in an amount of 34 % intercrops, 18 % grass silage and 16 % corn silage (referring to fresh weight) per livestock unit can be supplied. As there are several

[1] Syn-Energy „Klima- und Wasserschutz durch synergetische Biomassenutzung – Biogas aus Zwischenfrüchten, Rest- und Abfallstoffen ohne Verschärfung der Flächenkonkurrenz"; programme responsibility: Klima- und Energiefonds; programme management: Österreichische Forschungsförderungsgesellschaft mbH (FFG), report not published yet

farmers in and around the considered region eight provider groups (1-8 according to Table 6 and black bordered providers in Figure 1) were defined. The substrate costs were the same for each group.

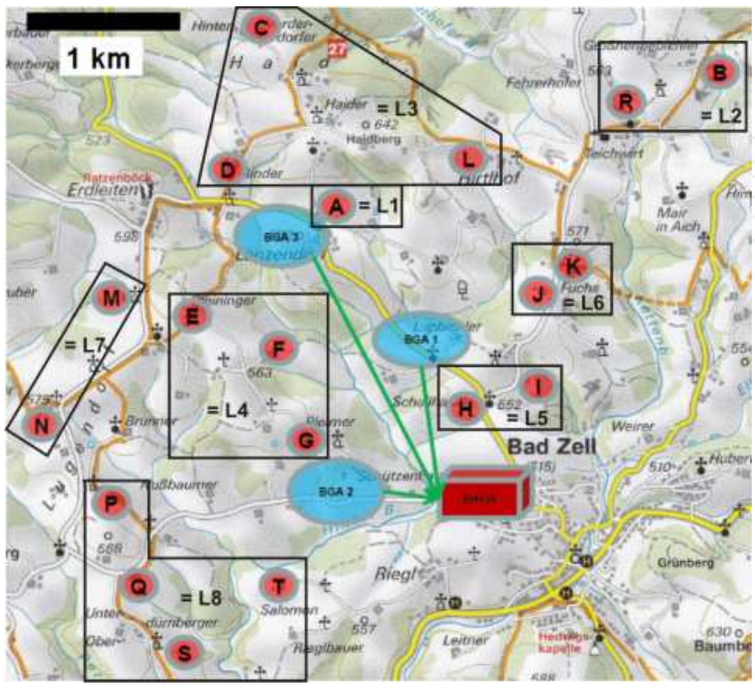

Fig. 1. Substrate providers (A-T) and possible fermenter locations (BGA1-3)

Provider Group	Distances in km to		
	Location 1	Location 2	Location 3
1 (A)	1.6	3.4	0
2 (B, R)	3.3	4.7	4
3 (C, D, L)	2.7	4.6	1.2
4 (E, F, G)	1.9	1.4	3.3
5 (H, I)	0.3	2.1	2.1
6 (J, K)	1.5	2.9	3
7 (M, N)	3.1	3	2.4
8 (P, Q, S, T)	3.8	1.9	3.7

Table 6. Transport distances for substrate provision

The providers differed in the amount of available resources as well as in the distance to each possible fermenter location, which directly correlates with transport distances and costs. Transport costs included fix costs for loading and unloading and variable costs depending on the distance (including unloaded runs). For solid substrates fixed costs of 2 €/t fresh weight were taken into account. Similarly, the conversion was made for the variable costs, which were assumed with 0.49 €/km. Fixed transport costs for manure were defined with 20 €/t dry mass with variable costs of 5 €/t dry mass per kilometer. For grass and corn silage a storage was taken into account. As it is not possible to bring the investment costs down to one number because they are highly depending on the local basic conditions a fix

investment of 150,000 € for a silage storage was taken into account. As soon as a location is chosen by the PNS a storage has to be included there. Two locations mean two times investment costs to store the silage that is used for biogas production.

Transportation of heat and biogas could be achieved via pipeline networks. Network energy demands as well as losses caused by transporting were included. Regarding heat it was assumed that the total produced heat amount could be used for district heating. As location 1 and 3 are in one line to the spa town one biogas pipeline could be used for both locations to transport biogas to the central CHP. Therefore no additional costs arise for a biogas pipeline from location 1, if location 3, which is farther away, supplies the center with biogas.

Because of different transport distances the PNS could decide which provision group and amount of substrate should be used to get the most economical optimum solution. The fermentation could run with various substrate feeds. Dependent on them fermenter sizes, costs and exposure times differed. Seven different fermenters were part of the PNS to find the most lucrative way of substrate input. The feeds are shown in Table 7.

