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Biogas digestate processing as a contribution to nutrient export from surplus regions – costs and greenhouse gas emissions

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The processing of slurry and biogas digestate reduces their volume and separates nutrient flows, especially in regions with nutrient surpluses. This makes it possible to cut transport costs for supra-regional utilisation and to configure tailor-made products for different customers. However, the additional capital and equipment costs can usually only be compensated by revenue from the CHP bonus for the use of excess heat from combined heat and power systems in biogas plants, unless high prices can be achieved for the products outside agriculture. The use of heat also has a considerable impact on the greenhouse gas emissions associated with processing. If reference emissions are charged because the heat is no longer available to replace fossil resources, this far outweighs savings from transport. However, it is not possible to draw general conclusions due to the diverse plant-specific conditions (amount and type of nutrient surplus, transport distance, heat availability, size of the plant, etc.). In individual cases, the processing of biogas digestate may well be economically viable, especially in the case of long transport distances.

Keywords
biogas digestate, processing, nutrient surpluses, nutrient export, greenhouse gas emissions, costs

The need to use the nutrients from regions with nitrogen and phosphorus surpluses supra-regionally will continue to increase due to the requirements of the amended Fertiliser Ordinance (DüV 2017). Regions with intensive livestock farming, which also have numerous biogas plants, are particularly affected. In the future, their digestate will increasingly compete with livestock manure for areas to be used for land application.

Due to the reduction in volume and the targeted separation of nutrient flows, the processing of digestate is seen as a way of removing nutrients from surplus regions. However, the advantages of processing are offset by costs, energy consumption and greenhouse gas emissions incurred by the construction and operation of the processing plants. For this reason, the “GärWert” project considered various baseline situations with different nutrient export requirements to determine whether costs or greenhouse gas emissions can be saved by processing compared to the utilisation of unprocessed digestate. The project explored only scenarios that envisage the processing products being marketed for agricultural purposes. It did not include non-agricultural customer groups who are more likely to pay higher prices for garden fertilisers and soils based on digestate products, such as private gardeners. This group therefore offers additional marketing potential for the future, at least for part of the supply (Dahlin et al. 2016, 2017).

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Procedure

The calculations were based on the example of digestate processing in a biogas plant (substrate input: 35% cattle slurry, 65% renewable resources) with 2 MW electrical output for the most common processing technologies. We recorded the expenditure and consumption of building materials, operating resources and energy for the entire process from leaving the biogas plant (overflow from secondary fermentation or after 150 days in the gas-tight system) to agricultural use (Table 1). This included advance expenditure on the production of technology, buildings or equipment.

Table 1: Processing technologies[1)] considered and their resulting products

Identification / Procedure		Resulting products	Heat requirement
BF	Drying of the solids resulting from digestate separation (screw press separator; SPS) and part of the liquids with a belt dryer, using all available CHP excess heat[2)] and subsequent exhaust air treatment, which produces a low-concentration ammonium sulphate solution (ASS)	Dried solids, Liquids after SPS, ASS (18%)	yes
ST	Separation (SPS), stripping of the liquids and extraction of an ammonium sulphate solution	Solids after SPS, NH_4-free liquids after separation (SPS), ASS (32%)	yes
VE	Separation (SPS), vacuum evaporation of the liquids with subsequent vapour scrubbing and production of an ammonium sulphate solution	Solids after SPS, NH_4-free concentrate, ASS (32%)	yes
M	Separation (SPS), additional separation of solids from the liquids by means of flocculation agents and decanter centrifuge (DC), then processing of the remaining liquids in a membrane plant with ultrafiltration (UF) and reverse osmosis (RO)	Solids after SPS and DC, Concentrates from ultrafiltration and reverse osmosis	no

[1)] A more detailed description of the processing technologies considered can be found in the final report on the GärWert Project (FNR 2017), Chapter Sub-Project 3.

[2)] After deduction of the process heat for the biogas plant (flat rate 25%).

The analysis also included the replacement of mineral fertilisers by the nutrients contained in the digestate and the processing products. For nitrogen, only the year of application was taken into account, as the supply from the organic N pool in subsequent years is difficult to estimate. Furthermore, we assumed that digestate and products which are used supra-regionally and transported over a distance of 20 km or more can be transported throughout the year to the receiving arable farming regions for logistical reasons. This eliminates the high demand for transport capacity which occurs at certain times during the land application phase. Land application is performed in a single operation (without reloading) within a radius of up to 15 km from the plant or the external storage facilities. For higher distances, multi-phase processes are used where transport and land application are separated. Transport distances of 10 to 300 km (10, 15, 20, 25, 50, 75, 150, 300 km) were considered. This allowed conclusions to be drawn on the advantages or disadvantages of processing techniques for nutrient surpluses both for large-scale and regional contexts.

In accordance with the Fertiliser Ordinance (DüV 2017), we added the nitrogen from digestate or from the resulting processing products to the upper limit of 170 kg N from livestock manure. Since June 2017, the possible amounts of digestate that can be applied per hectare have thus been limited, which increases the area required for each plant.

It was assumed that a revenue can be generated from the nutrients, for the share of products that are used supra-regionally. Depending on the product, a different revenue potential was assumed. The possible influence of revenue margins was not taken into account.

To assess greenhouse gas emissions, we took into account the direct emissions from the processing, storage and land application of digestate and processing products. In addition to gases that directly impact the climate – nitrous oxide (N_2O) and methane (CH_4) – we also included ammonia (NH_3) which indirectly impacts the climate. No direct emissions occur in the treatment processes under consideration here. Indeed, a large proportion of the ammonium nitrogen (NH_4-N) passes into the gas phase during drying. However, it was assumed here that an exhaust air treatment system is used, which retains 90% of the released NH_3 in an ammonium sulphate solution.

For some treatment methods, process heat is required. This can usually be provided by excess heat from the CHP (residual heat after the biogas plant's own heat requirements have been deducted). However, the use of this heat in this way might compete with other forms of heat utilisation. It could be marketed and thus generate income or be used to avoid greenhouse gas emissions by replacing fossil fuels. For this reason, two variants were calculated for technologies with heat utilisation: one which does not take heat into account and, in the case of heat-using technologies, one which takes opportunity costs or reference emissions into account for the amount of heat required.

For the economic feasibility studies, a third option was included: the CHP bonus which many existing plants receive until the end of their lifetime according to the Renewable Energy Law (EEG). However, this only applies if no heat use has taken place to date, entitling the plant to receive the CHP bonus.

Table 2 shows the separation efficiency of the individual processing steps on which the calculations are based. These were either determined within the scope of the project on test plants or are based on information provided by manufacturers. Details on the processing technologies can be found in the final report on the GärWert project, sub-project 3 (FNR 2017).

Table 2: Separation efficiency of the individual processing steps.

	Screw press separator	**Decanter centrifuge**	**Belt drying with exhaust air treatment**		**Stripping**		**Vacuum evaporation**		**Membrane technology**	
Input material	**Untreated digestate**	**Liquid after SPS**	**Solid after SPS, partially liquid**		**Liquid after SPS**		**Liquid after SPS**		**Liquid after DC**	**Filtrate after UF**
Product[1)]	**SPS solid**	**DC solid**	**Dry goods**	**ASS (18%)**	**N-reduced liquid**	**ASS (32%)**	**Concentrate**	**ASS (32%)**	**UF Concentrate**	**Concentrate RO**
TM	48%	60%	100%	[2)]	94%	[2)]	93%	[2)]	59%	100%[3)]
N_{tot}	17%	23%	57%	0%	43%	57%	44%	57%	38%	100%[3)]
NH_4-N	9.2%	15%	17%	75%	20%	80%	22%	78%	32%	100%[3)]
P_{tot} (P_2O_5)	22%	80%	100%	0%	100%	0%	100%	0%	58%	100%[3)]

[1)] Product to which the separation efficiencies in the table refer.
[2)] Addition of sulphuric acid.
[3)] Only traces of nutrients remain in the reverse osmosis permeate, resulting in a separation efficiency close to 100%.

The costs and emissions were calculated for the utilisation of both the processing products and the unprocessed digestate. The utilisation of the unprocessed digestate was used as a reference. Cost increases or savings or increased or reduced emissions due to processing are shown in comparison to utilisation of the unprocessed digestate. All results therefore refer to one cubic meter of unprocessed digestate.

Parameters for costs and greenhouse gas emissions

Table 3 shows the sources for the parameters for costs and greenhouse gas emissions related to processing and agricultural use of digestate and processing products.

Table 3: Sources for the parameters used in the cost calculations and greenhouse gas balance

Cost factors/Greenhouse gas sources	Quantities	Costs/Revenues	Greenhouse gases (GHG)
Material construction plant	Manufacturers, test plants	Manufacturers[1)]	ecoinvent (2015)
Operating equipment plant	Manufacturers, test plants	Electricity, heat: KTBL (2016) additional: test plants	Electricity: German electricity mix according to UBA (2019) Heat: Natural gas according to probas (UBA 2017) additional: ecoinvent (2015)
Material and technology storage	KTBL database for procedural costs	KTBL database for procedural costs	ecoinvent (2015)
Technology and diesel consumption for land application	KTBL database for procedural costs	KTBL database for procedural costs	ecoinvent (2015)
Mineral fertiliser replacement	Calculated	Nutrient value: KTBL (2016a) Revenue potential products: KTBL (2017)	N: TI (2016) P: KTBL (2016b)
Direct emissions from processing, storage and land application[2)]		not relevant	Emission factors see Table 4 and Table 5 Climate Impact N_2O, CH_4: Intergovernmental Panel on Climate Change (2006)

[1)] Plant costs include annual depreciation for buildings and technology as well as interest and repair/maintenance costs. Depreciation periods: buildings 30 years; technology 12 years (except separators: 8 years).

