Sustainable practices in biogas production

Sari Luostarinen, Elina Tampio, Suvi Lehtoranta, Helena Valve, Johanna Laakso, Saija Rasi, Ville Pyykkönen, Jukka Markkanen, Jaakko Heikkinen, Hannu Haapala, Erika Winquist, Kristiina Lång, Karetta Vikki & Tarja Silfver

PUBLICATIONS OF THE GOVERNMENT'S ANALYSIS,
ASSESSMENT AND RESEARCH ACTIVITIES 2023:53

tietokayttoon.fi/en

Government's analysis,
assessment and research activities

FINNISH
GOVERNMENT

Publications of the Government's analysis, assessment and research activities
2023:53

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Prime Minister's Office Helsinki 2023

Julkaisujen jakelu
Distribution av publikationer

Valtioneuvoston julkaisuarkisto Valto

Publikations-arkivet Valto

julkaisut.valtioneuvosto.fi

Prime Minister's Office

ISBN pdf: 978-952-383-075-2
ISSN pdf: 2342-6799

Layout: Government Administration Department, Publications

Helsinki 2023 Finland

Description sheet
26 September 2023

Sustainable practices in biogas production

Publications of the Government´s analysis, assessment and research activities 2023:53
Publisher Prime Minister's Office

Author(s) Sari Luostarinen, Elina Tampio, Suvi Lehtoranta, Helena Valve, Johanna Laakso, Saija Rasi, Ville Pyykkönen, Jukka Markkanen, Jaakko Heikkinen, Hannu Haapala, Erika Winquist, Kristiina Lång, Karetta Vikki & Tarja Silfver

Language English **Pages** 165

Abstract

At its best, biogas production is a solution that supports circular economy, climate goals, water and sea protection, security of supply, self-sufficiency, and rural vitality. Achieving the goals, however, requires minimization of emissions in the entire production chain, from feed materials to the use of end products. The implementation of biogas plants and the practices of operation and maintenance have a significant impact on the gaseous emissions resulting from the production. Inadequate practices lead especially to the deterioration of the climate impact of biogas production. Nitrogen emissions can also be high. The need for emission-reducing practices is significant regardless of plant size and feed materials. Gaseous emissions are most affected by the retention time of feed materials in the biogas reactor and the storage of digestate or its processed fractions. Proper maintenance of the facility, intact and durable structures, and minimizing the emission risks of biogas energy use are also important. The current steering instruments do not guarantee the sustainability of biogas production. The retention time needs regulation and both the environmental permitting and the emission calculation of the Sustainability Act instructions. Consideration of sustainable practices should also be required as part of various subsidies. The know-how to understand the entire biogas production chain and to increase its sustainability must be increased.

Provision This publication is part of the implementation of the Government Plan for Analysis, Assessment and Research. (tietokayttoon.fi) The content is the responsibility of the producers of the information and does not necessarily represent the view of the Government.

Keywords research, research activities, biogas, emissions, sustainable agriculture

ISBN PDF 978-952-383-075-2 **ISSN PDF** 2342-6799

URN address https://urn.fi/URN:ISBN:978-952-xxx-xxx-x

Kuvailulehti
26.9.2023

Kestävät käytännöt biokaasutuotannossa

Valtioneuvoston selvitys- ja tutkimustoiminnan julkaisusarja 2023:53
Julkaisija Valtioneuvoston kanslia

Tekijä/t Sari Luostarinen, Elina Tampio, Suvi Lehtoranta, Helena Valve, Johanna Laakso, Saija Rasi, Ville Pyykkönen, Jukka Markkanen, Jaakko Heikkinen, Hannu Haapala, Erika Winquist, Kristiina Lång, Karetta Vikki & Tarja Silfver

Kieli englanti **Sivumäärä** 165

Tiivistelmä

Parhaimmillaan biokaasutuotanto on kiertotaloutta, ilmastotavoitteita, vesien- ja merensuojelua, huoltovarmuutta, omavaraisuutta ja maaseudun elinvoimaisuutta tukeva ratkaisu. Tavoitteiden saavuttaminen edellyttää kuitenkin päästöjen minimointia koko tuotantoketjussa syötemateriaaleista lopputuotteiden käyttöön. Biokaasulaitosten toteutuksella sekä käytön ja ylläpidon käytännöillä on huomattava vaikutus tuotannosta aiheutuviin kaasumaisiin päästöihin. Puutteelliset käytännöt johtavat etenkin biokaasutuotannon ilmastokestävyyden heikkenemiseen. Myös typen päästöt voivat olla suuret. Tarve päästöjä vähentäville käytännöille on merkittävä riippumatta laitoskoosta ja syötemateriaaleista. Kaasumaisiin päästöihin vaikuttaa eniten syötemateriaalien viipymä biokaasureaktorissa ja mädätteen tai sitä jalostettujen jakeiden varastointi. Myös laitoksen asianmukainen huolto, ehjät ja kestävät rakenteet sekä biokaasun energiakäytön päästöriskien minimointi ovat tärkeitä. Nykyiset ohjauskeinot eivät takaa biokaasutuotannon kestävyyttä. Viipymäaika tarvitsee sääntelyä ja sekä ympäristöluvitus että uusiutuvan energian direktiivin päästölaskenta ohjeita. Kestävien käytäntöjen huomiointia tulee edellyttää myös osana erilaisia tukia. Osaamista biokaasutuotannon kokonaisuuden ymmärtämiseksi ja kestävyyden lisäämiseksi on lisättävä.

Klausuuli Tämä julkaisu on toteutettu osana valtioneuvoston selvitys- ja tutkimussuunnitelman toimeenpanoa. (tietokayttoon.fi) Julkaisun sisällöstä vastaavat tiedon tuottajat, eikä tekstisisältö välttämättä edusta valtioneuvoston näkemystä.

Asiasanat tutkimus, tutkimustoiminta, biokaasu, kestävä maatalous, päästöt

ISBN PDF 978-952-383-075-2 **ISSN PDF** 2342-6799

Julkaisun osoite https://urn.fi/URN:ISBN:978-952-xxx-xxx-x

Presentationsblad
26.9.2023

Hållbara metoder inom biogasproduktion

Publikationsserie för statsrådets utrednings- och forskningsverksamhet 2023:53
Utgivare Statsrådets kansli

Författare Sari Luostarinen, Elina Tampio, Suvi Lehtoranta, Helena Valve, Johanna Laakso, Saija Rasi, Ville Pyykkönen, Jukka Markkanen, Jaakko Heikkinen, Hannu Haapala, Erika Winquist, Kristiina Lång, Karetta Vikki & Tarja Silfver

Språk engelska **Sidantal** 165

Referat

När den är som bäst är biogasproduktion en lösning som stödjer cirkulär ekonomi, klimatmål, vatten- och havskydd, försörjningstrygghet, självförsörjning och landsbygdens vitalitet. För att nå målen krävs dock minimering av utsläpp i hela produktionskedjan, från insatsmaterialer till användning av slutprodukter. Införandet av biogasanläggningar och praxis för drift och underhåll har en betydande inverkan på de gasformiga utsläppen från produktionen. Otillräcklig praxis leder särskilt till en försämring av biogasproduktionens klimatmotstånd. Kväveutsläppen kan också vara höga. Behovet av utsläppsminskande metoder är betydande oavsett anläggningsstorlek och insatsmaterial. Gasformiga utsläpp påverkas mest av kvarhållandet av insatsmaterial i biogasreaktorn och lagring av rötrest eller dess bearbetade fraktioner. Rätt underhåll av anläggningen, intakta och hållbara strukturer samt minimering av utsläppsriskerna vid energianvändning av biogas är också viktigt. De nuvarande kontrollmetoderna garanterar inte hållbarheten i biogasproduktionen. Uppehållstiden behöver regleras och såväl miljötillståndet som hållbarhetslagens anvisningar för utsläppsberäkning. Hänsyn till hållbar praxis bör också krävas som en del av olika subventioner. Kunskapen om att förstå hela biogasproduktionen och att öka hållbarheten måste ökas.

Klausul Den här publikation är en del i genomförandet av statsrådets utrednings- och forskningsplan. (tietokayttoon.fi) De som producerar informationen ansvarar för innehållet i publikationen. Textinnehållet återspeglar inte nödvändigtvis statsrådets ståndpunkt

Nyckelord forskning, forkningsverksamhet, biogas, hållbart jordbruk, utsläpp

ISBN PDF 978-952-383-075-2 **ISSN PDF** 2342-6799

URN-adress https://urn.fi/URN:ISBN:978-952-xxx-xxx-x

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FOREWORD

The production and use of biogas offer solutions to renewable energy, climate change mitigation, sustainability of the food system, nutrient recycling, and other environmental issues. Biogas is seen as a solution to many challenges and great expectations are placed on it. To be able to respond to these challenges and meet the expectations, researched information is needed to ensure the ecological and economic sustainability of biogas production.

In the national biogas program according to the government program completed in January 2020, it is stated that the environmental and climate effects of the production and consumption of biogas must be mapped and the cost-effectiveness of the operation, especially as a climate measure, must be evaluated.

Measurement data is especially needed for various biogas plants and emissions from the storage, processing, and use of biogas plant feed materials and digestate. In addition to storage, the emissions from fertilizer application can also be a significant part of the overall sustainability of the biogas process. It is very important that the environmental and climate sustainability of the biogas investments/plants receiving financial support is ensured, so that unsustainable methods of operation are not supported.

The answers to the above-mentioned questions can be found in this final report of the “Sustainable practices in biogas production process chains (KEBIO)” project. The project also contributes to better consideration of the climate impacts related to biogas and the processing and use of digestate in national climate policy planning and implementation, in the greenhouse gas inventory and in reporting to the EU and the international climate agreement.

A Policy Brief has already been published about the project containing a summary of proposed measures to implement a more sustainable biogas chain. In addition, good practice guidelines have been drawn up for biogas plant operators on what are the best operating methods in terms of sustainability in the entire process. The final report is made available in Finnish and in English.

The steering group of the KEBIO project included Riikka Malila, Ville Laasonen and Hanne Siikavirta from the Ministry of the Environment, Harri Haavisto from the Ministry of Economic Affairs and Employment, and Veli-Pekka Reskola, Marja-Liisa Tapio-Biström and Sanna Tikander from the Ministry of Agriculture and Forestry. In addition, expert members of the steering group were Olli Mäki and Mari Tenhovirta from the Energy Authority and Karoliina Pietiläinen from the Ministry of Agriculture and Forestry. Warm thanks to the steering group for good and constructive cooperation during the project.

Many thanks to the entire KEBIO project research team for the expert conduction of this large and challenging project. During the work, we had several interesting and knowledge-enhancing conversations with you. Your work is very valuable for the advancement and development of the biogas industry, both in Finland and elsewhere.

Birgitta Vainio-Mattila (the Ministry of Agriculture and Forestry), chair of the steering group

1 Introduction

At its best, biogas production simultaneously supports the circular economy, climate goals, water and sea protection, security of supply, self-sufficiency, and rural vitality. Achieving the goals, however, requires minimizing emissions in the entire production chain.

Finland aims at increasing biogas production due to the numerous advantages it offers. Biogas itself is a versatile renewable energy source that can be utilized case specifically to produce heat, combined heat and power, or biomethane suitable for industry and transport. The second end product of the production, digestate, on the other hand, contains all the nutrients of the feed materials and the residue of the organic matter. Enhancing their recycling, especially for use in food production as fertilizer products, has been aimed for years with various means.

The increase in biogas production can promote a transition where the utilization of various organic wastes and side streams reduces both harmful environmental effects and dependence on fossil energy and mineral fertilizer products. At the same time, it participates in maintaining the organic matter contained in the arable soil and reduces the use of nutrients as a whole.

According to estimates, biogas production will at least double in Finland in the next few years. This is partly the result of the considerable public contributions that are allocated both to investing in production and to supporting the use of end products and thus the development of their market.