Feed [%]	Manure	Inter-crops	Grass silage	Corn silage
1	30	0	0	70
2	30	70	0	0
3	50	50	0	0
4	50	20	10	20
5	75	0	0	25
6	75	25	0	0
7	75	15	10	0

Table 7. Substrate feeds for fermentation

In Table 8 the substrate parameters are described. The optimization was based on two different cost situations (maximum and minimum) concerning substrate provision.

* decided by project partners	Manure	Corn silage	Intercrops	Grass silage
Dry Mass Content [%]	9	33	24	30
Substrate Costs* min. [€/t DM]	5	65	50	50
Substrate Costs* max. [€/t DM]	10	110	80	80
CH_4-output [m^3/ t DM]	200	340	300	300

Table 8. Substrate parameters and costs in € per ton dry matter and cubic meter methane per ton dry matter

Figure 2 shows the so called maximum structure for the PNS optimization, which includes all input and output materials with energy and material flows with economic parameters like investment or operating costs and prices. For the optimization three fermenter sizes (up to a capacity that serves a 250 kW_{el} CHP) were available for biogas production. Four combined heat and power plant capacities (up to 500 kW_{el}) were involved in the maximum structure. The fermenters could be heated by decentralized CHPs or with a wood chip furnace on site in case the biogas is transported to a central CHP.

The biomass furnace that could be a choice to provide fermenter heating was not implemented as separate technology in PNS' maximum structure, but a price of 5 ct/kWh heat was assumed (Wagner, 2008). Produced electricity could be fed into electricity providers' grid, thus benefiting from feed-in tariffs according to Austrian's Eco-Electricity Act (RIS, n.d.).