[2)] The use of emission reduction techniques was assumed for storage and land application.

Direct and indirect emissions

No emission factors currently exist for processed digestate. Therefore, we drew conclusions by analogy and employed mostly factors used in the agricultural emission inventory (Rösemann et al. 2017) for livestock manure and unprocessed digestate. The different properties of the processing products were taken into account in the selection of the emission factors. For example, we factored in a lower tendency to form a floating layer or an increased fluidity in comparison to the unprocessed digestate. While N_2O, CH_4 and NH_3 emissions may occur during storage (Table 4), direct NH_3 emissions are the most relevant during land application (Table 5). In addition, indirect nitrous oxide emissions caused by the deposition of ammonia or ammonium were considered for NH_3 (Rösemann et al. 2017).

Table 4: Emission factors used to calculate emissions from the storage of unprocessed digestate and processing products. Emission factors from the emission inventory for German agriculture were taken from Rösemann et al (2017).

Goods to be stored	Emissions factor (EF) N_2O-N kg/kg N_{tot}	NH_3-N kg/kg NH_4-N	CH_4 m³/m³ CH_4 1)	Source/ explanatory notes on emission factors
Unprocessed digestate				
Storage at a biogas plant	0	0	0	gas-tight digestate storage: no emissions
External digestate storage in the arable farming region	0.005	0.015	0.01	fixed cover; according to emission inventory: N species - EF for fermented livestock manure with fixed cover; CH_4 - EF for fermented energy crops and livestock manure 1)
Solids – storage at plant and in arable region				
Fresh solids	0.013	0.4	0.01	roofed, foil covering; N_2O and CH_4 according to emission inventory: N_2O - EF for solid manure; CH_4 - equivalent to slurry; NH_3 according to Möller et al. (2010)
Dried solids	0	0	0	roofed; stabilisation by means of drying: no emissions (according to FNR 2014)
Liquids – storage at plant and in arable region				
Liquids after separation, N-reduced liquids after stripping, Concentrates after vacuum evaporation and membrane filtration	0	0.015	0.01	fixed cover; according to emission inventory: N_2O - no floating cover, no emissions; NH_3 - EF for fermented livestock manure; CH_4 - EF for fermented energy crops and livestock manure 1)
ASS	0	0	0	Storage in stainless-steel tank, no emissions

1) The emission factor refers to the methane formation potential B0. The KTBL reference value (2015) was used instead of the value for B0 used in the emission inventory.

Table 5: Emission factors used for NH_3 losses after land application of unprocessed digestate and processing products. Emission factors from the emission inventory for German agriculture were taken from Rösemann et al (2017).

Product	NH_3-N kg/kg NH_4-N	Source/explanatory notes on emission factors
Solid processing products		
Fresh solids		
Broadcast, incorporation ≤ 1 h uncultivated field	0.09	According to emission inventory: EF for solid manure wide land application, incorporation ≤ 1 h
Dried solids		
Broadcast, incorporation ≤ 1 h uncultivated field	0	Stabilisation through drying: no emissions (see FNR 2014)

Table continued on next page

Product	NH_3-N kg/kg NH_4-N	Source/explanatory notes on emission factors
Digestate and liquid processing products		
Unprocessed digestate		
Trailing hose, incorporation ≤ 1 h uncultivated field	0.04	According to emission inventory: emission factor for cattle slurry (TM content comparable)
Trailing hose, underneath vegetation	0.35	
Liquids from separation of solid fraction, N-reduced liquids from stripping, concentrate from vacuum evaporation		
Trailing hose, incorporation ≤ 1 h uncultivated field	0.02	According to emission inventory: emission factor for pig slurry (TM content comparable: increased fluidity compared to cattle slurry)
Trailing hose, underneath vegetation	0.125	
Concentrate from membrane filtration		
Trailing hose, incorporation ≤ 1 h	0.01	According to emission inventory: EF for slurry (very free-flowing material with higher infiltration than pig slurry)
Trailing hose, underneath vegetation	0.1	
Ammonium sulphate solution		
Pesticide sprayer, in standing crop (cereal)	0.074	EMEP/EEA (2016)

Nutrient revenues

Revenues were only assumed for the proportion of nutrients used supra-regionally. In addition, we assumed that higher revenues can be achieved for solid processing products and concentrated nutrient solutions – in this case ammonium sulphate solution – than for unprocessed digestate or for the processed liquid fraction. Based on properties in comparison to synthetic fertilizers, such as nutrient availability or aspects of phytohygiene, product-specific factors were therefore established. These factors were used to determine the proportion of the nutrient value the farmers in the receiving region would probably be prepared to purchase (Table 6). We assumed the lowest level of payment for digestate. The revenue generated was calculated on the basis of the quantity of nutrients N and P that were used supra-regionally and available to plants in the application year, the nutrient value (according to KTBL (2016): € 843/t N; € 382/t P_2O_5) and the expected revenue potential ("nutrient value factor" in Table 6). For example, about 70% of 1 t total nitrogen from the liquids after separation with the screw press is available to plants in the year of land application. However, only 0.6 times the nutrient value is taken into account when calculating the revenues from this proportion (Table 6). In many nutrient-rich regions, however, the revenues calculated on the basis of these assumptions cannot be achieved if the nutrients are applied close to the plant. They are therefore particularly relevant for supra-regional commercialisation. When nutrients are sold to customers close to the plant, a lower revenue potential would have to be derived specifically for the region. In the following, it is assumed that the nutrients are not sold regionally, but that the share of digestate or digestate products used regionally is applied on the areas for the provision of substrate for the biogas plant.

Table 6: Revenue potential for unprocessed digestate and processing products used supra-regionally

Product	Advantages/disadvantages in comparison to synthetic fertilisers	Factor nutritional value[1)]	To be applied to nutrients in:
Raw digestate	Not sanitized	0.5	Unprocessed digestate
Solid processing products			
Fresh solids	Not sanitized but positive humus effect	0.9	Untreated solids screw press Solids membrane filtration (screw press plus flocculation/decanter)
Dried solids	Sanitized in addition positive humus effect	1	Dried solids from belt drying
Liquid processing products			
Liquids screw press	Not sanitized more favourable N_{min}/N_{org-} ratio compared to unprocessed digestate	0.6	Untreated fluids screw press
Processed liquids	Sanitized worse N_{min}/N_{org}- ratio compared to unprocessed digestate	0:6	N-reduced liquid fraction from stripping Concentrate from vacuum evaporation and membrane filtration
Ammonium sulphate solution			
ASS 17%	No hygiene concerns only easily available N_{min} lower N and S content than 30% ASS if necessary, additional requirements regarding land application technology	0.8	ASS from belt drying
ASS 30%	No hygiene concerns only easily available N_{min} if necessary, additional requirements regarding land application technology	0.9	ASS from stripping and vacuum evaporation

[1)] The nutrient value factor expresses the proportion of the nutrient value for which a revenue is expected to be generated. For nitrogen, the revenue relates only to the share available in the year of application, i.e. 100% of mineral (NH_4-N) and 5% of organic nitrogen. P was assumed to be entirely available in the year of application.

Nutrient export scenarios

In a number of regions, high nitrogen surpluses limit the possibilities for regionally using livestock manure and digestate produced. However, in other regions, phosphorus is the limiting factor. In regions with particularly high livestock numbers, phosphorus surpluses can be as high as 40% in some cases, and surpluses of nitrogen in extreme cases are even close to 50% (Osterburg et al. 2016, Janssen-Minssen 2016). Depending on the regional situation, significant benefits can therefore already be achieved by partially removing one of the two nutrients. This means that it is not always necessary for all digestate or processing products to be used supra-regionally. For this reason, in addition to complete export, we also considered scenarios in which the export target was related to either nitrogen or phosphorus (Table 7). Depending on the target nutrient, in the partial export scenarios P50 and N50, different products were considered for supra-regional utilisation depending on their nutrient content. For example, in the N scenario, concentrated ASS was first removed from the region, whereas P-enriched solid products were suitable for P export. The export requirement cannot be met by the products best suited to the scenario in all cases. In these cases, products that are not really worth transporting due to lower contents of the target nutrient must also be used supra-regionally.

In addition, complete export, i.e. the supra-regional utilisation of all of the digestate or all products, was also considered. By taking into account all of the digestate or all of the accumulated nutrients, it was possible to compare the technologies independently of individual nutrients. The advantages of individual processing technologies in this case are reflected by the extent to which the volume is reduced in comparison to the unprocessed digestate. This represents an extreme scenario which, in practice, is not likely to occur or only occurs in exceptional cases for plants that do not have any land. However, especially in north-western Germany, large quantities of slurry are already being used on a supra-regional scale.

For both the complete export and the P50 scenario, no advantages were expected for stripping in comparison to the unprocessed digestate, as stripping solely discharges N without reducing the volume. For the sake of completeness and to allow comparison of the individual scenarios, however, the results for stripping are also presented for these two scenarios. In the discussion, stripping is only dealt with in detail for the N50 scenario.

Table 7: Export scenarios under consideration

Scenario	**Export target**
100%	supra-regional utilisation of all nutrients = transport of the entire digestate or all processing products
P50	supra-regional utilisation of 50% of the P load in the digestate
N50	supra-regional utilisation of 50% of the N load in the digestate

Results and discussion

Mass distribution and nutrient content of the processing products

To generate savings in storage, land application and transport, mass distribution is essential, which also reflects the possible volume reduction. In the case of partial export with a focus on a specific nutrient, the nutrient content of the individual processing products also plays an important role. Mass distribution (Figure 1) and nutrient contents (Figure 2) result in the nutrient flows (Figure 3), i.e. the distribution of nutrients among the products.