For society's contributions to be targeted as desired and all the expected benefits to be realized, the entire biogas production chain, from raw materials to the use of end products, should take into account emission minimization to air and water at every step. For now, this may not be the case. For example, excessively striving for cost efficiency can result in investments and/or operating methods that do not pay attention to emission reductions, reduce the amount of biogas produced, and produce fertilizer products that are difficult to utilize in terms of quality and/or quantity. The emission risk is especially for greenhouse gas emissions that accelerate climate change and ammonia emissions that impair air quality, as well as nutrient emissions into waterways in connection with the use of digestate or fertilizer products processed from it. The formation of emissions is also monitored, and emission reduction targets and obligations have been set for them.

Ensuring sustainable practices should be at the center already when planning biogas plants. Both operators, permitting and monitoring authorities, and decision-makers need common instructions on what matters to pay attention to in order to ensure implementation of the most sustainable practices and minimization of emissions.

This report meets the information needs for ensuring the sustainability of biogas production identified in the national biogas program[1]. The report examines the emission risks of the different production stages of biogas plants and the methods of operation necessary to reduce emissions, focusing especially on gaseous emissions into the atmosphere. The report addresses the risk of nutrient release into water bodies from the use of digestate and fertilizer products processed from it in a more general way. The report was carried out in cooperation with Finnish Natural Resources Institute (Luke), Finnish Environment Agency (Syke) and Agrinnotech.

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[1] Ministry of Economic Affairs and Employment. 2020. Biokaasuohjelmaa valmistelevan työryhmän loppuraportti (Final report of the biogas working group). Publications of the Ministry of Economic Affairs and Employment 2020:3. http://urn.fi/URN:ISBN:978-952-327-482-2

2 Gaseous emissions from biogas production (summary of literature review)

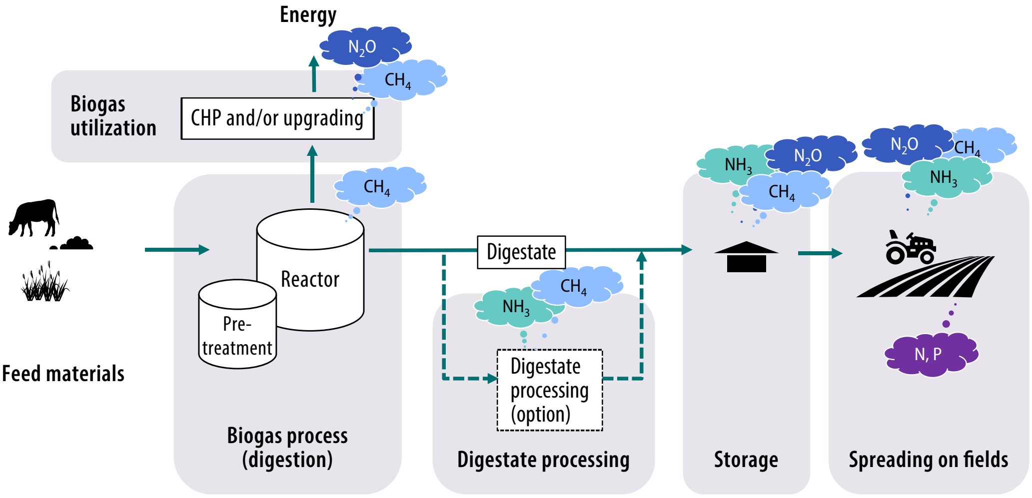
Elina Tampio (Luke), Suvi Lehtoranta (Syke), Karetta Vikki (Luke), Johanna Laakso (Luke), Sari Luostarinen (Luke)

This chapter presents data collected from the scientific literature review on gaseous emissions generated during biogas production, and the processing and use of its end products. Greenhouse gas (GHG) emissions formed in the biogas production chain include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions. Furthermore, the biogas process affects the state of nitrogen compounds and hence nitrogen loss as ammonia (NH_3).

Gaseous emissions may be formed at different phases of the biogas production chain (Figure 1). Potential methane emissions are linked to leakages during the biogas process, biogas utilization and digestate storage. Ammonia emissions may be released from the storages of digestate or further processed products from it, and from field spreading. Nitrous oxide emissions originate from soil processes after digestate spreading for fertilization purposes. All phases of the biogas production chain are potential sources of CO_2 emissions (e.g. fossil CO_2 from fuel consumption and biogenic CO_2 from digestion and storage phases). However, CO_2 was excluded from this review, which concentrates on the most harmful emissions of CH_4, N_2O, and NH_3.

The literature review was conducted by retrieving scientific articles published mainly in the 21st century. The review focuses on biogas plants digesting agricultural biomasses. Studies on full-scale plants were preferred but laboratory-scale studies were also included especially for digestate processing, storage and field spreading. The biogas production chain was divided into five phases, which are biogas process (digestion), biogas utilization, digestate processing, digestate storage, and digestate spreading (fertilizer use) on fields.

Figure 1. Simplified process scheme for biogas production with potential emission sources. The emissions from handling the feed materials were not included in the literature review.



A total of 70 publications focused on studying emissions from biogas production were reviewed. A quarter of the publications dealt with emissions and leaks from biogas reactor. Studies on emissions from digestate storage (26 articles) and field use (28 articles) included the highest number in the data. The lowest number of publications (10 articles) were found on the biogas utilization phase or digestate processing by various techniques. Most of surveys examined were European, with emphasis on Germany, Sweden, and Italy.

2.1 Biogas process (digestion)

Based on the reviewed literature, methane emissions from the biogas process have been measured regularly from wet digesters and only individual measurement results from different dry digesters have been reported (Liebetrau et al. 2013). Methane emissions are usually reported in the unit 'percentage of methane produced', meaning the proportion of the measured emission from the amount of methane in biogas collected. However, it is difficult to compare or unify the results of different studies due to the individuality of the studied plants and the emission measurement methods. In practice, the measurement methods used, the duration and repetitions of the measurement periods, the weather conditions during the measurement period (Hrad et al. 2015) and the plant's operating methods (Reinelt et al. 2017) and plant technologies vary.

The measured total methane emissions in the plant area vary in the literature studied between 0.02–23.8 % of the methane produced (Table 1). According to the studies, the largest sources of methane emissions are uncovered digestate storages and the gas losses in the CHP unit of combined electricity and heat production (Reinelt et al. 2022; Vergote et al. 2020; Fredenslund et al. 2018; Reinelt et al. 2017; Liebetrau et al. 2013).

Overall, the literature review shows that in more recent studies, the measured methane emissions from biogas plants are higher than previously estimated (Scheutz & Fredenslund 2019; Bakkaloglu et al. 2021; Reinelt et al. 2022). Research also suggests that methane emissions from sewage sludge digestion are on average higher (about 7.5 % of the methane produced) compared to plants using agricultural side streams (on average 2.4 % of the methane produced) (Scheutz & Fredenslund 2019). The reason cannot be identified, but the plants digesting sewage sludge are often older than the agricultural plants. A difference has also been observed between small- and large-scale facilities in favor of large facilities (Scheutz & Fredenslund 2019; Bakkaloglu et al. 2021). The lower methane emissions of a larger plant have been estimated to be due to more precise operating methods, such as better resource availability and maintenance (Scheutz & Fredenslund 2019).

However, measured research data on biogas process phases is limited and the presented results are partially contradictory due to the differences in plant techniques and measurement times, methods, and periods. The most significant sources of methane emissions from the biogas process have been determined to be the attachment of membrane domes used as reactor covers, holes in concrete walls/structures, pressure control valves (PVR), gas pipes and compressors, and mixers (Fredenslund et al. 2018; Reinelt et al. 2017; Tauber et al. 2019; Reinelt et al. 2022).

Table 1. Measured methane emissions from different stages of the digestion process. PRV = pressure release valves.

Process stage	CH_4-emission (% of CH_4 produced)	Median	Average	Examined plants (no.)	Measurements (no.)	Ref.
Mixing	0.005–0.311	0.031	0.09	13*	19*	1–2
Feeding	0.00052–0.16	0.004	0.04	4*	6*	1–2
Maintenance	5.04–5.46	5.04	5.04	2	2	1–2
PRV	0.04–16.2	1.1	3.7	8	*	3–6

Process stage	CH_4-emission (% of CH_4 produced)	Median	Average	Examined plants (no.)	Measure-ments (no.)	Ref.
Leakages from plants	0–4.41	0.006	0.33	13	54	1–2, 11
Plant area in total	0.02–23.8 **	2.85	4.38	52*	*	2, 3, 5, 7–15

* No exact information on numbers
** In addition to the biogas process, includes emissions from biogas utilization and digestate storage
1) Liebetrau ym. 2010, 2) Liebetrau ym. 2013, 3) Groth ym. 2015, 4) Reinelt ym. 2016, 5) Reinelt ym. 2017, 6) Reinelt & Liebetrau 2020, 7) Hrad ym. 2015, 8) Fredenslund ym. 2018, 9) Jensen ym. 2017, 10) Flesch ym. 2011, 11) Reinelt ym. 2022, 12) Avfall Sverige 2016, 13) Holmgren 2012, 14) Bakkaloglu ym. 2021, 15) Scheutz & Fredenslund 2019.

2.2 Biogas utilization

To utilize the energy content in biogas, the produced gas is usually led to either a boiler producing heat, a CHP unit producing electricity and heat, or a transportation fuel processing unit (biogas upgrading into biomethane followed by either pressurization or liquefaction into transportation fuel).

In the literature, estimates of methane emissions from biogas in a CHP unit varied between 0.17 and 3.72 % of the methane produced. In CHP units, methane emission is caused by incomplete combustion and, with it, unburned biogas that ends up in the exhaust gas. Some of the studies also looked at the emissions of nitrous oxide formed in the CHP unit. According to Liebetrau et al. (2013), N_2O emissions are a result of the high nitrogen content of the reactor feed materials and the resulting ammonia in the biogas (Liebetrau et al. 2013).

The most common techniques for biogas upgrading are various water or chemical scrubbers based on absorption (scrubbers), pressure swing adsorption (PSA), and membrane technologies, for which varying emission data have been reported in the literature. Methane emissions consist of leaks from upgrading equipment and methane that ends up in the exhaust gas, which cannot be fully recovered by the technology used. According to a report by Avfall Sverige (2016), methane emissions measured at Swedish biogas upgrading plants with different technologies (water scrubber, PSA, chemical scrubber) were on average 0.9 % of the methane produced, and most of this (0.75 % of the methane produced) consisted of methane in the exhaust gas. Still, the upgrading technology used has been found to have a significant impact on the result, and chemical scrubbers and membrane technologies are considered to have the lowest emissions compared to water scrubbers. No nitrous oxide emissions are reported to be produced during biogas upgrading. In addition, methane, nitrous oxide and ammonia emissions by either pressurization or liquefaction into transportation fuel are insignificant.

It is challenging to avoid emissions completely, because the combustion of biogas in the CHP unit and during the upgrading is always somewhat incomplete and a small amount of methane ends up in the exhaust gas. However, with the help of regular maintenance of the equipment, the performance of CHP engines and upgrading processes can be influenced and gas leaks prevented. In addition, the quantity of gaseous emissions could be influenced, for example, by post-treatment of the exhaust gas (catalytic or thermal oxidation).

2.3 Digestate processing

Digestate processing technologies aim to divide the digestate mass or the nutrients and organic matter into separate fractions and/or to concentrate nutrients. The goal is often to enhance the reuse of nutrients and organic matter in fertilization and soil improvement by concentrating and changing the nutrient ratios to make them more suitable for different end uses and/or to improve the transportability of the resulting fractions. The most common solution for digestate processing is mechanical separation, where separate liquid and dry fractions are formed from digestate by screw-pressing or centrifuging. Separation is usually also the first processing step when the aim is to refine the resulting fractions into even more concentrated fertilizer products with other processing technologies.