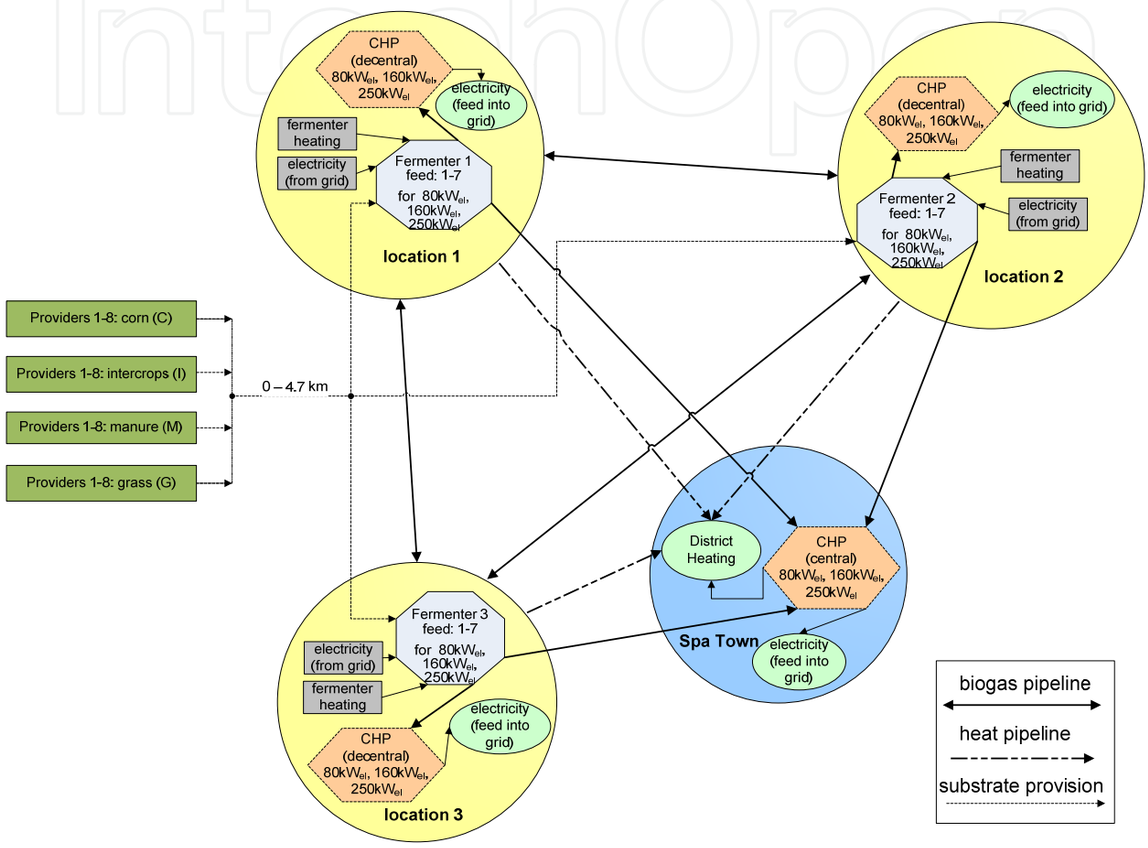

Fig. 2. Maximum structure for PNS Optimization

4.2 PNS optimum solution

The PNS optimization shows that the technology network providing the most benefit for the region includes two different locations (1 and 3) for biogas generation. At location 3 biogas is produced with substrate feed 4, a mixture consisting of manure, intercrops, grass and corn silage. The fermenter runs 7.800 full load hours and is able to provide a 250 kW$_{el}$ CHP with biogas. At location 1 the set up includes a fermenter with same capacity but different load. Substrate mixture 7 is used for biogas production which contains manure, intercrops and grass silage. Both fermenters are heated with a biomass furnace on site. All provider groups can supply the fermenters with at least one substrate. The optimal technology network includes two central 250 kW$_{el}$ CHPs supplied via biogas pipelines with biogas from both

locations. For the pipeline coming from location 1 no additional costs have to be incurred because the pipeline would be part of the routing from location 3 to the center. The produced heat covers the central heat demand for a price of 2.25 ct/kWh. The electricity is fed into the grid and feed-in tariffs of 20.5 ct/kWh can be gained. Figure 3 depicts the optimum structure for a situation with maximum substrate costs as listed in Table 8.

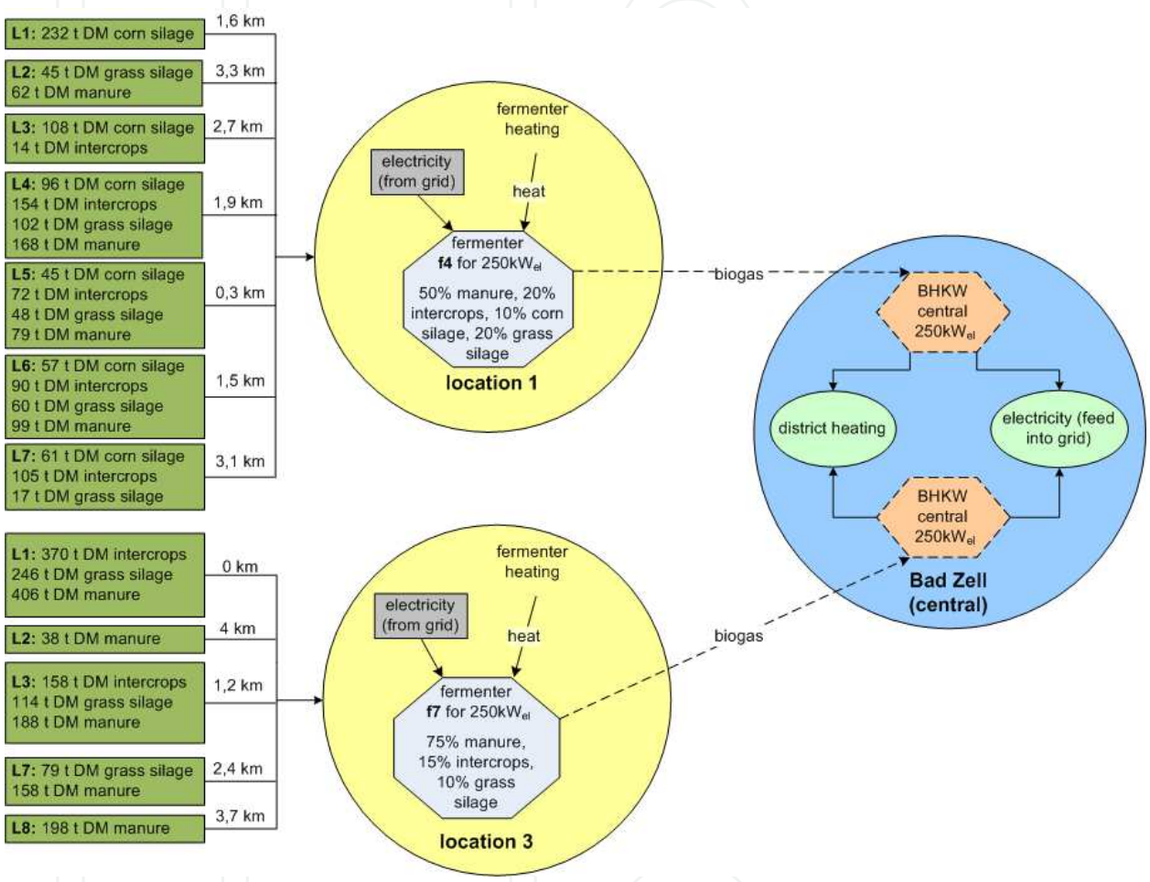

Fig. 3. Optimum structure of a technology network generated with PNS

With this technology network and 15 years payout period a total annual profit of around 196,350 € can be achieved (interest rates are not included). The total material costs including electricity consumed from the grid and costs for fermenter heating add up to approx. 438,000 €/yr with additionally 60,300 € per year for transportation. The total investment costs for this solution would be around 2,895,000 € including district heating and biogas network as well as the costs for fermenters and CHPs.