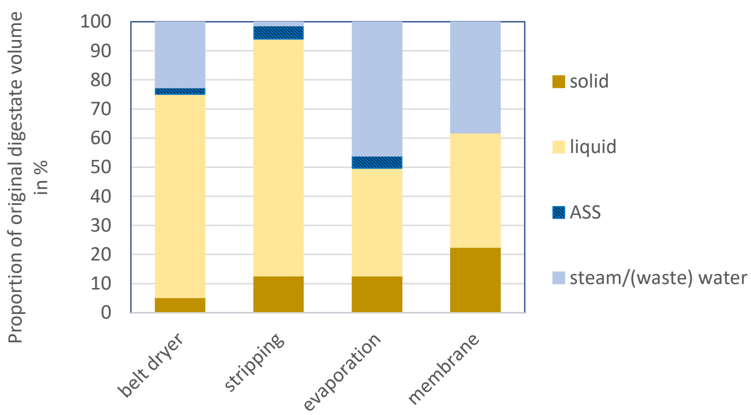


Figure 1: Mass distribution of the processing products in relation to the unprocessed digestate (= 100%)

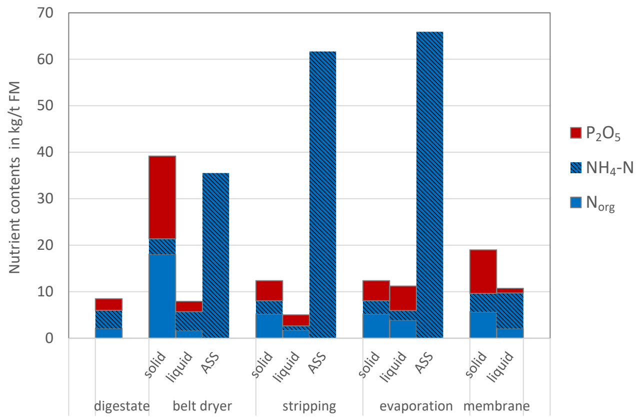


Figure 2: Nutrient content of the processing products

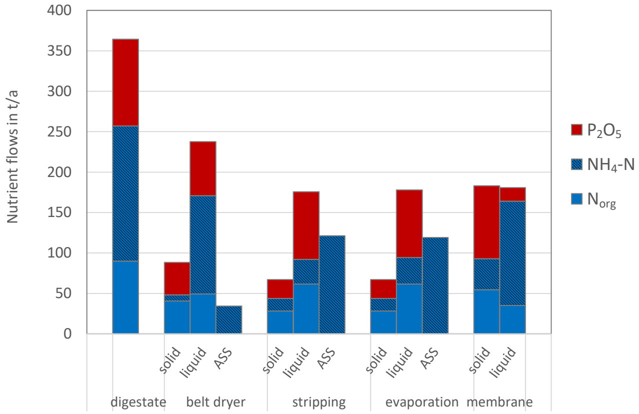


Figure 3: Nutrient flows with the processing products

Costs

Costs for the supra-regional utilisation of all nutrients (excluding process heat costs)

The costs for using all of the unprocessed digestate supra-regionally amount to € 25 per m^3 for a transport distance of 300 km after deduction of the nutrient revenues (Figure 4 on the left). Most of these costs are caused by transport. The storage and land application of digestate contributes much less to the total costs. Moreover, the revenues from the nutrients contained in the digestate are also negligible, not least because only part of the nitrogen is taken into account in the revenues (see Table 6).

On the one hand, the processing of digestate results in additional costs, especially for the installation of the plant, but also for electricity and other operating supplies (Figure 4 on the left). On the other hand, there are also some savings, especially for the transportation of products, as well as higher nutrient revenues. The process heat required for some technologies is not yet taken into account in Figure 4. Stripping is only shown for comparison purposes, for the reasons mentioned above under “Nutrient export scenarios”.

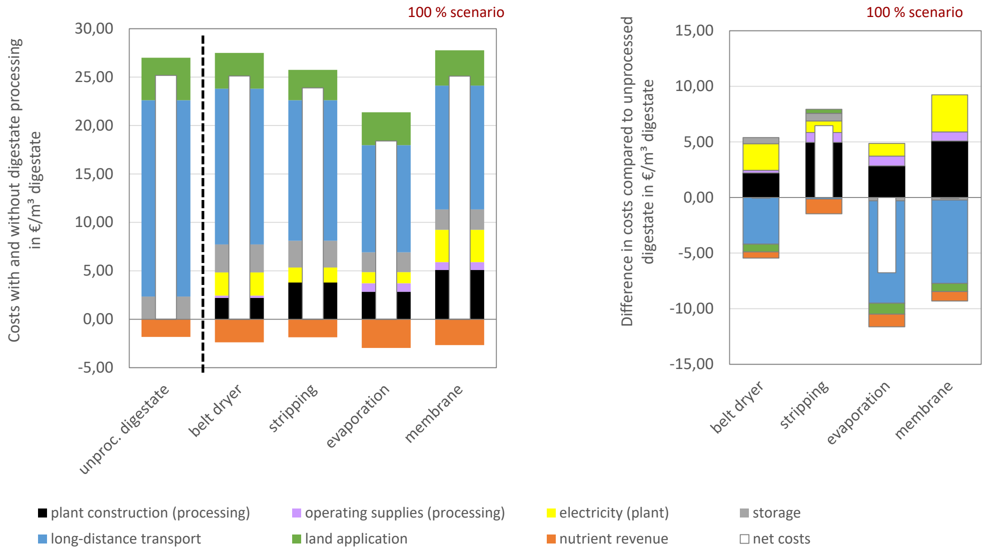


Figure 4: Left: Costs for the supra-regional utilisation of all nutrients with the unprocessed digestate or processing products. Right: Additional costs or savings through digestate processing and utilisation compared to utilisation of the unprocessed digestate. All data for a transport distance of 300 km without taking into account the process heat requirements of some technologies.

In order to make the differences between the individual technologies clearer, the difference between the individual cost categories and the unprocessed digestate is shown in Figure 4 on the right. The zero line in this representation corresponds to the net costs for utilising the unprocessed digestate in this scenario (= balance result (white bar) in Figure 4 on the left; € 25.17 /m^3). Additional costs compared to the unprocessed digestate are shown as positive figures and savings are shown as negative figures. In this case, the balance represents the net costs of the process compared to the unprocessed digestate per cubic meter of digestate. The figures below represent the data using the same format. The absolute costs are not shown, as changes due to the different export targets result almost exclusively in different transport costs.

The plant costs play a particularly important role in the case of stripping and evaporation. The electricity costs are particularly high for membrane filtration due to the high electricity required to power the pumps in the filtration units. They are also substantial for belt drying where exhaust air treatment requires high levels of electricity. Significant savings can be achieved in transport and, to a lesser extent, land application thanks to vacuum evaporation and membrane filtration, as the volume to be transported or stored is halved. With membrane filtration, however, these savings are almost completely offset by the high system and energy costs. The same applies to belt drying with exhaust air treatment; the costs saved for transport compared to the unprocessed digestate are offset by the additional costs for processing.

Buyers were assumed to be more willing to pay higher prices for processing products than for the unprocessed digestate (Table 6), which can generate additional nutrient revenues. However, compared to the other cost factors, these revenues only have a minor impact on the overall result.

For the scenario considered here (300 km, utilisation of all nutrients, process heat not taken into account), significant net savings of around € 6.80 per m^3 of initial digestate can only be achieved by means of vacuum evaporation compared to the utilisation of unprocessed digestate (Figure 4 on the right). With belt drying or membrane technologies, no costs or hardly any costs can be saved under these conditions. If the approaches currently being investigated for more energy-efficient ultrafiltration or replacement technologies can be implemented for ultrafiltration (Bruess et al. 2018), a significant cost reduction might be possible for this technology. This could result in advantages over the unprocessed digestate, at least for the conditions in this scenario (300 km; complete export).

Costs taking into account process heat

If the opportunity costs for the required process heat are taken into account (Figure 5 in the centre), this significantly increases the costs for drying and vacuum evaporation due to the high heat requirement. For stripping this is less significant, since far less heat is used. Viewed from this angle, membrane technology is the most favourable processing technology because it does not require any heat. Evaporation incurs additional costs compared to the utilisation of unprocessed digestate, despite high savings for long-distance transport.

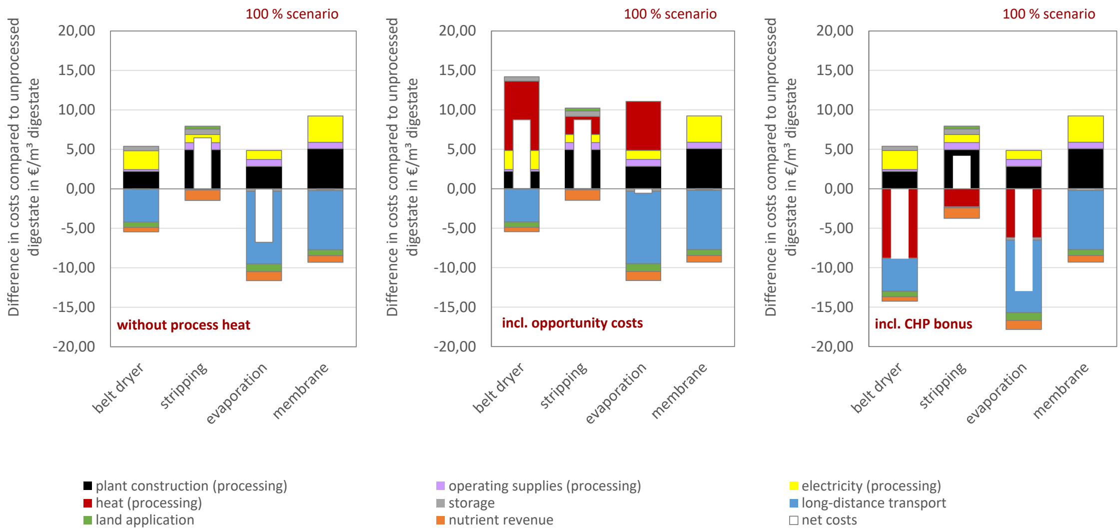


Figure 5: The impact of taking into account process heat on the costs of digestate processing and utilisation for complete export (“100%”) and a transport distance of 300 km; representation is a comparison with utilisation of unprocessed digestate. Left: without consideration of the process heat for processing, centre: representation taking into account opportunity costs, right: representation taking into account revenues from the CHP bonus.
Costs for the utilisation of the unprocessed digestate as a comparison (= zero line/reference value): € 25.17/m³.