Advanced digestate processing is still quite rare, apart from separation, and many processing techniques are still being developed. Consequently, emissions during processing have rarely yet been measured in the literature, and little measured data is available. During digestate separation, with, e.g., screw-press or centrifuge, small amounts of gaseous compounds can escape, because the equipment is not gas-tight. However, the residence time of the digestate in the separator is usually short, and the methane emissions formed during the separation have been reported to be only 0.001–0.1 % of the plant's methane output (Liebetrau et al. 2013, 2010).

From thermal drying of the digestate, no methane emissions have been reported (Awiszus et al. 2018a), but ammonia can evaporate during the process. The amount of ammonia emission depends on the ammonium concentration in the digestate, as well as the drying conditions, especially pH and temperature, and has reported to vary between 0.08–0.2 g/m^3 (Awiszus et al. 2018b). High temperature increases nitrogen evaporation, but on the other hand significantly shortens the drying time (Pantelopoulos et al. 2016). Nitrogen loss during drying (up to 98 % of the soluble N in the digestate, Maurer & Müller 2012) can be prevented by lowering the pH of the material to be dried to an acidic level (pH 5.5–6.5) (Pantelopoulos et al. 2016). In addition, recovery of the evaporated gas fraction is often integrated in the drying processes, in which case the ammonia nitrogen can be recovered, for example, with the help of an acid scrubber, thus avoiding ammonia emissions.

2.4 Digestate storage

Methane, ammonia, and nitrous oxide emissions can be formed during the storage of digestate or fractions processed from it. The emission risk is affected by the storage conditions, especially the temperature, but also the storage time and the properties of the digestate or its processed fractions (such as pH). The formation of methane emissions during storage results from decomposition of the digestate's organic matter under the storage conditions. The decomposition of the digestate during storage also increases the risk of nitrogen emissions (NH_3 and N_2O).

The most significant factor influencing the emission potential of digestate storage is the retention time of digestible biomass in the reactor and potential post-digestion tank. Insufficient retention time and high loading in the reactor will lead to inadequate degradation of the organic matter. In this case, a higher amount of digestible organic matter ends up in the digestate and decomposes during the storage phase, forming methane emissions. Despite the importance of the retention time in the reactor, its effects on the emissions from the digestate storage have been studied relatively little.

Digestate contains more ammonium nitrogen than the original feed materials because nitrogen is mineralized from the organic nitrogen compounds to ammonium nitrogen during the biogas process. During the storage of digestates, the risk of ammonia emissions increases if the storage temperature rises. In the storage of sludge-like digestates, methane emissions have been studied to be the highest in summer, when the air temperature rises above 10–15 degrees (Ericsson et al. 2020; Maldaner et al. 2018). The time of day has also been found to influence the quantity of emissions (Hrad ym. 2015; Maldaner ym. 2018).

Methane emissions can be reduced by storage conditions. The high temperature of the digestate discharged from the reactor (usually around 37–42 or 52–55 °C, depending on the process temperature) can be lowered by cooling the removed digestate. With the help of heat exchangers, this heat can be further utilized to heat the reactor or its feed materials. The structure of the storage containers can also slow down the temperature changes of the digestate and affect the formation of emissions. The amount of digestate in the storage tank and the storage time also impact the quantity of gaseous emissions. The greater the amount of digestate stored is, the greater the CH_4 and N_2O emission per ton of digestate formed (Vergote et al. 2020).

2.4.1 Covering digestate storage

The covering of the digestate storage significantly affects the gaseous emissions. Storing sludge-like digestate and separated liquid fractions in open, i.e., uncovered tanks, increases the risk of gaseous emissions (CH_4, N_2O, NH_3), while the use of various storage covers reduces them. To prevent nitrous oxide emissions, storage tanks should be equipped with tight covers. Covers can be, for example, tent-like covers and tight concrete covers, which at the same time prevent rainwater from entering the tanks and equalize the temperature of the tanks. With cattle slurry-based digestates, a fibrous part often rises to the surface of the storage container and forms a crust. The crust has been found to reduce ammonia and methane emissions in manure storage, but on the other hand increase N_2O emissions (Baldé et al. 2018; Petersen et al. 2013).

When storing solid digestates or separated solid fractions, the walls and roof of the storage windrows or containers reduce the evaporation of ammonia from the digestate surface, and the effect increases the more closed the structure is. At the same time, rainwater is prevented from entering the mass, which helps it to remain airy. This reduces the risk for methane emissions (Majumder et al. 2014) and can also reduce the formation of anoxic conditions favorable for the formation of N_2O.

2.4.2 Emissions from fractions separated from digestate

There is a high risk of ammonia emissions in the storage of separated liquid fractions (Holly et al. 2017; Zilio et al. 2020), because most of the soluble nitrogen in the digestate ends up in the liquid fraction during separation. The liquid fraction also often contains most of digestate's easily degradable organic matter, which increases the risk of methane emissions (Holly et al. 2017). Thus, it can be concluded that measures to reduce emissions should be directed to separated fractions, especially to the storage of liquid fractions. Covering the storages and a sufficient retention time in the biogas reactor are important factors in terms of minimizing the emission potential of liquid fractions as well.

Solid fractions separated from digestate have been found to have a low ammonia and methane emission risk due to the fraction's low soluble nitrogen content and high proportion of fibrous and non-degradable matter (Amon et al. 2006; Holly et al. 2017). The oxygen conditions prevailing in solid fractions minimize the formation of methane due to the decomposition of organic matter, moreover, in the oxygen conditions of the surface, the oxidation of methane to carbon dioxide can occur (Majumder et al. 2014). However, the emissions of N_2O from solid fractions can be significant because oxygen-free and low-oxygen areas present in the storage piles. The storage time of solid fractions is also important for the amount and composition of emissions from storage. Overall, according to studies, the separation of digestate has a favorable effect in terms of reducing emissions.

From the reviewed emissions from digestate storage (Table 2), it can be concluded that the variability of emissions is large due to the numerous factors affecting them (e.g., temperature, retention time in the reactor, digestate properties, storage method). In addition, all results could not be unified due to missing information and different units used. Also, the seasonality of the measurements makes it difficult to extrapolate the results to the whole year. Different measures can also have cross-effects, meaning that they can reduce a certain emission, but potentially increase the risk of another emission. For example, methane and ammonia emissions can be reduced with separation of digestate, but the process can increase nitrous oxide emissions.

Table 2. Literature review on emissions from digestate storage.

Emission	Unit	Min	Max	Average	Median	Number of measurements	Ref.
CH_4	$gCH_4/m^3/d$	0	52.0	11.0	4.6	34	1–8
	$\%CH_4$	0.00013	12.0	3.8	2.2	20	1, 2, 8–12
	$gCH_4/m^2/d$	0.04	62.4	14.5	6	7	13, 14
N_2O	$gN_2O/m^3/d$	0.004	2.7	0.4	0.1	10	6, 7, 8
	$gN_2O/m^2/d$	0.06	14.0	2.9	0.4	7	3, 7, 8
NH_3	$gNH_3/m^3/d$	0.0	96.3	20.9	6.7	27	6, 15–17
	$gNH_3/m^2/d$	0.02	80.0	16.8	11.1	22	3, 15, 17
	gNH_3/m^3	2.4	256.2	113.3	97.2	4	16, 18

1) Baldé ym. 2016, 2) Balsari ym. 2013, 3) Baral ym. 2018, 4) Gioelli ym. 2011, 5) Maldaner ym. 2018, 6) Perazzolo ym. 2015, 7) Rodhe ym. 2015, 8) Vergote ym. 2020, 9) Hrad ym. 2015, 10) Liebetrau ym. 2013, 11) Liebetrau ym. 2010, 12) Reinelt ym. 2017, 13) Majumder ym. 2014, 14) Reinelt ym. 2022, 15) Baldé ym. 2018, 16) Holly ym. 2017, 17) Zilio ym. 2020, 18) Amon ym. 2006

2.5 Digestate use in fertilization

The fertilizer use of digestate has several positive effects on soil structure and plant nutrition. In the digestion process, the total nutrient content of the feed material remains unchanged, but the process converts organic nutrients, such as nitrogen, into a soluble form that is better available for crops (e.g. Clemens et al. 2006). Higher pH, lower viscosity, higher soluble nitrogen, and lower levels of organic nitrogen compared to e.g. untreated slurry are properties that improve the fertilizer value of digestate (Anderson-Glenna & Morken 2013).

2.5.1 Significance of spreading method

Digestate spreading on fields uses the same equipment as is used for the application of raw manure, and similar principles also apply for gaseous emissions to reduce them. The most suitable and low-emission techniques aim to minimize the contact of digestate and air (in terms of time and surface area) and to ensure direct contact with the soil (e.g. Möller & Stinner 2009). In several studies, the lowest measured methane and nitrous oxide emissions have been achieved by band application (hoses) of the digestate near the soil surface and immediate incorporation to a depth of 3–5 cm (e.g. Wulf et al. 2002; Häfner et al. 2021). The injection of digestate also has its advantages, but on the other hand it has been found to promote the emergence of anaerobic micro-environments in soil and increase the emission of nitrous oxide compared to band application and incorporation (Severin et al. 2016). The least recommended technique is broadcasting, where high air contact and uneven application result of digestate greatly increase the risk of GHG emission and nutrient loss through evaporation (NH_3) and runoff, as well as increase the odour effects of application (Crolla et al. 2013).

2.5.2 Emissions from soil after spreading

The use of digestates and other organic fertilizer products as a source of nitrogen increases the soil microbial activity compared to mineral fertilizers, since carbon is simultaneously added to the soil. This reduces the oxygen content in the soil pores and may lead to anaerobic conditions (Giles et al. 2012). Such conditions increase the risk for the formation of N_2O emissions. Especially injection technique has been found to increase N_2O emission compared to broadcasting (Wulf et al. 2002; Severin et al. 2016). The anaerobic microenvironment formed into the injection spot is favourable for denitrification, and the overlying soil layer has been shown to be a hotspot for nitrous oxide emission (Dittert et al. 2001). However, the addition of organic matter into the soil is beneficial to maintain its good structure and carbon content (see Chapter 4).

The risk for methane emission (CH_4) is highest during the storage of the digestate and the effect of field spreading has been found to be minimal. Also, methane emissions from soil after application do not significantly differ from untreated manure (Holly et al. 2017). However, the soil conditions play an important role for methane emissions, and the digestate injected into wet soil increased methane emissions considerably compared to dry soil (Wulf et al. 2002). In the same study, untreated slurry induced a higher methane emission than digestate, as it contained more easily degraded organic matter for microbes. Severin et al. (2016) reported higher methane emission from a deeper injection depth of digestate than from a shallower depth. These studies confirm the good soil structure as contributing to the preservation of aerobic conditions in the mitigation of GHG emissions.

Table 3 shows the results of gaseous emission measurements of digestate application on soils in the literature review. The results of the various studies are difficult to unify since some of them had been carried out in laboratory conditions and some in field. A large range in the results may be due to different test conditions and the values cannot be directly compared without careful reading of the underlying research.

Table 3. Gaseous emissions of the digestate application on fields in the reviewed literature.

Emission	Unit	Min.	Max.	Average	Median	Number of measurements	Ref.
CH_4	mg/ha/h/kg of dry matter	0.0	3.8	0.44	0.0004	19	1–11
N_2O	g/ha/year/kg of nitrogen fertilization	0.003	1 119	120	25	62	1,3,4,5, 8–24
NH_3	% total nitrogen fertilization	0.4	31	9	5	20	6,13,18, 24–27

1) Collins ym. 2011, 2) Czubaszek & Wysocka-Czubaszek 2018, 3) Dietrich ym. 2020, 4) Eickenscheidt ym. 2014, 5) Heintze ym. 2017, 6) Holly ym. 2017, 7) Odlare ym. 2012, 8) Pampillon-Gonzales ym. 2017, 9) Pezzolla ym. 2012, 10) Rosace ym. 2020, 11) Wulf ym. 2002, 12) Abubaker ym. 2013, 13) Amon ym. 2006, 14) Häfner ym. 2021, 15) Johansen ym. 2013, 16) Köster ym. 2011, 17) Köster ym. 2015, 18) Möller & Stinner 2009, 19) Rodhe ym. 2015, 20) Senbayram ym. 2009, 21) Severin ym. 2016, 22) Sänger ym. 2011, 23) van Nguyen ym. 2017, 24) Verdi ym. 2019, 25) Nicholson ym. 2018, 26) Riva ym. 2016, 27) Zilio ym. 2021, 28) Chen ym. 2011

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3 Emission measurements

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3.1 Description of measurement sites

Emission measurements were carried out at two farm-scale biogas plants in 2021 and 2022. One of the studied plants uses wet digestion technology and the other is based on dry digestion.