With minimal substrate costs (see Table 8) there is no change in the optimal structure, but the revenue is higher commensurate to the lower substrate costs (one-third reduction). The revenue for the structure with minimal substrate costs excluding interest accounts for a yearly amount of about 280,400 €.

4.3 Scenarios

To prove plausibility of the optimum PNS structure two scenarios were carried out, both for minimum as well as for maximum substrate cost situations. In the first case the maximum structure was reduced by taking away corn availability. With that only five substrate mixtures could be used for biogas production. The second scenario was set up to get an idea how feed-in tariffs can influence the outcome of an optimization. Therefore it was not allowed that a network set-up results e.g. in two 250 kW_{el} CHPs if a 500 kW_{el} instead could be taken.

4.3.1 Scenario I – No corn silage

As already mentioned in the beginning corn is currently a dominating substrate for biogas production. To show the potential of intercrops no corn is available in this scenario. Not to lose the comparability the amount of corn was compensated with an additional availability of intercrops. The calculation was based on the CH_4-outputs and adds up to additionally 904 t intercrops. With that 2,170 t/yr intercrops, about 1.7 times more than in the basic maximum structure shown in Figure 2, are available in the maximum structure of this scenario. Under these conditions PNS could choose between five different substrate feeds.

The optimization results in a technology network including two locations using the whole amount of available intercrops as shown in Figure 4.

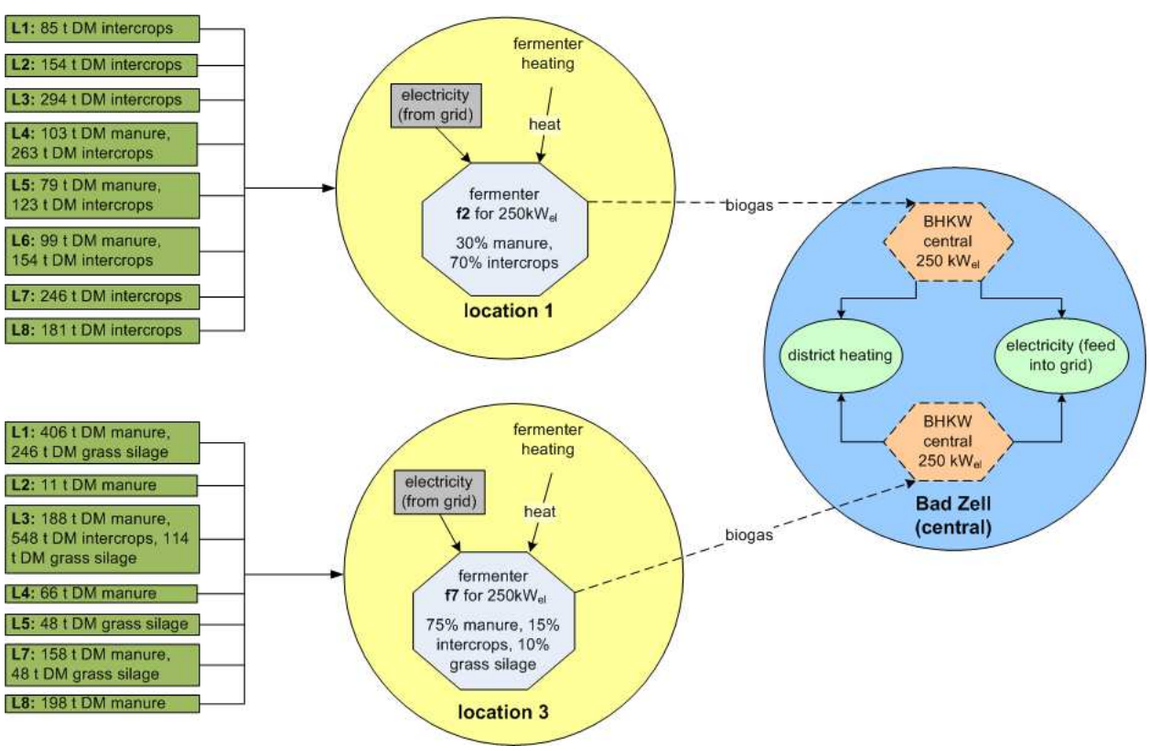

Fig. 4. PNS optimum structure for scenario 1 without corn silage availability

At location 3 a fermenter processing substrate feed 7 with a capacity to produce biogas to supply a 250 kW_{el} CHP runs 7,800 full load hours a year. A second fermenter placed on