However, if the plant can claim the CHP bonus for using heat (Figure 5 on the right), the heat-using technologies have economic advantages. The use of all residual heat was assumed for belt drying here, resulting in the revenues far exceeding the savings from long-distance transport. In total, the net savings under these conditions amount to almost € 9. Significant revenues from the CHP bonus can also be achieved for vacuum evaporation with lower heat requirements. As a result, the net saving compared to unprocessed digestate rises to approx. € 13 per m³ of digestate.

Costs depending on the export target

In addition to complete export, we also considered partial export scenarios for the target nutrients N and P. This is because there is not always a surplus of all nutrients. Rather, some regions only need a reduction of one of the two nutrients discussed in the context of the revision of the Fertiliser Ordinance. The different processing technologies result in a different distribution of the two nutrients in the resulting mass flows (Figure 3). In some cases, the resulting processing products differ considerably with regard to their nutrient contents and mass distribution (Figure 2 and Figure 1). This factor can be used specifically to minimise the transport requirements by first using the products with the highest concentration of the target nutrient for supra-regional utilisation. In this respect, it should be considered whether other technologies are more advantageous for a 50% P or N export (P50 or N50) under these conditions than for complete export (100%). In fact, depending on the target nutrient, other processing technologies may be suitable for partial export. In both scenarios, the net cost of utilising the unprocessed digestate is € 16/m^3, as half of the total digestate has to be transported.

Scenario P50

For example, belt drying shows slight advantages for the partial export of phosphorus (Scenario P50) compared to the supra-regional utilisation of all nutrients (Figure 6 in the centre). Already in the first step – separation with the screw press – there is a concentration of phosphorus in the solid fraction (Table 2, Figure 2), which is the case for all technologies considered here. In addition, during belt drying, further phosphorus is transferred into the dry material by adding part of the liquid fraction. In total, about 35% of the P is thus available in a form that is suitable for transport (Figure 3). The savings incurred by transport and land application for a supra-regional utilisation of 50% of the total P compared to the unprocessed digestate compensate for the additional costs incurred by the processing. This results in a saving of about one euro per cubic metre of initial digestate.

As expected, there are no advantages for stripping, as this technology recovers only N. Evaporation also halves the volume of the liquid fraction (Figure 1). The concentrate therefore has higher P concentrations than the initial product (liquid fraction from SPS) (Figure 2), further reducing transport costs. However, only some of the products need to be transported to achieve the export target. Hence, savings in transport compared to complete export have only a limited effect and cannot compensate for the high plant and operating costs. Overall, at just under 90 cents per cubic metre of unprocessed digestate, a significantly lower net saving is achieved compared to the use of all nutrients (scenario 100%, Figure 6 on the left).

Membrane technology leads to a significantly larger proportion of the phosphorus contained in the digestate being transferred to the solid fraction. This is achieved by additionally separating the solids with the decanter centrifuge (Figure 3). In order to use 50% of the P supra-regionally, none of the liquid product has to be transported here. In this scenario, therefore, the highest savings for membrane filtration are achieved through lower transport requirements compared to the unprocessed digestate. However, due to the high plant and energy costs, no cost savings are possible compared to utilisation of the unprocessed digestate; indeeed, additional costs of € 1.10 per cubic metre of initial digestate are incurred. Alternatively, for the P50 scenario, after separating the solids in two stages (SPS and DC), further processing of the liquid fraction could be dispensed with, as the export target is already met. Accordingly, investment and energy costs would be significantly lower. At the same time, however, storage and output costs would be higher, because twice as much liquid product would be produced than when using membrane technology. This option was not examined in the project.

Scenario N50

If primarily nitrogen has to be exported from the surplus region (scenario N50; Figure 6 on the right), there is a cost advantage for stripping compared to unprocessed digestate, in contrast to the two scenarios considered so far. The aim of stripping is to recover N from the liquid fraction: Approx.

47% of the total nitrogen load of the digestate is bound in a highly concentrated ammonium sulphate solution (ASS). It is possible to almost achieve the export target of 50% of the digestate's N load by solely extracting the ASS on its own. This leads to significant savings in long-distance transport as the high costs of transporting the barely reduced liquid fraction are largely eliminated. However, due to the high plant costs, savings of only about € 1.60 per cubic metre can be achieved compared to the unprocessed digestate. The same applies to vacuum evaporation, but in this case the total volume is significantly reduced. This saves additional costs for land application. In total, the use of vacuum evaporation results in a cost saving of € 6 per cubic metre of unprocessed digestate.

In the N50 scenario, belt drying results in only minor changes to the net costs compared to the utilisation of the unprocessed digestate. The savings from transport are lower than for the P50 scenario, as it produces only a small amount of nitrogen in the form of ASS and no strong concentration of nitrogen in the dry material occurs. Thus, a comparatively large proportion of the liquid fraction still has to be utilised supra-regionally, so that in the end additional costs are roughly equivalent to the savings from processing.

Despite reduced total volumes, membrane filtration leads to significant additional costs of approx. € 4 per cubic metre of initial digestate. Unlike for phosphorus, this technology does not result in a significant concentration of nitrogen in any of the processing products (Figure 2). Therefore, the savings in long-distance transport for this target nutrient are significantly lower than for P export and cannot compensate for the high processing costs.

Nutrient revenues

Nutrient revenues play a minor role in the overall result of the cost calculations. This is because the calculation takes into account only the nutrients from digestate or processing products that are used supra-regionally for the revenues. Furthermore, only the quantity available to plants in the year of application was taken into account – a significant aspect for nitrogen (Table 6). In the P50 scenario (Figure 6, in the centre), the nutrient revenues for the processing technologies are lower than for the unprocessed digestate, despite the higher revenue potential of the products. This is because 50% of the nitrogen in the unprocessed digestate is also used supra-regionally and is at least partially remunerated. In contrast, processing results in the P export target being achieved almost exclusively by exporting products with low or poorly available nitrogen contents (solid products, N-reduced liquid fractions). This means that only little and mainly organic nitrogen is used supra-regionally. This difference to the unprocessed digestate cannot be offset by higher revenue potentials for the nutrients contained in the processing products. On the other hand, nitrogen export (N50) can lead to very high revenues for ASS, as it contains only mineral nitrogen, which is fully credited and highly remunerated. This leads to additional revenues, especially for stripping and vacuum evaporation, compared to the unprocessed digestate (Figure 6 on the right). If all nutrients are taken into account (100% scenario), higher revenues for the products are fully realised (Figure 6 on the left).

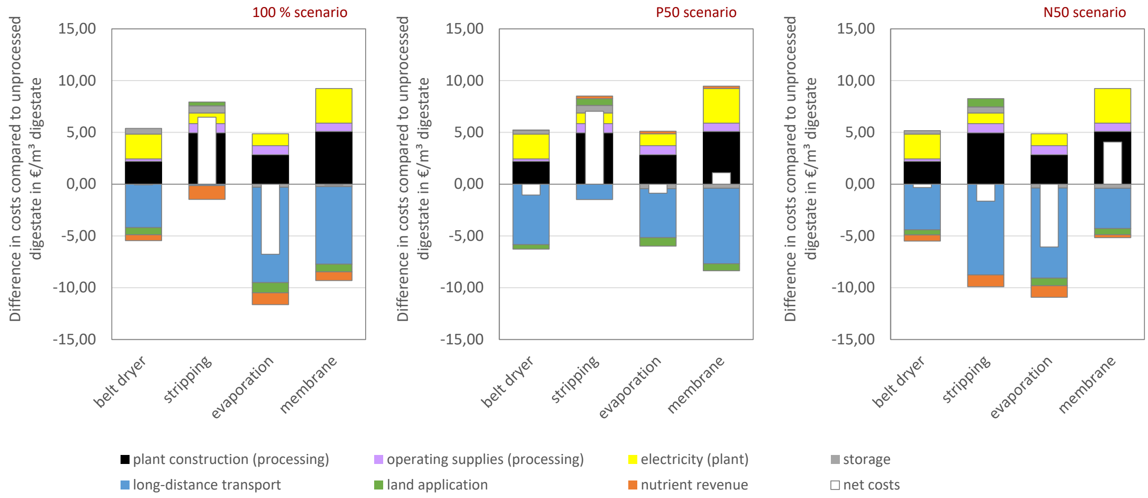


Figure 6: Costs of digestate processing compared to the utilisation of unprocessed digestate depending on the export target for a transport distance of 300 km for the supra-regionally utilised part, not taking into account process heat. On the left: export target for all nutrients, centre: export target for 50% of the phosphorus load in the unprocessed digestate, right: export target for 50% of the nitrogen load in the unprocessed digestate.
Nutrient revenues were only assumed for nutrients that are used supra-regionally.
Costs for the utilisation of unprocessed digestate for comparison (= zero line/reference value in the respective scenario): 100% € 25.17/m^3; P50 and N50 € 15.99/m^3.