The studied wet digestion plant operates in connection with a loose housing system for dairy cattle. The plant processes about 7,000 tons of feed materials per year. About 20 t/day of dairy cow slurry, about 1 t/day of young cattle's farmyard manure (with straw bedding) and 200–300 kg/day of surplus grass fodder are fed in the reactor. The reactor volume is 600 m^3 and the hydraulic retention time (HRT) is 30 days. After the reactor, the digestate is directed to a screw press, which separates it into liquid and solid fractions (Table 4). The liquid fraction (6 400 t/y) is pumped into an open storage tank (area 2 000 m^2) and used as fertilizer. The solid fraction (500 t/y) is taken to a covered storage pile, from where it is used as bedding in the barn. The dairy farm uses the energy produced by the plant as electricity (365 MWh) and heat (750 MWh), a total of 1,250 MWh in 2021.

The studied biogas plant based on dry digestion consists of two 1 000 m^3 reactor silos, a storage area, a leachate tank, two gas storages, a container for technical devices, and a water scrubbing equipment for the biogas. The facility uses approximately 1,800 t of grass from green manuring as the main feed material and approximately 220 t of horse manure and 120 t of poultry manure as additional feed per year. The dry matter content of the feed materials varies between 25–35 %. The HRT of the two reactor silos is 4–5 months each. The silos are filled in an alternating cycle so that the biogas production is steady, and there are 3–4 batches each year, depending on the biogas consumption. The plant's annual energy production in 2021 was 930 MWh. Part of the raw gas is piped half a kilometer away to the facility center, where it is used to heat the production buildings. Biogas energy is also used to heat the biogas process. Most of the biogas is purified at the plant to form biomethane and led through a pressurization unit to a public gas station (for traffic) in connection with the farm. About 770 MWh of biomethane for traffic was produced in 2021.

Table 4. Biogas production (2021) of the two biogas plants on the emission measurement sites and the composition of the digestates.

Biogas plant	Biogas produced, MWh		Dry matter, %	Organic matter, g/kg dm	NH_4-N, kg/t	Ntot, kg/t	Ntot, %
Wet digestion	1 250	Solid fraction	46.3	406	1.0	9.7	0.97
-	-	Liquid fraction	2.5	16	1.5	2.5	0.25
Dry digestion	930	Digestate	24.8	208	1.4	7.4	0.74

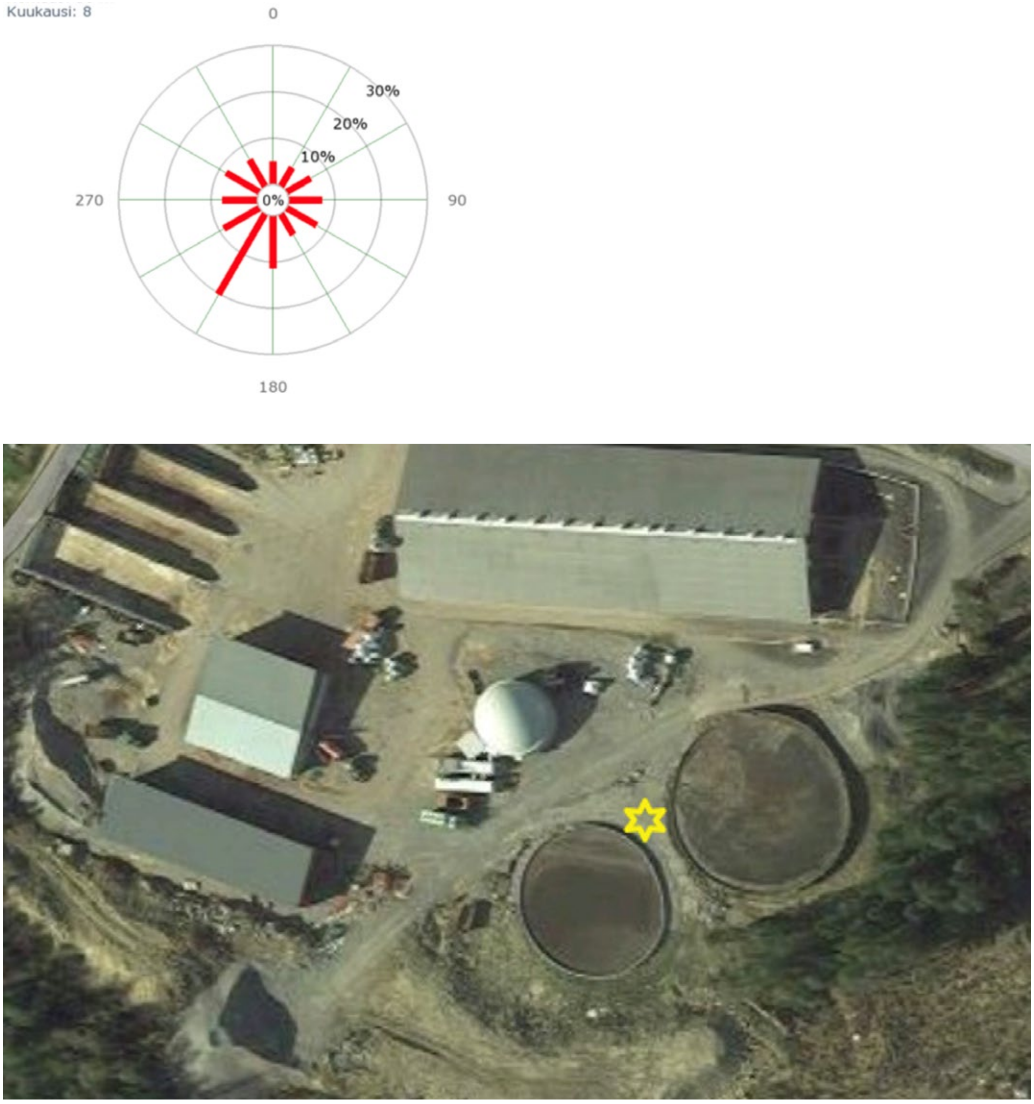
3.2 Biogas plant with wet digestion

The emissions of the wet digestion plant were measured from the storage tank of the separated liquid fraction of the digestate located in connection with the plant, both in summer (August 23, 2021) and in winter (March 4–6, 2022). The average temperature was 10.7 °C during the summer measurement and -1.3 °C during the winter measurement.

3.2.1 Methods

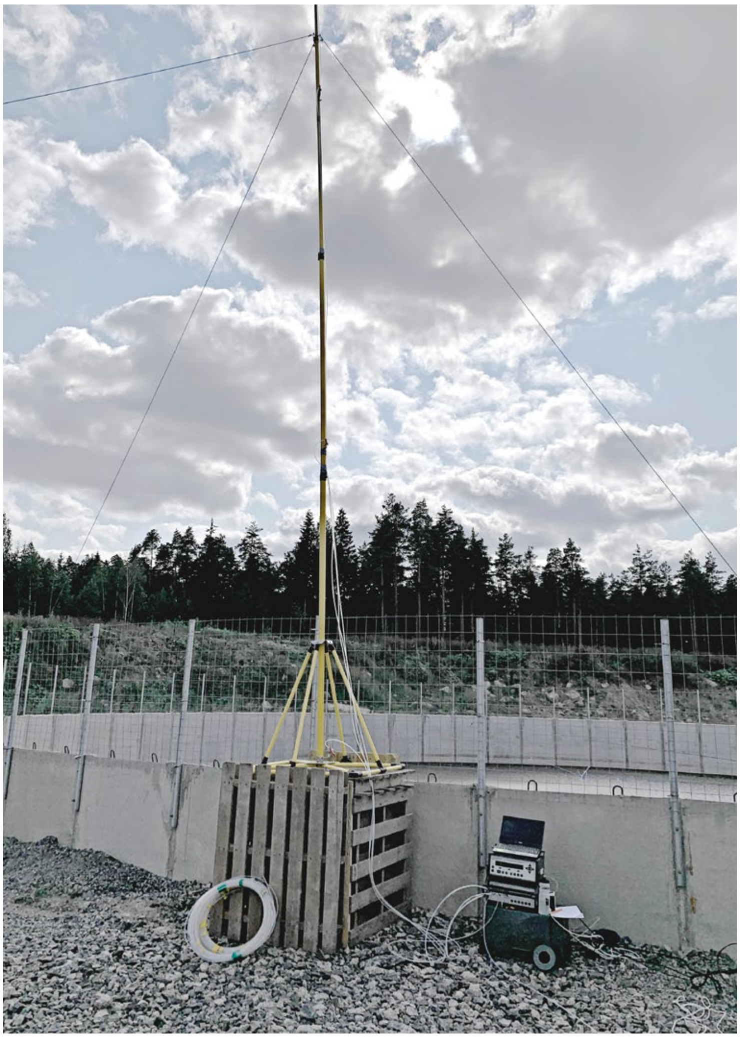
The emissions of the wet digestion process were measured next to the storage tank with a measuring mast (Haapala & Hellstedt 2019), which was placed downwind. The location of the measuring mast was chosen using a statistical wind rose (Figure 2) and confirmed according to the period's weather forecast. In addition, the wind direction was measured on site.

Figure 2. Wind rose of the measurement site (month 8), based on which the mast was placed downwind of the tank to be measured to the north-northeast (star).



The suction lines of the photoacoustic emission analyzer (Innova 1412 Gas Monitor, Innova 1409 Multipoint Sampler, LumaSense Technologies, DK) were attached to the mast at four heights. In the method, the heights of the measurement points are calculated based on the size of the tank and the distance from the mast, so that each point represents an equal volume of air. In this case, the heights were 128, 386, 781 and 1 319 cm from the ground level. The Teflon pipes were each connected to their own channel of the analyzer (Figure 3).

Figure 3. The measurement mast positioned downwind of the measurement site. The mast has four measurement points, the heights of which depend on the size and distance of the site. The suction hoses placed at the measuring points were connected to the photoacoustic analyzer.



In addition to the mast measurement, a chamber method was tried. In it, the measuring chamber was lowered on the surface of the liquid fraction at eight measurement points. A suction line was led from the chamber to the photoacoustic analyzer (Figure 4). In the chamber method, each measurement point represents a certain surface area, so the result is calculated as their weighted average (Table 5).

Figure 4. The chamber measurement method, where the chamber was lowered into the tank to float at eight measuring points. A suction line was led from the chamber to the photoacoustic analyzer.