location 1 and with same efficiency is supplied with substrate feed 2 consisting of 70 % intercrops and 30 % manure. It turned out that with this structure the outcome has yearly revenue of approx. 208,000 €. Compared to the optimum structure it is higher, but the basic conditions are different. Therefore this solution did not come up in the optimization of the maximum structure in the beginning. But it clearly shows that intercrops have a great potential to produce electricity and heat within a highly profitable biogas network without being in competition with food or feed production. But the precondition would be that in the case study a higher amount of intercrops is available as feedstock.

4.3.2 Scenario II – 500 kW_{el} CHP unit

Operating a 500 kW_{el} CHP goes along with reduced feed-in tariffs of 20 €/MWh according to Austrian's Eco-Electricity Act. The positive effect of lower investment and operating costs for larger capacities is therefore narrowed by less revenue for produced electricity. If is forbidden to use two CHPs with same capacity at one location in the maximum structure to gain higher feed-in tariffs the next larger CHP capacity has to be taken although this would

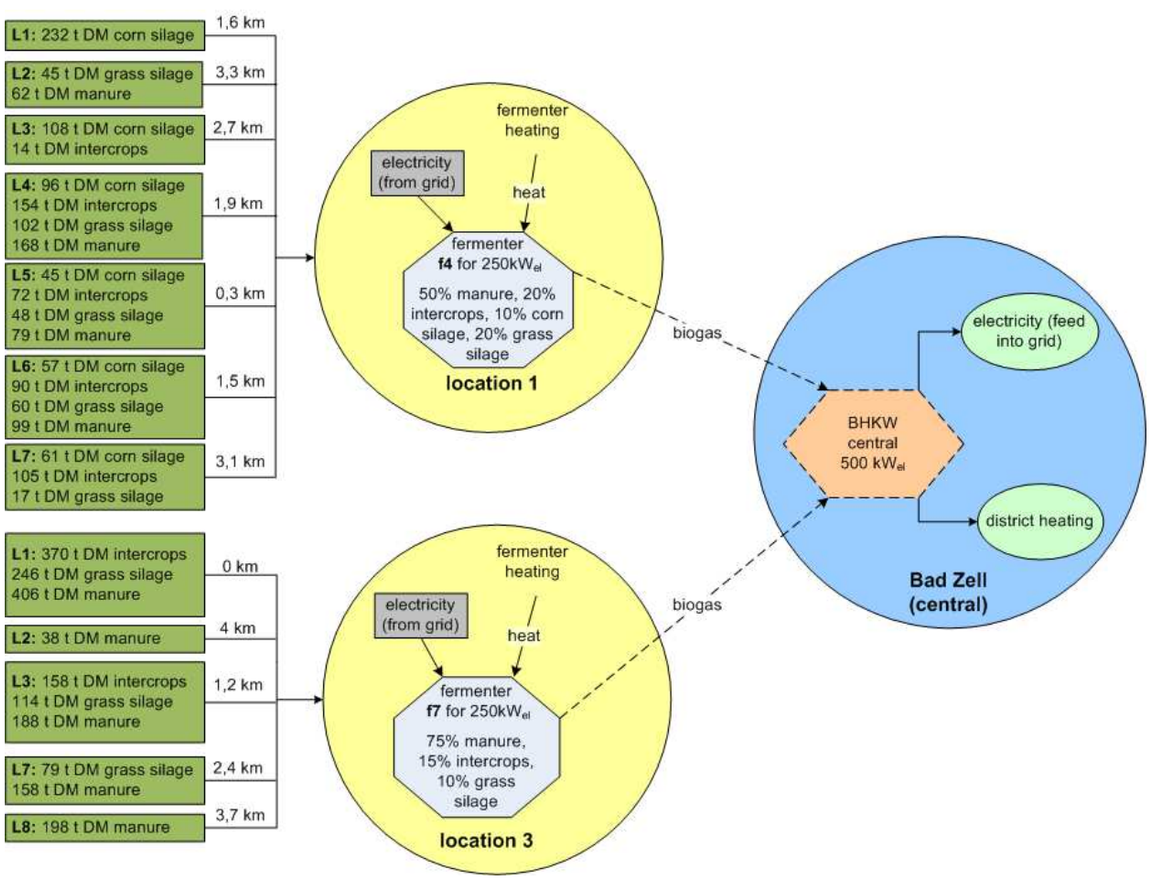

Fig. 5. PNS optimum structure with a central 500 kW_{el} CHP

go along with shortened revenue. With this precondition the optimization of the maximum structure presented in Figure 2 but with only one central 500 kW_{el} CHP unit whereas the rest of the optimum structure (Figure 3) stays the same.