If heat costs or CHP revenues are considered, the costs change in the two partial load scenarios, as described for the 100% scenario.

Costs in relation to the transport distance

The advantages of reduced transport volumes are particularly noticeable for long-distance transport. However, not all surplus regions require very long transports. For most of the processing technologies and scenarios considered, lower savings in transport costs are achieved in regionally limited surplus regions. As a result, processing products no longer have a cost advantage over unprocessed digestate. The following figures (Figure 7 ff) show only the net costs in comparison to the unprocessed digestate. Thus, the balance values in Figure 5 correspond to the values for 300 km in Figure 7 (influence of heat in the 100% scenario), and the values in Figure 6 correspond to those for 300 km in Figure 8 (comparison of export target).

Transport distance and heating costs

If process heat is not taken into account (Figure 7 above; 100% scenario), vacuum evaporation, which is advantageous for 300 km, does not even achieve savings compared to the utilisation of unprocessed digestate at transport distances under 150 km. If the opportunity costs for heat have to be estimated (Figure 7 in the centre), Figure 5 already showed that processing does not result in any savings, even with transport over long distances. If, however, a CHP bonus can be generated (Figure 7 below), the two technologies with high heat requirements – belt drying and vacuum evaporation – result in lower costs than for unprocessed digestate, even when it is used close to the plant. However, this only applies to a limited extent to smaller biogas plants (no figure); in contrast to the 2 MW plant size shown here, these plants likely incur considerably higher specific capital costs.

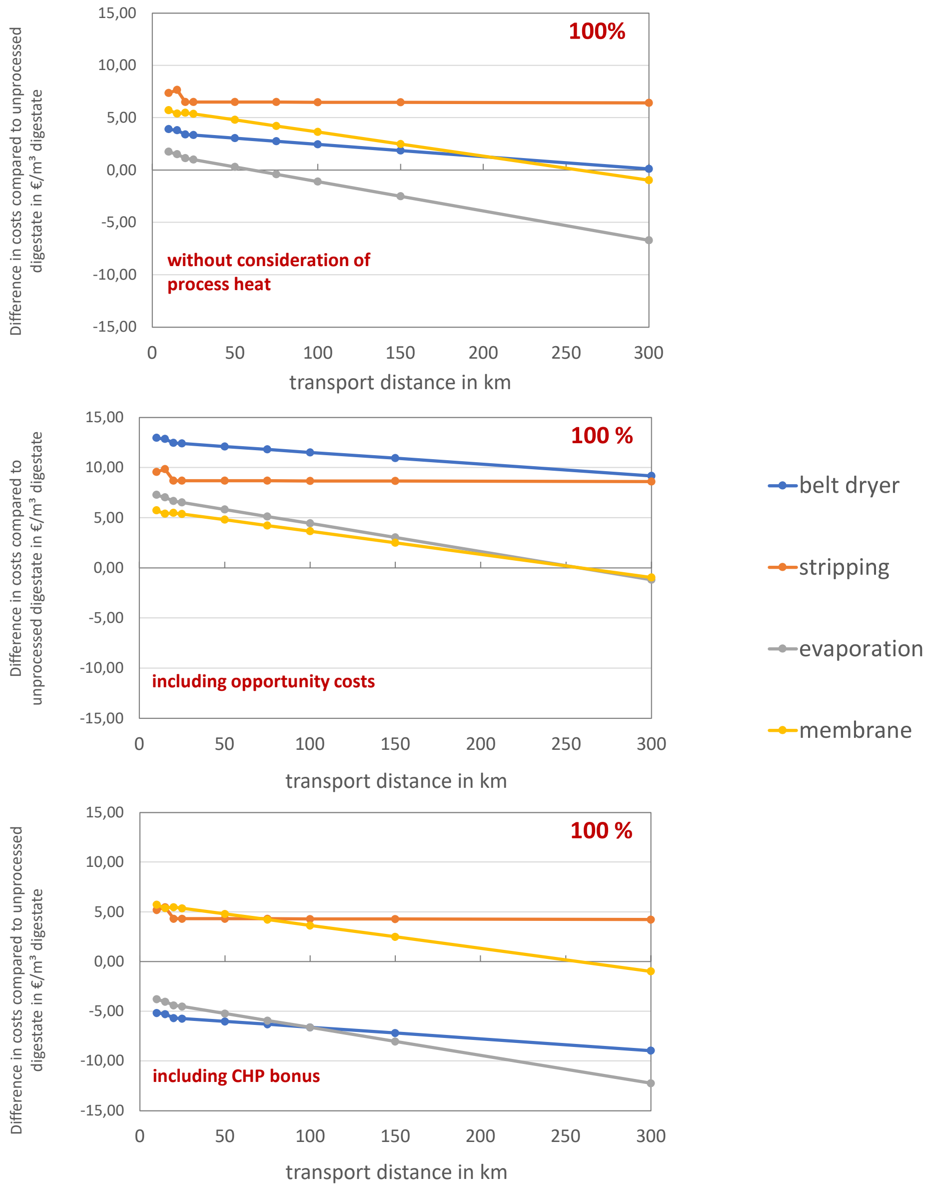
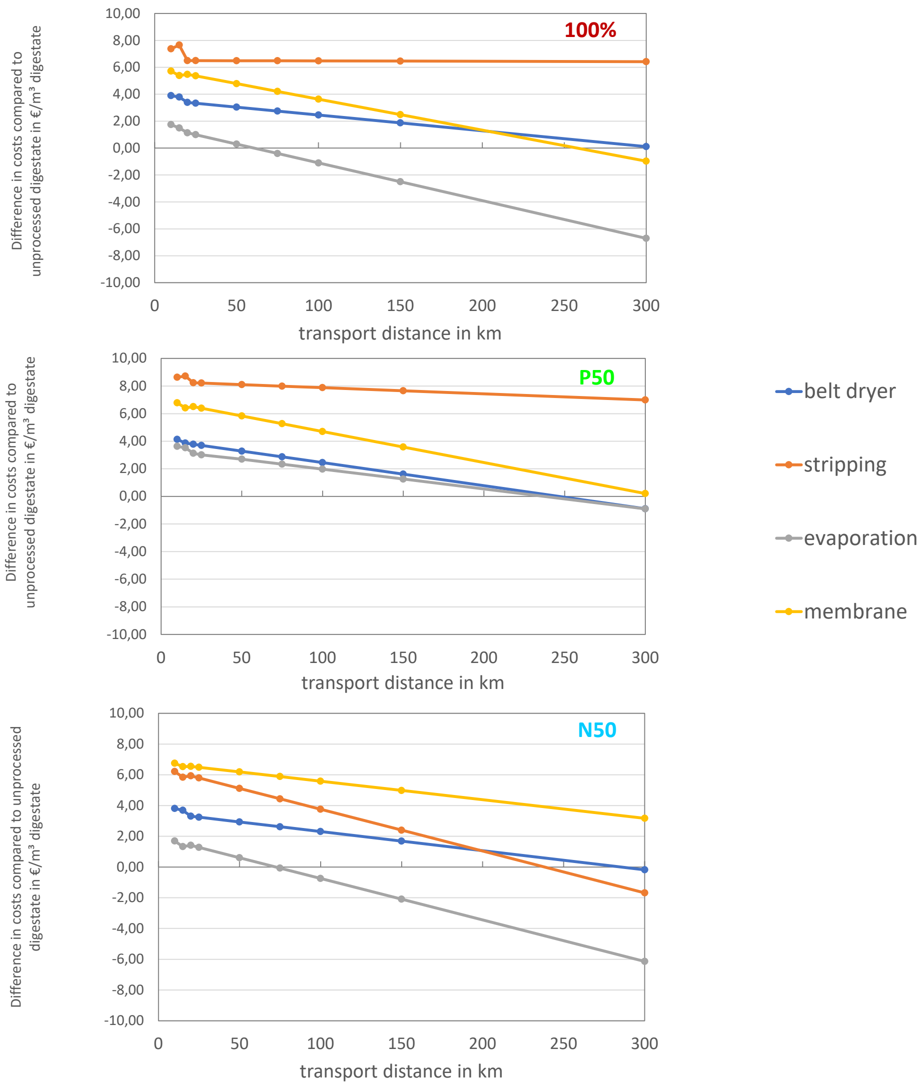


Figure 7: Costs of digestate processing and utilisation compared to unprocessed digestate depending on transport distance for entirely supra-regional utilisation (100% scenario) and with different considerations of process heat. Top: without taking into account the process heat demand of some processing technologies; centre: opportunity costs for process heat; bottom: generation of the CHP bonus for process heat.

The pattern for stripping is different from the other technologies. First, there is an increase in costs for distances between 10 and 15 km. Then, the total costs drop noticeably compared to the other processing technologies and largely remain constant for all further distances. At 20 km, there is a switch from single-phase to multi-phase logistics in the calculations. From this distance onwards, the transport outlay for the products from stripping roughly corresponds to the costs for the digestate in the 100% scenario under consideration (cf. for 300 km Figure 6 above), regardless of the distance. This is because this technology hardly reduces the total volumes, which must always be transported in full in the 100% scenario. For short distances, where transport and land application are performed in a single phase, this leads to a cost increase at distances between 10 and 15 km due to the longer distance between the farmyard and the field. Other technologies, however, allow savings to already be achieved because lower volumes of liquid fraction (evaporation, membrane) and solid fraction (belt drying) need to be transported. For this reason, the costs rise more significantly when switching to discontinuous logistics with cheaper lorry transport for products from stripping than for those issuing from the other processing technologies.