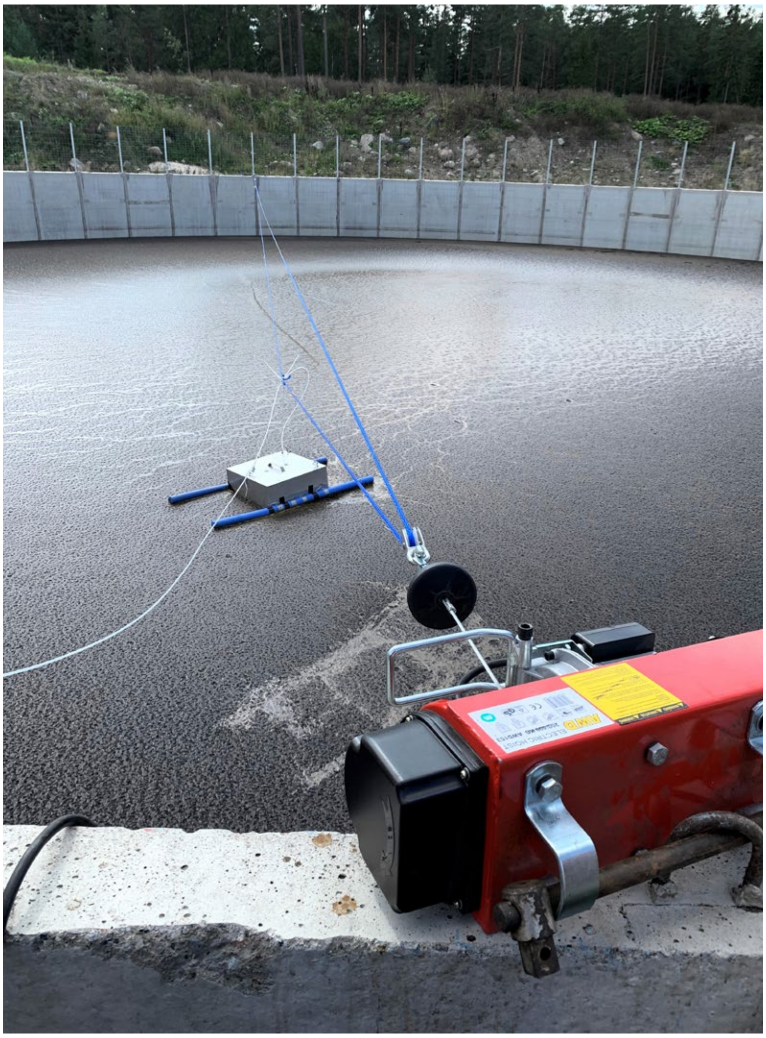


Table 5. The location of the chamber measuring points in the storage tank for separated liquid fraction (Æ 26 m).

Measuring point	From tank edge, m	Representing, m^2	%
1	1.63	116	21.9
2	4.88	83	15.6
3	8.13	50	9.4

Measuring point	From tank edge, m	Representing, m^2	%
4	11.38	17	3.1
5	14.63	17	3.1
6	17.88	50	9.4
7	21.13	83	15.6
8	24.38	116	21.9
Total	**-**	**531**	**100.0**

3.2.2 Emission calculation

The result given by the analyzer is the concentration expressed as ppm. However, the emission was converted to weight units. When the plant's biogas and methane production is known, the emission can be further calculated as a percentage of the methane produced.

In addition to the concentration, the emission is affected by time (the length of the measurement period), the molar weight of the gas, as well as the prevailing temperature, air pressure and wind speed.

The molar volume of the gas (V_m) is calculated according to the following equation, where R is the general gas constant (»8.314 J/(mol K), T is temperature and p is pressure:

$$V_m = \frac{RT}{p}$$

When the concentration (ppm) and molar volume are known, the amount of moles contained in a cubic meter of gas is obtained. From this, the molar mass is used to arrive at the mass of the gas in a cubic meter of air. Through the speed of the wind, we can further arrive at the flow rate and the emission rate.

The obtained emission measurement results were calculated in weight units (g/h, g). This is how the emission of the measurement period was obtained. The total emission of the process was calculated from that and the gas output.

In addition to the wind direction and speed, air temperature and air pressure, which influence the emission calculation, were monitored as environmental factors. The data was collected from the nearest official measuring station of the Finnish Meteorological Institute. Wind speed and direction were also monitored on site.

3.2.3 Results for the wet digestion measurement

August measurement

Lowering the chamber to the surface of the liquid fraction clearly increased the measured emission concentrations. This was seen from the chamber method (Figure 5) and from the simultaneous mast method (Figure 6).

The methane concentrations measured from the mast were initially at the level of 4–5 ppm, but when the chamber was lowered to the surface, the values measured from the chamber increased radically (to the level of 1 000–2 000 ppm). In the mast, this change was most visible at the lowest measuring point, where the concentration increased fourfold. At higher measuring points, which were also farther from the chamber, this was hardly visible. The same phenomenon was observed for ammonia. This means that the chamber broke the surface of the stored liquid fraction and caused an emission burst. Although efforts were made to lower the chamber to the surface as carefully as possible, the effect was visible in the results every time.

Figure 5. Methane and ammonia concentrations in the eight measuring points of the chamber method (N=92) in consecutive measurements (measuring number) at 11:00–17:00 o'clock, August 23, 2021.

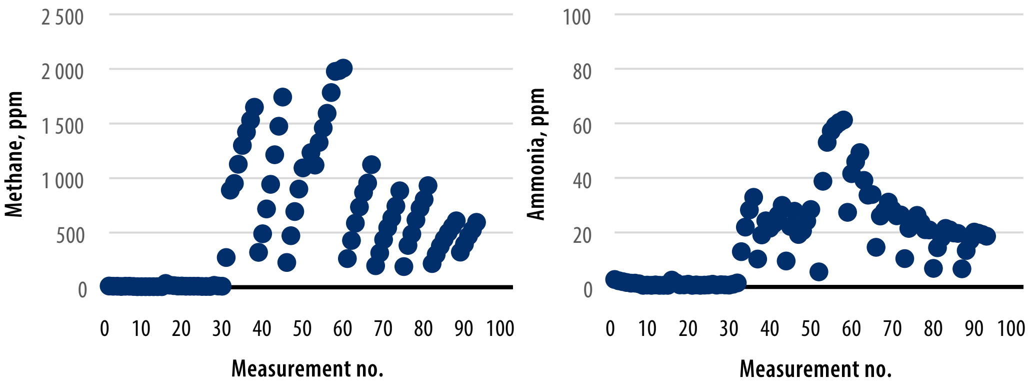
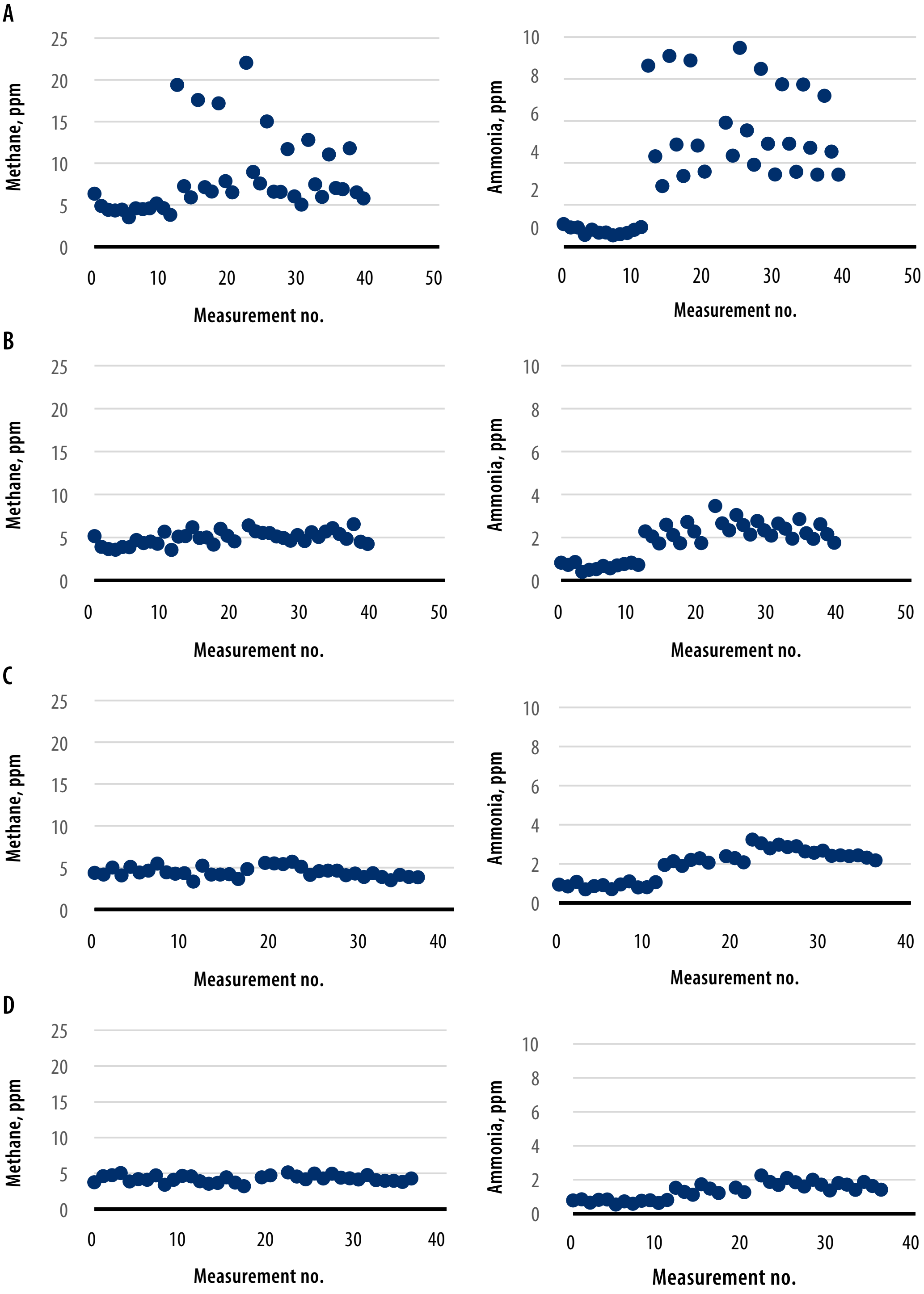


Figure 6. Methane and ammonia concentrations (ppm) during the August measurement (N=40) in consecutive measurements (measuring number) at 11.30–17:00 o’clock, August 23, 2021, using the mast method. The measuring points were a) 128, b) 386, c) 781 and d) 1 319 cm from ground level.



As the chamber method disturbed the emission measurement by breaking the surface of the liquid fraction, the results from the mast method prior to lowering the chamber were chosen as the reliable values used in further processing of the results (Table 6).

Table 6. Methane and ammonia concentrations (ppm) (N=10) in the August measurement. Measuring points 1–4 were 128, 386, 781 and 1 319 cm from ground level.

Measuring point	1	2	3	4	Average
Methane	4.6	4.25	4.46	4.30	4.405
Ammonia	0.77	0.67	0.89	0.72	0.763

The temperature (10.7 °C) and wind velocity (2.6 m/s) were calculated as the average of the measurement period from the measured data of a nearby airport. The calculation of air pressure used the normalized value of 760 mmHg.

The obtained results, methane 4.405 ppm and ammonia 0.763 ppm, mean that during the measurement period (5.3 h) methane emission from the storage tank was 698 g/h and ammonia emission 177 g/h. The methane emission from the storage tank under the prevailing measurement conditions would therefore be 6 112 kg/year and the ammonia emission 1 551 kg/year assuming the emissions were constant. Annually, the biogas plant produces 255 000 m^3 of biogas, which contains 69 % methane. Thus, the methane emission from the liquid fraction storage tank is 5.02 % of the methane produced during the summer measurement (Tables 6 and 7).

Table 7. Methane and ammonia emissions during the August measurement.

Biogas production, m^3/a	255 000
Biogas methane content, %	69
Density, kg/m^3	0.657
Methane production, kg/a	115 599
Methane emission, kg/a	6 112
Methane emission, % of methane produced	5.02
Ammonia emission, kg/a	1 551

March measurement

The measurements were repeated at the same location in winter conditions in March 4–6, 2021. The chamber method was no longer used, as it was found to disturb the process and not suitable for the site. The longer measurement period than before revealed momentary higher values in the methane emission, which were best seen at the lowest measuring points of the mast. The average methane concentration (2.095 ppm) and ammonia concentration (0.299 ppm) were significantly lower than in the August measurement period (Figure 7, Table 8).