The revenue is narrowed but not as much as it was in scenario 1. To use a 500 kW_{el} central CHP would cause a revenue reduction of yearly 50,000 € within a payout period of 15 years.

4.3.3 Comparison of PNS' optimum solution and the scenarios

Table 9 overviews the results of the three optimizations described before.

	Optimum Structure		Scenario 1		Scenario 2	
Substrate costs	max.	min.	max.	min.	max.	min.
Investment costs [€]						
Total investment costs	2,894,519	2,894,519	2,894,519	2,894,519	2,824,519	2,824,519
Products [MWh / yr] and Revenues [€/yr]						
Total produced electricity	3,826	3,826	3,900	3,900	3,826	3,826
Total produced heat	4,591	4,591	4,680	4,680	4,591	4,591
Revenue for electricity fed in (205 € / MWh)	784,281	784,281	799,500	799,500	707,766	707,766
Revenue for district heating (22,5 € / MWh)	103,296	103,296	105,300	105,300	103,296	103,296
Total revenue [€/yr]	887,576	887,576	904,800	904,800	811,062	811,062
Operating Costs [€/yr]						
Fermentation	114,423	114,423	116,090	116,090	114,423	114,423
CHPs	75,556	75,556	75,556	75,556	51,346	51,346
Transport	60,286	60,286	64,121	64,121	60,286	60,286
Substrates	213,561	129,488	213,400	131,740	213,561	129,488
Electricity	34,432	34,432	35,100	35,100	34,432	34,432
Total operating costs [€/yr]	498,258	414,185	504,267	422,607	474,048	389,975
Operating result without depreciation	389,319	473,392	400,534	482,194	337,015	421,088
Depreciation for 15 years*	192,968	192,968	192,968	192,968	188,301	188,301
Operating result with depreciation*	196,351	280,424	207,566	289,226	148,714	232,787

Table 9. PNS results summary

It turned out that the profitability of a fermenter on location 2 is lower than on the other locations. It was never preferred in any optimum structure. The other locations have one advantage – the shared usage of biogas pipelines whereas low additional costs for location 1 have to be born. There are never heating pipelines from the different locations to the center considered in the optimum technology networks. Just the biogas is transported; heat is produced centrally and distributed within a district heating network, although additional biomass furnaces are required. In scenario 1 the missing corn silage availability was compensated by a higher amount of intercrops, referring to the CH_4 content, and it shows

the best revenue, because of higher plant utilization and higher revenue for electricity and heat production. Although in the optimal scenario the amount of corn relating to the total feedstock was not even 17 % of the total (dry matter) the compensation for corn with intercrops results in higher revenue. For more corn that intercrops compensate in the input the impact would be even higher. Therefore it is obvious that intercrops can be a profitable feedstock to run a biogas plant. For the case study the availability of intercrops would have to be raised as described before which would lead to the best technology network for the region.

The system has two limiting factors; on the one hand the distances between the fermenter locations and the feedstock providers accompanying different transport costs and on the other hand the limited resource availability. It could be shown that it is not lucrative to run a central CHP with higher capacity (500 kW_{el}) as feed-in tariffs are lower and less revenue can be gained. Nevertheless, from the point of view of sustainability, it would be preferable to substitute two smaller CHPs with a bigger one. An adaptation of reimbursement schemes to the solutions presented is recommended.

5. SPI evaluation

Based on the economic results of the PNS optimization and previous SPI evaluation of different intercrops, a footprint for the PNS results was calculated. The evaluation includes every substrate, transport, net electricity and infrastructure for fermenters and CHP units. SPIonExcel already provides a huge database of LCIA datasets which can be used for modeling the scenarios. In case of intercrops substrate the SPI value for conservation tillage + self-loading trailer from Table 4 was used.