Transport distance and export target

If we compare the impact of the transport distance on the costs for the different export targets (Figure 8), vacuum evaporation is the only technology to offer advantages over unprocessed digestate for distances up to 150 km, but only for complete and 50% N export (100%, N50; Figure 8 above and below). Compared to the utilisation of unprocessed digestate, all other technologies only achieve savings at 300 km, if at all. In the direct vicinity of the plant, however, this is not possible, even with vacuum evaporation. Costs saved for transport outweigh the additional costs for processing the digestate only for distances from 50 to 75 km.



	scenario	transport distance in km								
		10	15	20	25	50	75	100	150	300
costs for transport and application of untrieated digestadte in €/m³ digestate (= baseline/reference value without processing)	100%	7,61	8,83	7,54	7,86	9,43	11,01	12,58	15,73	25,17
	P50 / N50	7,07	7,68	7,17	7,33	8,11	8,9	9,69	11,26	15,99

Figure 8: Costs of digestate processing and utilisation compared to unprocessed digestate depending on transport distance and on the export target. Top: export target for all nutrients, centre: 50% of the phosphorus load in the unprocessed digestate, bottom: export target 50% of the nitrogen load in the unprocessed digestate.
No costs or income for the required process heat were considered.

Greenhouse gases

Greenhouse gas emissions caused by the supra-regional utilisation of all nutrients

Many of the observations described above regarding the determining factors and advantages of individual processing technologies apply in a similar form to greenhouse gas emissions. However, the overall conclusion is in part different to the conclusions for the cost considerations due to factors such as direct emissions.

If we first consider the greenhouse gas emissions generated by the supra-regional utilisation of the entire digestate (100% scenario) without processing (Figure 9, on the left), it becomes clear that transport has the greatest effect, as was the case for the costs. In addition, the direct losses of NH_3, N_2O and CH_4 during storage and land application of the digestate are of particular importance. One reason for this is the assumption that after the legally required 150 days in a gas-tight system at the biogas plant the digestate is stored in the region where it has been transported. There it is not possible to store the digestate in a gas-tight manner because the retained methane cannot be used. The replacement of mineral fertilisers also has a significant effect on greenhouse gases. The production of mineral fertilisers requires a high energy input and issues nitrous oxide emissions, thus offsetting a significant proportion of the emissions from the transport and land application of digestate (approx. 40%). The net emissions for complete nutrient export without prior processing are almost 31 kg CO_2eq/m^3 digestate for a transport distance of 300 km (Figure 9 on the left).

If the digestate is treated in processing plants, the construction of these plants results in only minor greenhouse gas emissions compared to other emission sources. The most important additional source of greenhouse gas emissions compared to unprocessed digestate is electricity for all processing technologies. This applies in particular to drying, because exhaust air treatment is assumed to require high levels of electricity, and to membrane filtration which operates at high pressures. At lower overflow speeds, fouling/scaling otherwise occurs more frequently. As is the case for the costs, greenhouse gas emissions from long-distance transport are avoided to a large extent with drying, evaporation and membrane technologies. This is not possible with stripping because it does not reduce the volume.

Processing has both positive and negative effects on direct emissions (Figure 9, on the right). For example, it is possible to avoid direct or indirect losses of N (N_2O, NH_3) from storage and land application which impact the climate. This is because the liquid products from processing have lower emission factors than the digestate, unless the latter is stored in a gas-tight manner (cf. Table 4 and Table 5). In the 100% scenario, in which all of the digestate is stored open, the savings achieved in this way by means of stripping and evaporation outweigh the additional emissions from the separated solids, which are higher than those from the digestate. The effect is even more pronounced for drying. The stabilised dried solids are assumed to generate no emissions during storage and land application. In addition, NH_3 losses from the drying process are avoided as far as possible through exhaust air treatment.

In contrast, membrane technology leads to an increase in N losses. This is because separation with the decanter results in larger quantities of solid fraction and, in turn, larger quantities of organic and mineral N (cf. Figure 3). NH_3 and N_2O emissions from the solid product are therefore higher than for the other technologies and exceed the savings arising from storage and land application of the liquid fraction. This is mainly due to the high greenhouse gas potential of nitrous oxide, so that additional N_2O emissions from storage have a disproportionate effect on the system's GHG emissions.

While drying and evaporation together prevent greenhouse gas emissions compared with supra-regional utilisation of the entire digestate volume (100% scenario), stripping and membrane filtration lead to additional emissions (Figure 9, on the right). Improvements in membrane technology (Bruess et al. 2018) could possibly lead to advantages for these technologies, at least for widespread nutrient surpluses and the resulting long transport distances.

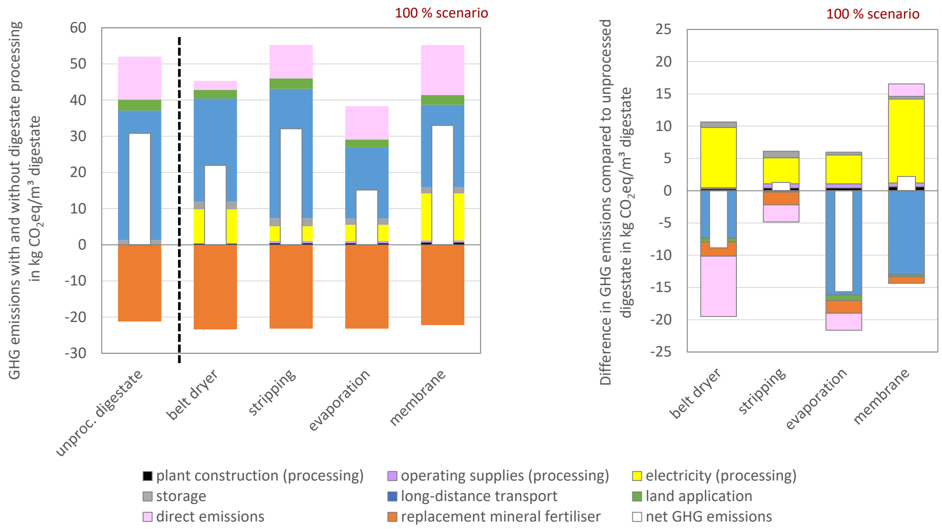


Figure 9: Left: greenhouse gas emissions for the supra-regional utilisation of all nutrients with the unprocessed digestate or processing products. Right: increased or reduced emissions due to additional digestate processing and utilisation. All data based on a transport distance of 300 km without considering the process heat requirements of some technologies.

Greenhouse gas emissions taking into account process heat

The net balances of technologies that use process heat deteriorate significantly when taking into account the greenhouse gas emissions for the required process heat (Figure 10, on the right; reference natural gas). Even for the assumed long transport distance of 300 km, none of the technologies under consideration results in emission savings compared to the utilisation of the unprocessed digestate under these conditions. Even membrane filtration, which is not dependent on process heat, causes more greenhouse gas emissions than the unprocessed digestate, at least with the current technology (see above). However, as described above, improvements are currently being developed. For plants without freely available heat, these developments could result in membrane technology being the only technology that can achieve greenhouse gas savings compared to the use of digestate supra-regionally when long distances have to be covered.

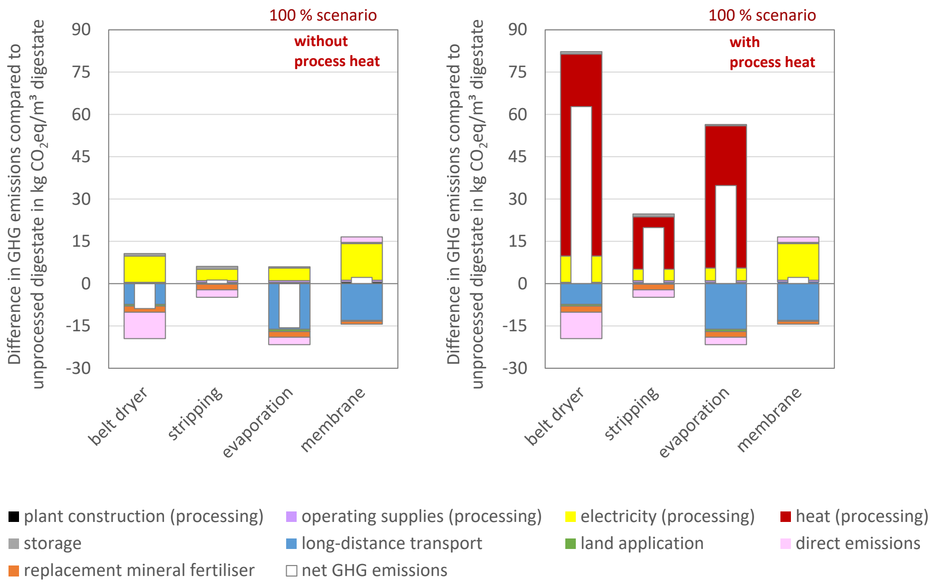


Figure 10: Influence of taking into account process heat on greenhouse gas emissions from digestate processing and utilisation for complete export (100% scenario) and a transport distance of 300 km; representation in relation to the utilisation of unprocessed digestate. Left: without taking into account the process heat demand of some processing technologies, right: representation taking into account reference emissions for fossil resources that are not replaced (natural gas). Emissions from the utilisation of unprocessed digestate for comparison (= zero line/reference value): 30.8 kg CO_2eq/m^3.

Greenhouse gas emissions as a function of the export target

In all three export scenarios considered (P50, N50, 100%), drying and vacuum evaporation make it possible to save greenhouse gas emissions compared with the utilisation of unprocessed digestate (Figure 11). As expected, stripping only achieves this for the nitrogen target (Figure 11, on the right). In the case of membrane technology, the net balances are higher than those for digestate utilisation without processing in all scenarios.

As for costs, if only 50% of the P or 50% of the N is to be used supra-regionally, the effect of reducing the volume with processing is less significant. For some technologies, however, the advantage of a concentration in individual products is evident, e.g. in ASS resulting from stripping and evaporation (Figure 11, on the right) or in the dry material resulting from belt drying or the solids from membrane filtration (Figure 11, in the centre).