Figure 7. Methane and ammonia concentrations (ppm) during the March measurement (N=2376) in consecutive measurements (measuring number) from March 3, 2022 11:00 o'clock to March 6, 2022 12:00 o'clock, using the mast method. The measuring points were a) 128, b) 386, c) 781 and d) 1 319 cm from ground level.

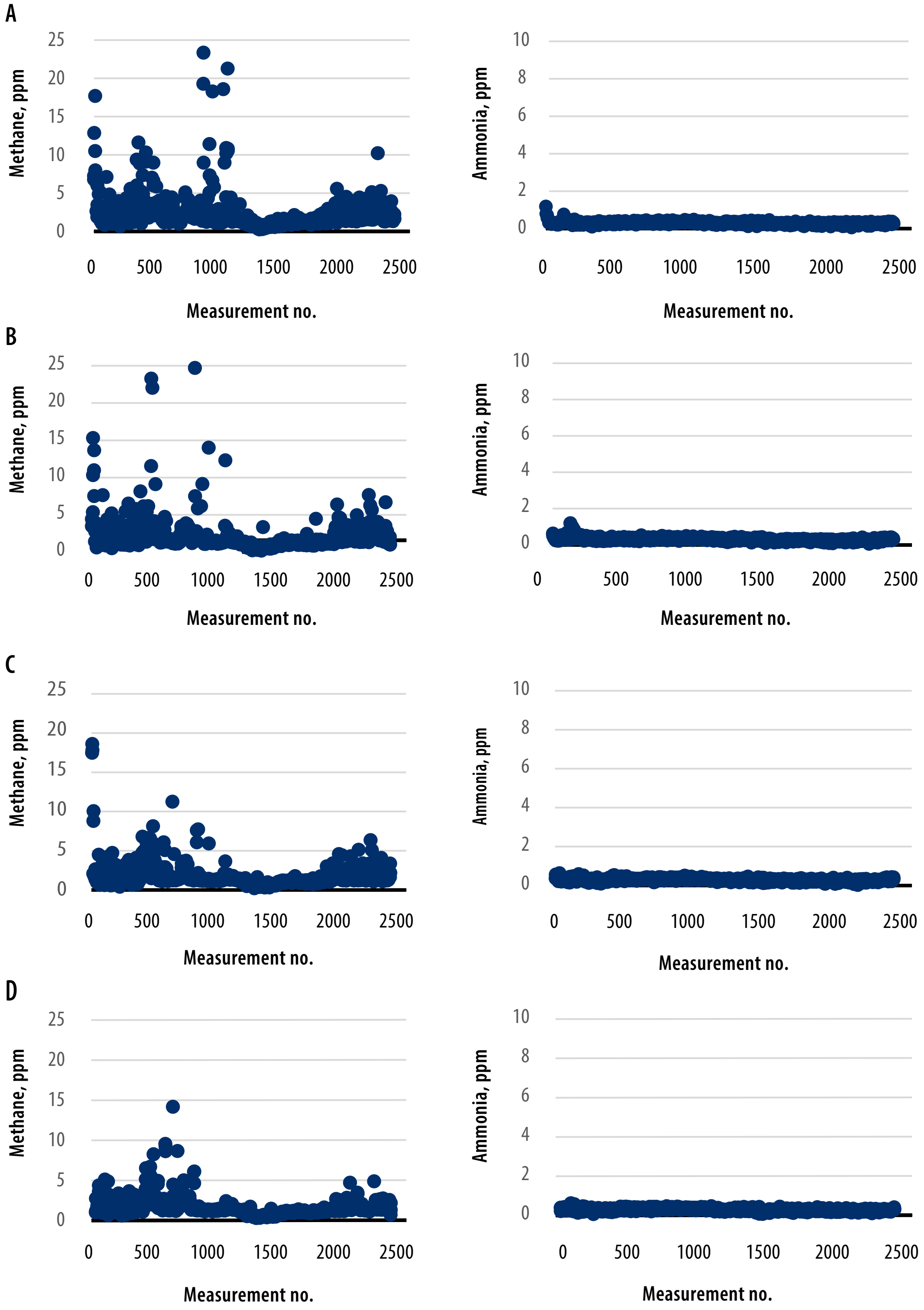


Table 8. Methane and ammonia concentrations (ppm) in the March measurement (N=594). Measuring points 1–4 were 128, 386, 781 and 1 319 cm from ground level.

Measuring point	1	2	3	4	Average
Methane	2.59	2.27	1.86	1.65	2.095
Ammonia	0.30	0.31	0.30	0.29	0.299

The obtained results, methane 2.095 ppm and ammonia 0.299 ppm, mean that during the measurement period (49.3 h) the methane emission from the liquid fraction storage tank was 10.48 kg/day and the ammonia emission 2.58 kg/day. The methane emission under the prevailing measurement conditions would thus be 3 826 kg/year and the ammonia emission 940 kg/year if the emission were constant. Annually, the biogas plant produces 255 000 m^3 of biogas, which contains 69 % methane, so the methane emission from the liquid fraction storage tank in connection with the winter measurement is 3.2 % of the methane produced (Tables 8 and 9).

Table 9. Methane and ammonia emissions in the March measurement.

Biogas production, m^3/a	255 000
Biogas methane content, %	69
Density, kg/m^3	0.657
Methane production, kg/a	115 599
Methane emission, kg/a	3 826
Methane emission, % of methane produced	3.20
Ammonia emission, kg/a	940

3.2.4 Discussion for the wet digestion measurement

The summer and winter measurements showed that temperature is a significant factor influencing the gaseous emissions from digestate storage. The summer measurement did not coincide with a very warm time, and the measurement period was short, but it still had a clearly higher emission level than in winter. The winter results are consistent with previous measurements of slurry tanks (Haapala & Hellstedt 2019), where the gas concentrations measured from the tank were minimal in winter. It is therefore clear that the summertime emission is higher than that of wintertime, but to obtain a more comprehensive annual result, emission measurements would be needed in different weather conditions (warmer summer, colder winter).

During the emission measurement, the wind direction was in accordance with the forecast. The mast was thus all the time below the wind, and variations in wind direction did not significantly affect the results. As expected, the gases emitted from the site moved close to the ground, and the measuring points at the bottom of the mast detected most of it. In the future, for longer-term measurements, it would be necessary to use more masts to accurately measure the emission regardless of possible changes in wind direction.

The measurement period in August was short, but its results are quite representative due to the continuous operation of the biogas plant. Still, longer measurement period is recommended. During longer measurements, momentary emission spikes were observed, which indicate that emission bursts occur from time to time in the liquid fraction storage tank.

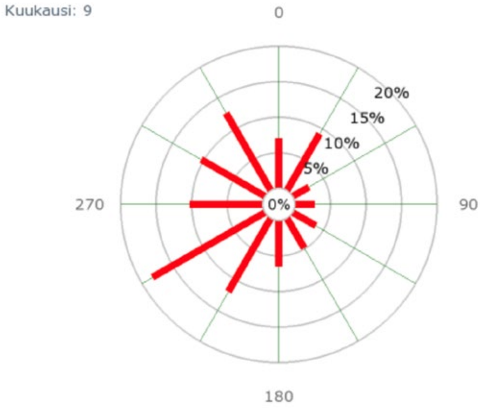
3.3 Biogas plant with dry digestion

Gaseous emissions from a biogas plant with dry digestion were measured only once during September 3–8, 2021. The temperature varied then from 8 to 15 °C.

3.3.1 Measurement method

The emissions of the dry digestion plant were measured, as in the wet digestion plant, with a measuring mast (Haapala & Hellstedt 2019) placed downwind (Figure 8). The prevailing wind direction and speed during the measurement period were measured. The suction lines of the photoacoustic emission analyzer were fixed at four heights, which were 87, 268, 541 and 914 cm from the ground level due to the size and distance of the site (Figure 9).

Figure 8. The wind rose of the measurement site (month 9) and the location of the measurement mast (star) below the direction of the prevailing wind. The two reactor silos of the dry digestion plant are located between the yellow arrow and the star. The storage site used for the short-term storage of both raw materials and digestate is located above the yellow arrow diagonally to the lower left of the reactor silos. The field where the digestate was spread after the silo was emptied can also be seen in the lower left corner of the picture.



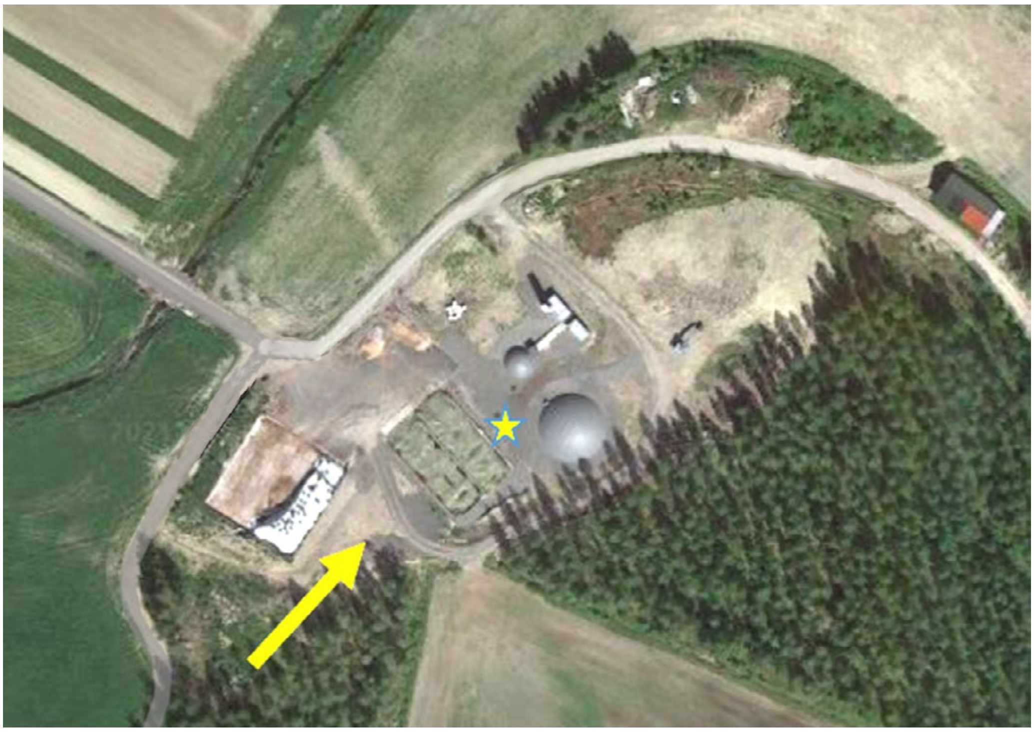


Figure 9. The measurement mast positioned downwind of the measurement site. The mast had four measurement points, the heights of which depend on the distance to the site.

Due to the batch-type nature of the dry digestion plant, the measurement period was longer than in the wet digestion plant. The measurement period was 108 hours (4.5 days), during which the batch of the second reactor silo was stopped, emptied, and filled again, but not yet covered, and biogas collection was not started again. The other silo was in the biogas production phase all the time. The measurement period was timed with the emptying of the first silo, where the batch was changed so that 48 % of the measurement was during the biogas production phase, 20 % during the active emptying phase and 32 % after the emptying. In this way, data describing the different stages of the batch process was collected (approx. 100 observations per day). However, it was not possible to limit the measurement event only to the first silo, but the possible emissions of both silos and the digestate storage site above the wind affected the emission measurement.

The measurement focused especially on the silo emptying phase. It was started before the end of the batch towards the end of the biogas production phase, and it was stopped when the reactor silo was empty and waiting to be refilled. The measurement period therefore did not cover the entire batch. Still, based on the measurement data, the emission of a typical, approximately 4-month (120-day) long batch process of one silo was also estimated. The calculation was done considering the fact that both reactor silos were in use during the measurement. Since the contribution of the second reactor silo was in the biogas production phase throughout the measurement, a correction was made in such a way that half of the emission measured during the last days of biogas production phase of the first silo was subtracted from the results.