SPI evaluation results					
		electricity		heat	
	overall SPI [km²]	production [MWh/a]	SPI [m²/MWh]	production [MWh/a]	SPI [m²/MWh]
Optimum solution	93.08	3,825	21,503	4,591	2,360
Scenario 1 - No corn	89.32	3,900	20,236	4,680	2,221
Scenario 2 - 500KW_{el} BHKW	91.51	3,825	20,876	4,591	2,539

Table 10. LCIA results based on PNS scenarios

The overall footprint points out the environmental impact for one year of production. In case of the optimum solution it would need 93.08 km² of area which has to be reserved to embed the production sustainably into nature. The overall footprint is shared between both products according the amount of output and the price per MWh (electricity: 205 €/MWh; heat: 22.5 €/MWh). Price allocation of the footprint leads to a higher footprint for the higher valued product.

Scenario 1 has a benefit from the ecological point of view and almost equal revenue according to Table 9. For scenario 2 there is only a slightly difference to the optimum solution because of two small CHP units instead one.

Main impact categories are in every case 'fossil carbon', 'emissions to water' and 'air'. This mainly derives from the utilization of net electricity which contributes around 45 % to the whole footprint. Main contribution to this categories stemming from net electricity and

machinery input in agriculture which are still mainly fossil based. This is also the main optimization potential for a further decrease of the footprint.