The export target also changes the amount of direct emissions in comparison to the unprocessed digestate. This is because half of the unprocessed digestate is stored at the plant, i.e. in gas-tight facilities, in the partial export scenarios (P50, N50). Compared to the 100% scenario, this leads to significantly lower total emissions for the utilisation of the unprocessed digestate; they fall from 31 kg to only 8.6 kg CO_2eq/m^3 digestate. This reduction in the storage of digestate outweighs the positive effects of processing on the emissions of the various liquid products (cf. Table 4). Compared to the utilisation of the unprocessed digestate, no direct emissions can therefore be saved by vacuum evaporation and stripping, in contrast to complete export (100%) (Figure 11, in the centre (P50) and right (N50)). For membrane filtration, which, as described above, leads to high emissions from the solid fraction, there are much higher direct emissions for both partial export scenarios in comparison to the unprocessed digestate. Only drying with exhaust air treatment still show clear advantages in terms of direct emissions, even for 50% P or N export. In the P50 scenario, drying performs better overall than vacuum evaporation, because additional savings can be achieved for transport under these conditions.

All technologies with ASS production (drying, stripping, evaporation) achieve appreciable reductions in greenhouse gas emissions compared to digestate for 50% nitrogen export (Figure 11, on the right). This is particularly noticeable for stripping and evaporation, where a large proportion of the nitrogen is transferred from the liquid fraction to the ASS.

Of all scenarios and treatment technologies the highest net greenhouse gas emissions compared to unprocessed digestate result from membrane technology with N as the target nutrient. Alongside high direct emissions, this is because transport savings are not very high, caused by a low concentration of nitrogen in the individual processing products.

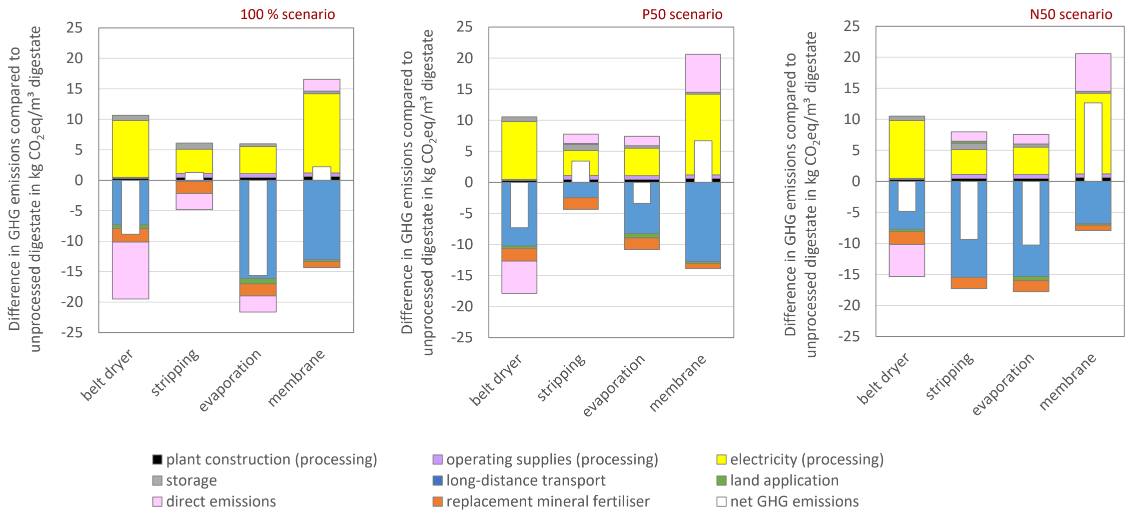


Figure 11: Greenhouse gas emissions from digestate processing compared to the utilisation of unprocessed digestate depending on the export target, not taking into account the process heat and for a transport distance of 300 km for the supra-regionally utilised part. Left: export target for all nutrients, centre: export target for 50% of the phosphorus load in the unprocessed digestate, right: export target for 50% of the nitrogen load in the unprocessed digestate. Emissions from the utilisation of the unprocessed digestate for comparison (= zero line/reference value in the respective scenario): 100% 30.8 kg CO_2eq/m^3; P50 and N50 8.6 kg CO_2eq/m^3.

Replacement of mineral fertilisers

The greenhouse gas balance also included the nutrients in the products that were utilised regionally, while the cost considerations were based on the assumption that revenues are only generated from the products used supra-regionally. Therefore, all technologies in all scenarios save greenhouse gas emissions by replacing mineral fertilisers in comparison to unprocessed digestate. At first glance, this may seem to contradict the partially higher direct emissions. However, the N_2O losses from storage have a disproportionately high impact due to their high greenhouse gas potential. For the replacement of mineral fertilisers, however, the form of the N loss is irrelevant. Thus, for example, in membrane filtration, high emissions from storage losses (NH_3 and N_2O) are partially offset by significantly lower NH_3 losses when the concentrates are applied to the land.

Greenhouse gas emissions in relation to transport distance

Transport distance and emissions from heat use

Shorter transport distances also result in correspondingly lower net greenhouse gas savings compared to the utilisation of unprocessed digestate. However, from distances of 20 km onwards, emissions can be avoided by means of belt drying and evaporation, if process heat is not taken into account and a complete export of the load is aimed at (Figure 12 above), albeit initially only reduced to a small extent. In contrast, under these conditions, none of the technologies considered has yet achieved cost savings, even for a distance of 100 km (Figure 7).

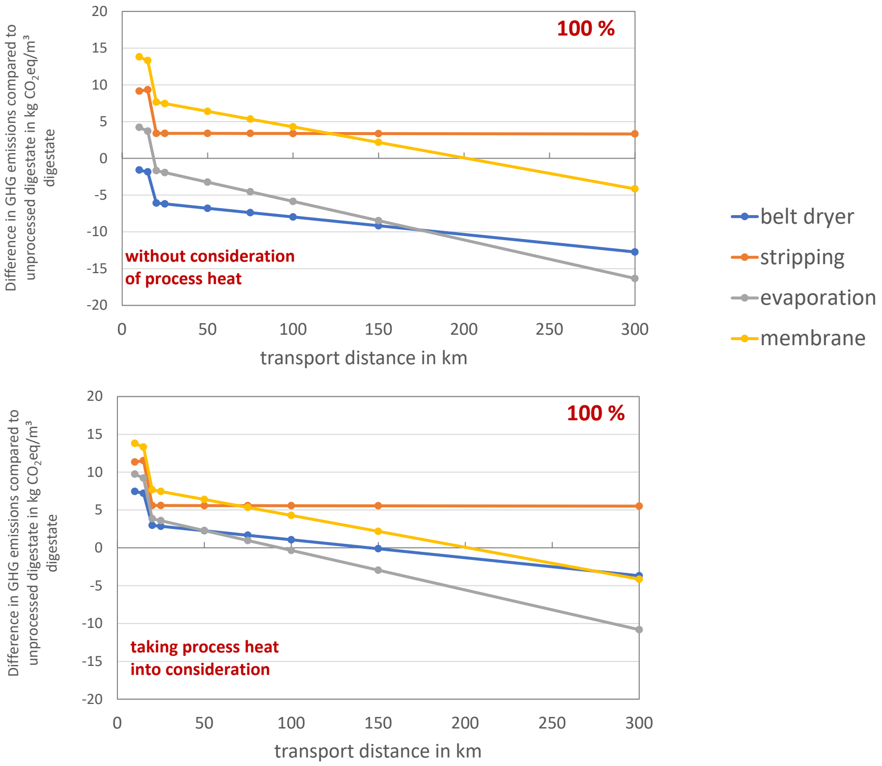


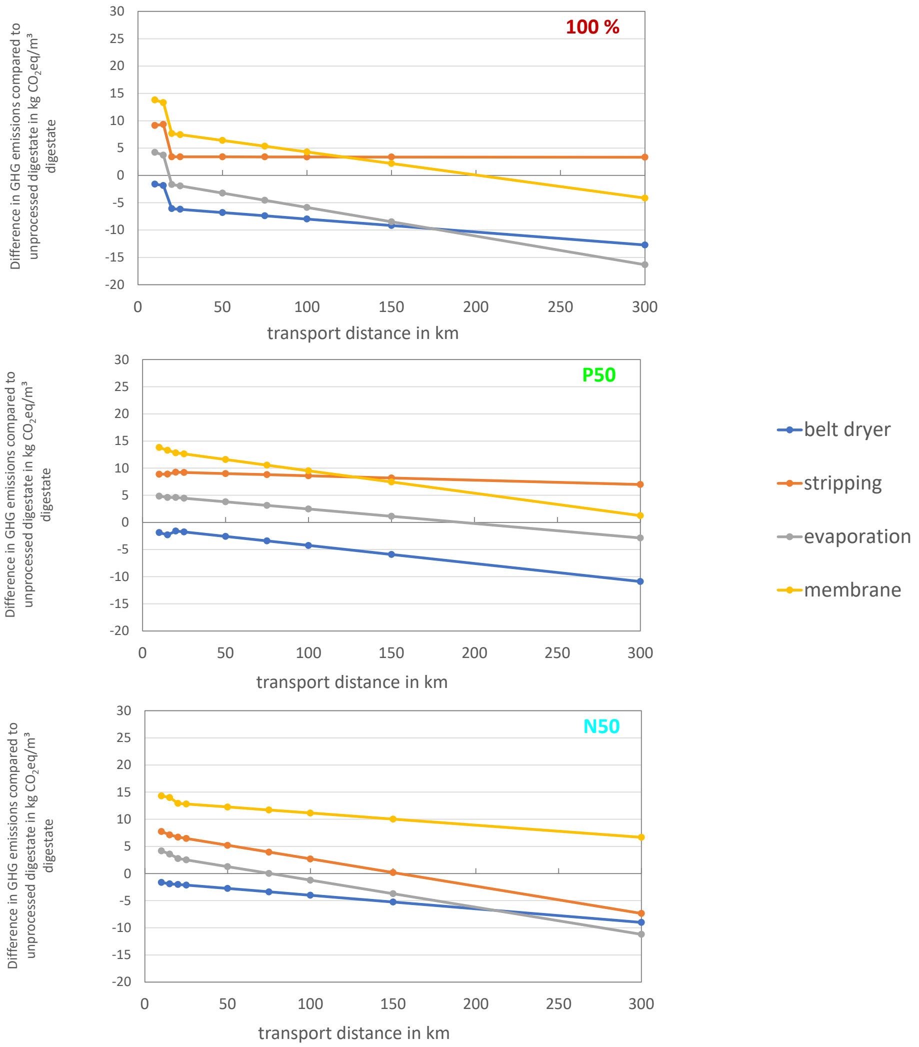
Figure 12: Greenhouse gas emissions from digestate processing and utilisation compared with unprocessed digestate depending on transport distance for entirely supra-regional utilisation (100% scenario) without (top) or with (bottom) consideration of process heat.