The temperature and wind speed needed for the emission calculation were calculated as averages for each phase (Table 10). The normal air pressure value of 760 mmHg was used as air pressure in the calculation.

Table 10. Average temperature and wind speed during the biogas production phase and emptying phase and after the emptying (N=455).

-	Temperature, °C	Wind speed, m/s
During biogas production phase	7.9	4.1
During emptying the silo	11.5	2.7
After emptying the silo	14.7	3.6

3.3.2 Results for the dry digestion plant

The measured methane concentrations (ppm) at the dry digestion plant clearly rose during the emptying phase of the silo monitored (observation points 200–300) and remained at a higher level thereafter. The methane concentration was highest at the lowest measuring point and decreased the higher the measuring point was. Ammonia emission did not show a respective change, but its concentration remained at a low level throughout the measurement period (Figure 10, Tables 11 and 12).

Figure 10. Methane and ammonia concentrations (ppm) during the measurement period (N=455) in consecutive measurements (measurement number), 4.5 days between September 3, 2021 (starting at 14:00 o’clock) and September 8, 2021. Measuring points were a) 87, b) 268, c) 541 and d) 914 cm from ground level.

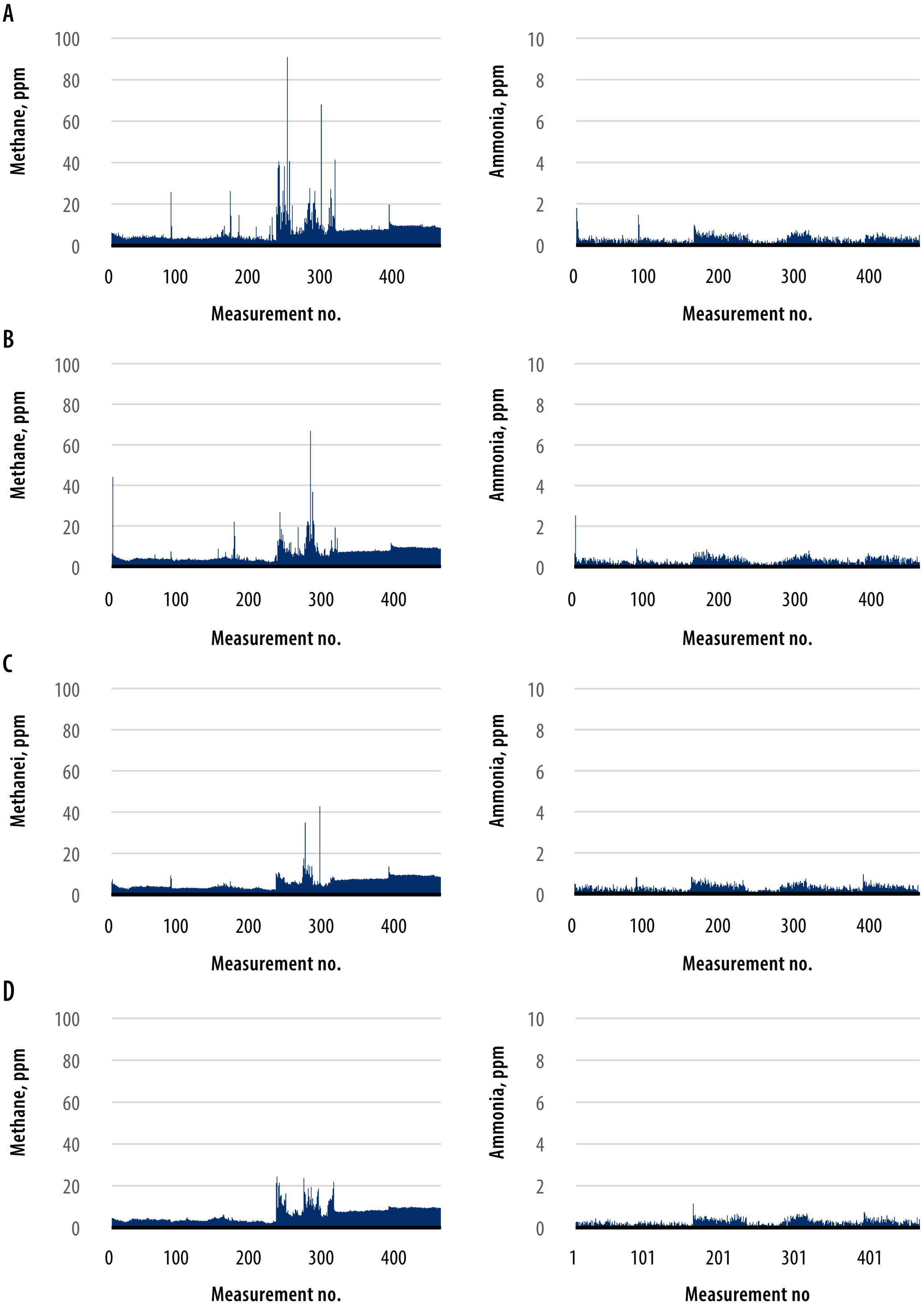


Table 11. Methane concentration (ppm) during biogas production phase and emptying phase and after the emptying (N=455). Measuring points 1–4 were 87, 268, 541 and 914 cm from ground level.

Measuring point	1	2	3	4	Average
During biogas production phase	4.40	4.02	3.56	3.57	3.888
During emptying the silo	14.84	10.47	10.47	7.69	10.869
After emptying the silo	8.64	9.23	9.45	8.18	8.876

Table 12. Ammonia concentration (ppm) during biogas production phase and emptying phase and after the emptying (N=455). Measuring points 1–4 were 87, 268, 541 and 914 cm from ground level.

Measuring point	1	2	3	4	Average
During biogas production phase	0.32	0.30	0.26	0.31	0.296
During emptying the silo	0.33	0.32	0.31	0.33	0.321
After emptying the silo	0.31	0.33	0.30	0.33	0.316

During the measurement period, the measured methane emission from the dry digestion plant was a total of 276 kg (Table 13). The measurement period focused on the emptying phase, but based on the results, an estimate for the emission during the entire batch was made. The measurement period during the final phase of the biogas production phase was only two days. When the duration of the entire batch is known (120 days) and it is assumed that the emission remains constant, the emission during the entire batch (biogas production phase) can be estimated. This way, it was estimated that 94 % of the total methane emission was released during the 120-day batch, 2 % during emptying and 4 % after emptying before the reactor silo is refilled. Respective ammonia emission would be 25 kg (Table 14). Relative to the entire batch, it was estimated that 89 % of the total ammonia emission occurred during the 120-day biogas production phase, 1 % during emptying and 10 % after emptying.

Table 13. Average (mg/s) and cumulative (kg) methane emission during 4.5-day measurement period over the different phases.

	Over the measurement period	
	mg/s	kg CH_4
During biogas production phase	1 802	76
During emptying the silo	4 148	70
After emptying the silo	4 790	130
Total	-	276

Table 14. Average (mg/s) and cumulative (kg) ammonia emission during 4.5-day measurement period over the different phases.

	Over the measurement phase	
	mg/s	kg NH_3
During biogas production phase	235	4
During emptying the silo	104	3
After emptying the silo	211	18
Yhteensä	-	25

3.3.3 Discussion for the dry digestion plant

During the emission measurement of the dry digestion plant, the wind direction was predicted to be from west-southwest to east-southeast. The mast was thus all the time below the wind and the wind direction fluctuations did not significantly affect results.

There is a possible error in the estimate of the total emission over the entire batch period because the measurement covered only part of the 120-day batch. The measurement was aimed at the final days of the batch (biogas production phase) and emptying, and the emission of the preceding days was not measured. The emission of a single batch is most likely not constant during the biogas production phase, as was assumed in the estimate, but at the beginning it increases and in the final phase it declines according to the growth and decline of the biogas yield. However, the measurement site had two parallel reactor silos in use at the same time, the inputs of which were in different phases with each other, and the emission measurement could not be limited only to one of the silos. The measured emission can therefore be assumed to be representative and describe the entire production unit. However, this should be verified with a longer-term emission measurement.

According to the plant operator, the biogas yield of the silo to be emptied had not yet completely ceased, but the yield would probably have been enough for about another two weeks. However, the batch was stopped to balance the biogas production for the demand of the gas refueling station.

The share of the emissions of the different phases of the overall batch process is clearly focused on the biogas production phase, representing more than 90 % of the total emissions. In reducing methane emissions from a dry digestion plant, special attention should be paid to emissions during biogas production and the source of emissions should be determined. It can be a steady leak or a specific leak point that should be sealed. Compared to the total emission of the batch, the emission during and after emptying the silo remained low, although there were clear emission peaks. This is since emptying phase is a short period. In addition, the plant aims to control emissions before emptying the silo by sucking the remaining biogas from the digestate before opening the silo cover.

During the emission measurement, the wind direction was from the direction of the digestate storage site. Before starting a new batch, horse and poultry manure were in the storage site to wait for the refill. Correspondingly, the digestate from the previous batch was spread on a nearby field also upwind. The significance of these environmental conditions for the measured emission is difficult to assess.

To get a more accurate picture of the emissions of the batch process, emissions should be monitored throughout the batch. In addition, it should be ensured that the stored manure or digestate do not interfere with the emission measurement of the plant itself. Measurements should also be made in winter conditions because the temperature has been found to affect the emissions. A comparison should also be made between a batch whose biogas production has already declined and the current measurement, where the batch was still producing biogas at the time of emptying the silo. It would also be good to monitor the plant's emissions with a portable measuring device to find out potential leakages.

3.4 Conclusions from the emission measurements

In terms of measurement methodology, the mast measurement was successful and provided reliable information on the quantity of gaseous emissions.

In the measurements of the liquid fraction storage tank of the wet digestion plant, the chamber method affected the measurement site by cracking the surface crust of the liquid fraction, and its use is not recommended in the future. Lowering the chamber to the surface should be done very carefully, which is very difficult to do in practice.

In the measurements of the dry digestion plant, it was clear that during the silo emptying, the methane emission temporarily increases significantly. Removing the cover and then the digestate releases methane trapped in the digestate. However, the share of the emptying phase in the total emission remains small compared to the emission during the biogas production process due to its short duration. The estimate of the total emission of the batch process could be refined if the measurement period was longer and focused on the entire batch period.

The weather during the measurement period, especially the temperature, has a significant effect on the emission being lower in cold. Temperatures above 20 degrees did not occur during the current measurement period, in which case the emission would probably have been higher than measured. To get a more comprehensive result, measurements in different weather conditions (hotter summer, colder winter) would be needed. Wind speed also has a significant effect on the measurement results of concentrations (ppm), so its measurement must be done carefully. More accurate local measurement of wind speed would improve resolution and dynamics, i.e. a more accurate picture of instantaneous emissions would be obtained

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3.5 Nitrous oxide emissions during field application of slurry

The nitrous oxide emissions caused by the application of slurry were examined using the previously unpublished data from field measurements made in 2005–2007. The results are from two fields: grass production on clay soil in Jokioinen, on which cattle slurry was spread, and grain (barley) producing sandy soil in Ypäjä, on which pig slurry was spread. In addition to the raw slurry, a respective digestate was available, as well as its separated solid and liquid fractions in the barley experiment. The application method was either surface application or injection with conventional equipment or wing coulters. Nitrous oxide emissions were measured from test plots fertilized in connection with sowing using the chamber method approximately twice a month for 7 months. The summed-up results of 147 measuring points over a period of at least 7 months were available for the analysis, and they have been processed separately for grass and grain.

From the results of the grain experiment, no consistent difference could be observed between raw slurry and digestate or between application methods (Table 15). In 2005, there were no statistical differences between the treatments, but in 2006, the injected raw slurry had the highest emissions, while the emissions of the surface-applied liquid fraction separated from the digestate were less than a third of that. Similar results were obtained in 2007, when two applications of the liquid fraction resulted in lower emissions than in the injection of raw slurry. However, the differences seem random between years and treatments.