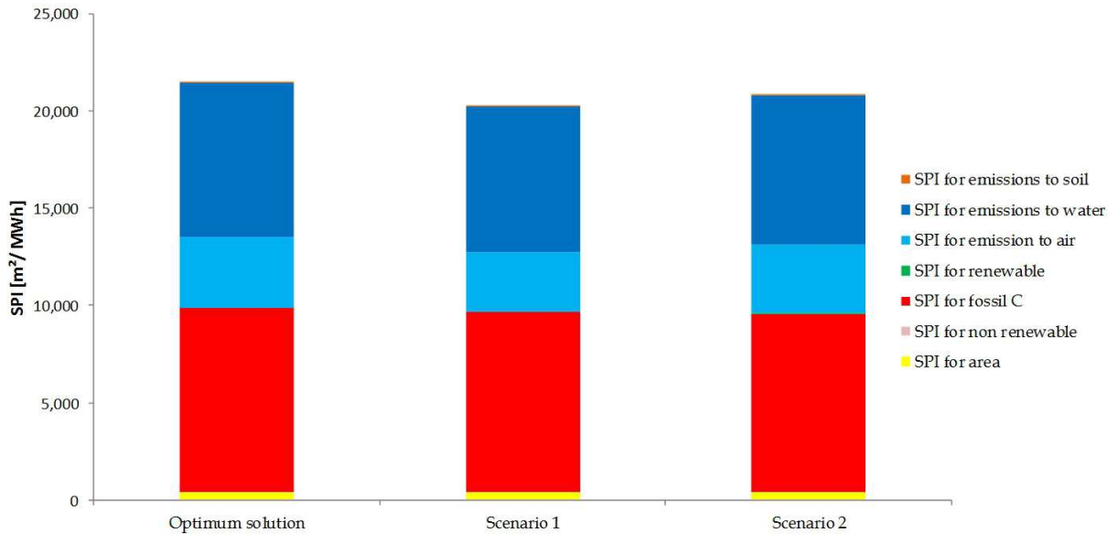

Fig. 6. SPI category comparison

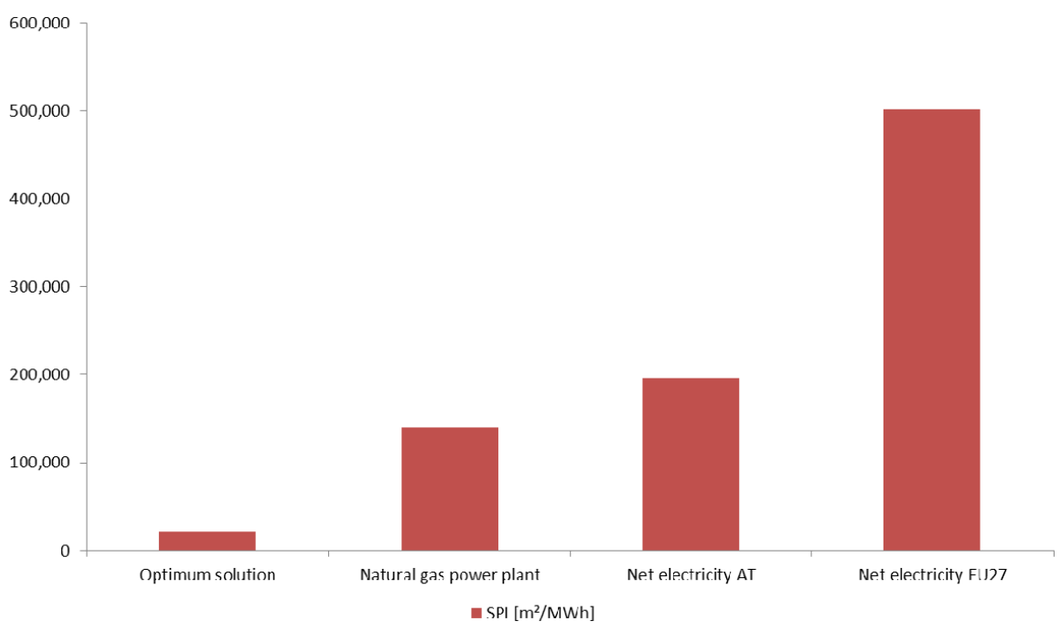

Fig. 7. Comparison of electricity production

Compared to other electricity provision system the optimum solution from the PNS has an ecological benefit in footprint ranging from 61 to 96 % which is pointed out in Figure 7. Although the footprint of the optimum solution could be optimized by using the produced electricity for itself and not selling to the grid (which has economic reasons because of high feed-in tariffs) the ecological benefit compared to other sources is obvious. Every contribution to a greener net infects simultaneously all net participants.

6. Conclusion

The three pillar principle of sustainability serves as conceptual framework to conclude this study. Not only economic and ecological factors are important to implement innovative structures. Often we forget about the social component, the third pillar of sustainability. Not to do so farmers' opinion about intercrops where taken into account. It turned out that intercrops production also abuts on farmers' psychological barriers and the need of intensive cooperation among farmers in the surrounding of a biogas plant. In conjunction with economic risk and high investments, determining farm management for at least 15 years it becomes obvious, that well-considered decisions are to be made. Therefore, it is not astonishing that farmers hesitate, if economic benefits do not clearly compensate social an managerial risks of biogas production from intercrops. Furthermore, the situation that biogas production from corn is favorable regarding practicability in comparison to biogas production from intercrops, reduces farmers motivation to decide for the latter. But even the growing and harvesting of intercrops requires additional work and the strict time frame to cultivate fields, the risk of soil compaction through harvest and potential lower yields of main crops after winter intercrops are counter-arguments to cooperate with farmers already running biogas plants. Higher feed-in tariffs for biogas from intercrops seem to be inevitable and sensitization of decision makers and farmers is needed to emphasize that the planting of intercrops holds many advantages and that intercrops reduce the ecological footprint decisively. Although a higher energy input for agricultural machines is required because of the additional workload for intercrops. In summary the energy balance per hectare including biogas production points out a benefit. In times of green taxes a reduction of CO_2 emissions can diminish production costs. More biogas output per hectare raises the income beside minimized mineral fertilizer demand reduces costs and lowers the ecological footprint. Furthermore, biogas production from intercrops contributes to a reduction of nitrate leaching and nitrous oxide emissions from agriculture. With the transport optimization in-between the network the ecological footprint decreases caused by intelligent fermenter set-up going along with less transport kilometers and fuel demand. A farmer association running an optimal network described before lowers the investment risk and ensures continuous operation and stable substrate availability. On the other hand an association has the potential to strengthen the community and the social cohesion of regions. Some of the advantages mentioned before effect the regional value added positively. On closer examination it could be shown that intercrops can play an important role in sustainable agriculture for the future by running a social and ecological acceptable network and still being lucrative for the operators and the region. Finally biogas production from intercrops does not affect the security of food supply. On the contrary it may even increase productivity in the case of stockless organic farming.

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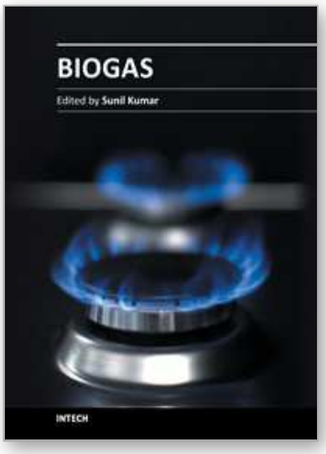

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This book contains research on the chemistry of each step of biogas generation, along with engineering principles and practices, feasibility of biogas production in processing technologies, especially anaerobic digestion of waste and gas production system, its modeling, kinetics along with other associated aspects, utilization and purification of biogas, economy and energy issues, pipe design for biogas energy, microbiological aspects, phyto-fermentation, biogas plant constructions, assessment of ecological potential, biogas generation from sludge, rheological characterization, etc.

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