If reference emissions for process heat are taken into account, greenhouse gas emissions of heat-using technologies increase substantially for some technologies (Figure 12 below). This is because it is assumed that the heat required for processing is no longer available for other uses, which would replace fossil resources. The penalty charged to heat-using technologies is correspondingly high. Under these conditions, none of the technologies can save greenhouse gas emissions compared to unprocessed digestate, even for a distance of 300 km. However, membrane filtration, which is powered uniquely by electricity, causes only minimal additional emissions. If this technology were to become more efficient (Bruess et al. 2018), it could possibly lead to greenhouse gas savings for widespread surplus regions in the future.

The decrease in emissions between distances of 15 and 20 km is because we assumed that the products would have to be stored in the regions purchasing them for distances over 20 km. In addition to a change in the logistics process (single-phase to multi-phase), the direct emissions issued by the unprocessed digestate are affected (gas-tight storage at the plant; supra-regional storage not gas-tight). We assumed lower emission factors for the liquid processing products than those for the open storage of unprocessed digestate (Table 4). Therefore, for distances of 20 km and above, emissions from storage can be saved compared to the unprocessed digestate.

Transport distance and export target

The decrease in greenhouse gas emissions between a 15 and 20 km distance described above for the 100% scenario was either not observed or found to be only minimal for the partial export scenarios P50 and N50. This is because half of the digestate is still stored in gas-tight facilities, which means that fewer direct emissions can be saved with processing than for complete export (100%). In this scenario, greenhouse gas emissions can be saved by means of drying and vacuum evaporation already from distances of 20 km onwards compared to the utilisation of unprocessed digestate (Figure 13 above). In the P50 scenario, this is only possible with drying from a distance of about 75 km from the plant; for all other technologies greenhouse gas emissions are saved from a distance of more than 150 km (Figure 13, in the centre). When N is the target nutrient, the greenhouse gas emissions generated by drying, stripping and evaporation are lower than those generated with digestate utilisation without processing from distances of about 100 km onwards (Figure 13 bottom).



	scenario	transport distance in km								
		10	15	20	25	50	75	100	150	300
costs for transport and application of untrieated digestadte in kg CO2eq/m³ digestate	100%	-7,43	-5,86	-1,8	-1,21	1,69	4,6	7,51	13,33	30,79

Figure 13: Greenhouse gas emissions from digestate processing and utilisation compared with unprocessed digestate depending on the transport distance and on the export target. Top: export target for all nutrients, centre: export target for 50% of the phosphorus load in the unprocessed digestate, bottom: export target for 50% of the nitrogen load in the unprocessed digestate.
No costs or income for the required process heat were considered.

Comparison of the results: the effects of processing on costs and greenhouse gases

As mentioned above, the results for greenhouse gas emissions and costs often point in the same direction. For example, some important factors generate costs and emissions at the same time or contribute to savings in both areas. This applies in particular to the transport of digestate and products, which generates both costs and greenhouse gas emissions and can possibly be reduced by processing. Similarly, the energy requirements of the technologies lead to a substantial increase in both costs and emissions; this increase is slightly higher in percentage terms for greenhouse gases than for costs. The individual items do not always have the same effect on the analysis of costs or greenhouse gases. For example, plant costs account for 18% of total costs for the capital-intensive membrane technology (100% scenario, heat not considered, nutrient revenues considered). The greenhouse gas emissions resulting from plant construction, on the other hand, account for only 2% of total emissions (100% scenario, heat not considered, replacement of mineral fertilisers considered). Also, if there is a surplus of previously unused CHP excess heat at a biogas plant, considerable additional revenues can be generated from CHP by means of heat-using processing technologies such as belt drying or vacuum evaporation. There is no equivalent in the calculation of greenhouse gas emissions, as no emissions are credited for additional heat use in these scenarios. For greenhouse gas emissions, direct emissions from processing, storage and land application are an additional factor. For example, the advantage of belt drying over unprocessed digestate in the 100% scenario (without heat) is more or less solely because direct emissions are completely avoided (Figure 11, on the left). In contrast, direct emissions from membrane technology are responsible for additional greenhouse gas emissions compared to the use of unprocessed digestate, especially in the partial export scenarios considered (Figure 11, centre and right).

Overall, in some scenarios, the assessment of individual technologies therefore varies considerably depending on whether one is analysing the scenario from a cost perspective or a greenhouse gas perspective. For example, from a cost perspective, vacuum evaporation is preferable to non-processing of the digestate for all distances with 100% export, providing that heat is available, thus resulting in revenue potential from the CHP bonus (Figure 7, on the right). On the other hand, it only has a positive greenhouse gas effect for a transport distance of between 15 and 20 kilometres (Figure 12, on the left). Membrane filtration would never be used to minimise costs in the 100% export scenario. On the other hand, from an emissions point of view, it is preferable to not treat the digestate for distances of 300 km and beyond. These examples show that there can be both synergies and conflicts between the climate protection goals and economic optimisation goals of a plant. This point may require attention when defining the political regulatory conditions.

Conclusions

For regions with a high demand for the export of digestate and the resulting long transport distances, the processing of digestate enables the reduction of costs and greenhouse gas emissions. Depending on the target nutrient and the extent of export, different technologies are available. However, the advantage of processing is significantly lower for medium and short distances. Under these conditions, most technologies incur additional costs or emissions compared to the supra-regional utilisation of the unprocessed digestate.

Belt drying in conjunction with exhaust air treatment and vacuum evaporation are particularly suitable if costs or emissions related to process heat requirements are not taken into account and if there are no regional heat utilisation possibilities. If nitrogen is the export target, considerable savings can also be achieved with the stripping technology for long distances. Membrane filtration does in most cases not lead to any savings, not least because of its high electricity requirements, despite considerably reduced transport volumes. This technology, which is the only one that does not require heat, needs to be further improved to enhance its energy efficiency and develop less energy-intensive alternatives to ultrafiltration.

Technologies with high heat requirements, such as belt dryers or evaporation, are unsuitable if no heat is available, and costs or emissions for the process heat demand have to be factored in. However, if a CHP bonus can be claimed, these technologies have considerable cost advantages.

General conclusions on the individual technologies can only be drawn to a limited extent. The merit of the individual technologies depends on the regional and plant-specific conditions, such as

- target nutrient for export,
- export requirements (partial or complete export),
- availability of heat,
- size of the plant,
- marketing opportunities for processing products.

Processing has only a minor impact on the greenhouse gas emissions of the biogas electricity produced by the plant under consideration, as the emissions per kWh_{el} are predominantly from the renewable resource supply and the operation of the biogas plant (process electricity demand, CH_4 losses, etc.). Only crediting of reference emissions for process heat has a significant effect, because this eliminates the credit for the replacement of fossil fuels.

In addition to the energy efficiency of the technologies, it is necessary to more effectively avoid emissions from the storage of enriched solid products from the separation process. Another goal should be to achieve a more targeted separation of phosphorus. Although current technologies achieve a concentration of phosphorus in one of the products, significant amounts of nitrogen, potassium and organic matter are still present. Therefore, solid products with a good humus effect, for example, can hardly be used in regions with a good phosphorus supply. In arable farming regions with a high P requirement, however, the acceptance of such products is low. The high content of organic nitrogen is difficult to calculate for the nutrient supply of the plants and must nevertheless be included in the nutrient profiles which are subject to regulation. A number of pilot projects deal with phosphorus removal, but until recently only small-scale pilot plants have been established. Initial concepts are being implemented, mainly in the Netherlands, but also in Germany (Bilbao et al. 2017, Lentz und Schlotmann 2018, Niehues 2018, Rabener 2018, Verband der Landwirtschaftskammern 2011, Weltec Biopower 2018). They involve separating the three main nutrients by combining different technologies and converting them into different products. This would allow for a targeted and situation-specific use of nutrients in surplus regions. In addition, this approach offers the possibility of producing user- and application-specific fertilisers, which could be marketed at significantly higher prices. As a result, the assessment of the technologies could turn out to be much more positive than in the case of purely agricultural exploitation, as assumed here. This is because customers in the agricultural sector are not willing to pay high prices. Furthermore, remuneration was assumed only for partial quantities.

The assumptions made in the calculations have a decisive influence on the results of the greenhouse gas analyses. This applies in particular to the storage of digestate and processing products. For example, there are currently no scientifically substantiated emissions ratios for the various products as well as a lack of sufficient empirical values for the probable storage form (open/gas-tight), especially in the region where the products are used. These assumptions should be verified.

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