Table 15. Nitrous oxide emission in grain experiment (barley) with application of raw pig slurry, digested pig slurry and separated fraction of the digested pig slurry. The experiment was conducted in 2005–2007.

Fertilizer	Application method	N_2O-N (kg ha^{-1} 7 months^{-1})		
-	-	2005	2006	2007
Mineral fertilizer	Surface	1.4±0.3^{a}	2.4±1.0^{ab}	0.8±0.1^{d}
Raw slurry	Surface	1.7±0.3^{a}	3.0±0.7^{ab}	1.1±0.3^{cd}
-	Injection	2.1±0.4^{a}	2.5±0.9^{ab}	2.8±0.1^{b}
-	Wing coulter	2.6±0.4^{a}	3.6±1.8^{a}	-
Digestate	Surface	2.4±0.9^{a}	1.5±0.6 ^{abc}	1.6±0.6^{bcd}
-	Injection	2.4±0.4^{a}	1.5±0.1 ^{abc}	2.8±0.9^{bc}

Fertilizer	Application method	N_2O-N (kg ha^{-1} 7 months^{-1})		
-	Wing coulter	2.5 ± 0.7^{a}	1.5 ± 0.2^{abc}	-
Liquid fraction of digestate	Surface	2.0 ± 0.8^{a}	0.9 ± 0.5^{bc}	1.0 ± 0.1^{cd}
-	Injection	1.6 ± 0.7^{a}	1.2 ± 0.4^{abc}	1.0 ± 0.1^{d}
-	Wing coulter	1.6 ± 0.6^{a}	0.9 ± 0.3^{abc}	-
Solid fraction of digestate	Immediate mulching	-	1.8 ± 0.8^{abc}	-
-	Mulching in 1 h	-	1.7 ± 0.6^{abc}	1.4 ± 0.5^{bcd}
Solid fraction of digestate	Immediate mulching	-	1.8 ± 0.8^{abc}	-

The letters in superscript show statistically significant difference between the treatments within a year.

In the grass experiment, nitrous oxide emissions were smaller for the application of digested cattle slurry than for raw cattle slurry in 2005 (Table 16). In the other years, there were no statistically significant differences between the treatments.

Table 16. Nitrous oxide emissions in grass experiment with application of raw cattle slurry and digested cattle slurry. The experiment was conducted in 2005–2007.

Fertilizer	Application method	N_2O-N (kg ha^{-1} 7 month^{-1})		
		2005	2006	2007
Mineral fertilizer		0.7 ± 0.1^{ab}	0.5 ± 0.1	0.8 ± 0.1
Raw slurry	Surface	1.2 ± 0.8^{a}	0.5 ± 0.2	1.7 ± 0.5
	Injection	1.3 ± 0.3^{a}	0.8 ± 0.2	1.4 ± 0.2
Digestate	Surface	0.5 ± 0.2^{b}	0.5 ± 0.3	1.6 ± 0.6
	Injection	0.7 ± 0.2^{ab}	0.6 ± 0.3	1.2 ± 1.0

The letters in superscript show statistically significant difference between the treatments within a year.

Nitrous oxide emission increased with increasing fertilization level, but the difference was not statistically very clear (Figures 11 and 12). Despite the higher fertilization level of grass, the emissions from the grass experiment were lower than those of the grain experiment.

Figure 11. The effect of fertilization level on nitrous oxide emission in the grain experiment.

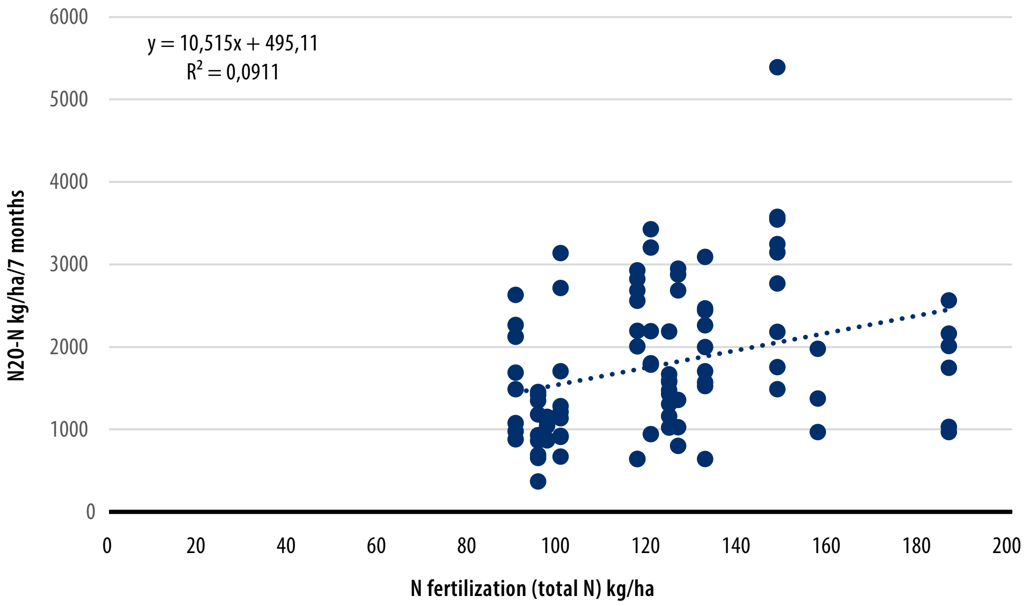
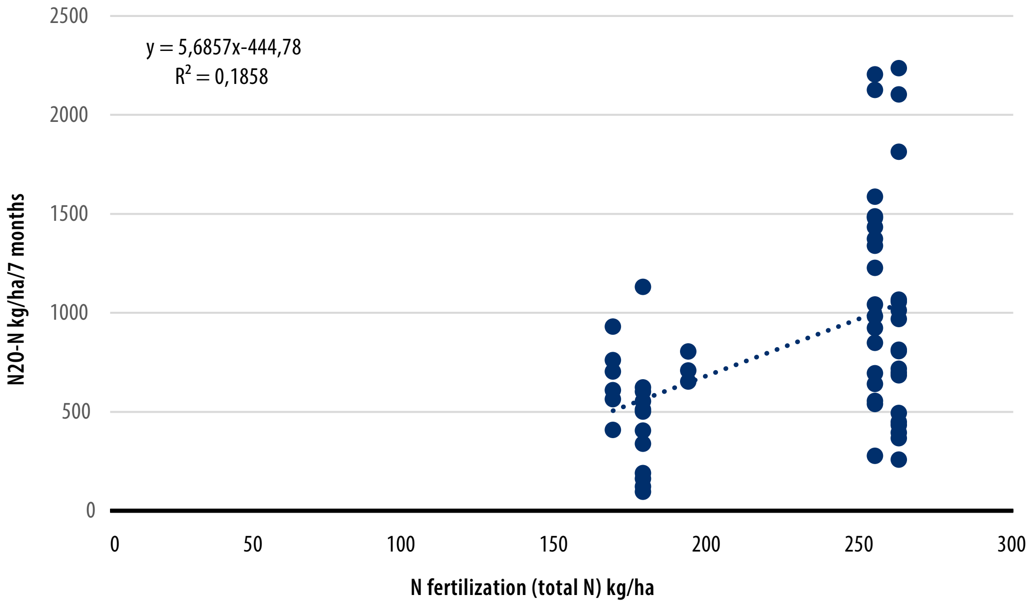


Figure 12. The effect of fertilization level on nitrous oxide emission in the grass experiment.



The emissions measured during the seven months of the grain experiment varied between 0.8–3.6 kg N_2O-N (average value 1.8). In the grass experiment, the results varied between 0.1–2.2 kg N_2O-N/ha/year (average value 0.85). Since the wintertime N_2O emissions are about half of the whole year's emissions, these results are in line with the average annual results measured from grain fields in Finland (3.5 kg N/ha/year from annual crops and 1.8 kg N/ha/year from grass; Regina et al. 2013).

It was not possible to reliably compare the differences between digested and raw slurry over years (by combining the entire measured data), because the fertilization levels vary between the treatments and the average fertilization levels are weighted differently for raw slurry and digested slurry. However, the results of comparisons made over the years suggest that digestion does not significantly change the level of N_2O emissions resulting from the application of slurry.

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4 The impact of biogas production on digestate carbon content and its persistence in soil

Jaakko Heikkinen (Luke)

The impact of biogas production on the carbon content of the feed materials and further to soil carbon with digestate fertilizer use was studied as a literature review and via modeling.

4.1 Literature review

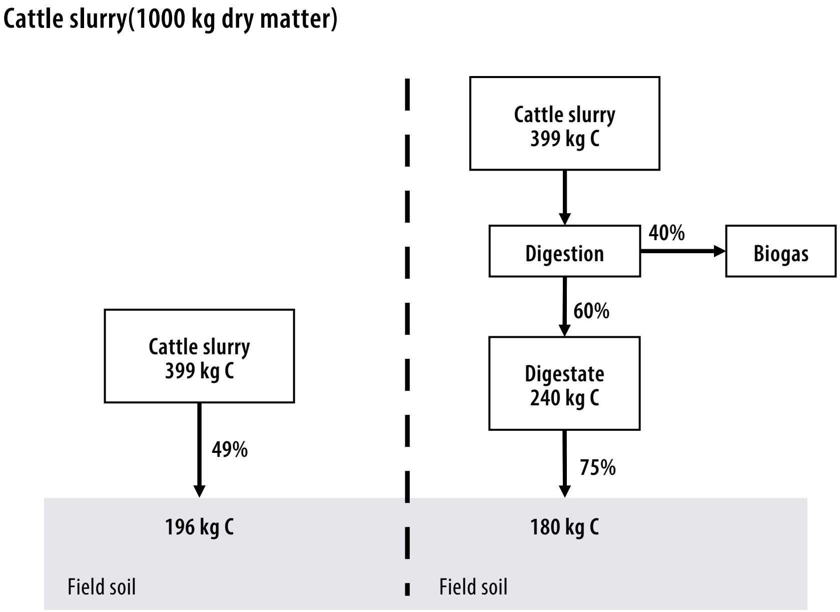
The persistence of the digestate carbon in the soil depends on the chemical quality of the digestate, the climatic conditions and the properties of the soil in the field parcel where the digestate is spread. Biogas production can also have indirect effects on the carbon balance of the soil, if it affects the land area in agricultural use or the crop rotations and thereby the amount and quality of the carbon that ends up in the soil as crop residues.

As a result of biogas production, the carbon remaining in the digestate is in a chemically more stable form than in the original feed material. In the biogas process, the main part of the carbon in the easily degradable forms like fatty acids, cellulose, hemicellulose and protein is converted into biogas carbon compounds, while the amount of slowly decomposing lignin remains unchanged in the process. Möller (2015) estimates that as a result of biogas production, biomass stability increases by 29–625 % compared to unprocessed biomass. The effect depends on the quality of the biomass used as feed and the chosen processing technology, but the determination method that measures stability has also been found to influence the results. Part of the organic matter of the digested biomass (20–95 %) breaks down into methane and carbon dioxide in the process, reducing the amount of easily degradable carbon contained in the digestate. Biodegradable carbon recovered for soil amendment purposes contains carbon that is more difficult to decompose and is therefore more stable, but the total amount of carbon is lower than in the unprocessed biomass.

The effects of the digestate use on the soil carbon balance have been studied by e.g. Bachmann et al. (2014), Möller (2009), Nilsson et al. (2020) and Thomsen et al. (2013). Based on the summary studies by Möller (2015) and Insam et al. (2015), the biogas process does not have a significant effect of increasing or decreasing soil carbon. This is consistent in the sense that in the relatively short-term biogas process, only quickly degradable carbon is lost, which is also easily degraded in the soil’s own decomposition processes, while the biogas process does not necessarily affect the more persistent carbon that is more relevant in terms of the soil’s carbon balance. The persistence of carbon in the soil can possibly be improved by further processing the digestate, for example by composting, separating the liquid and solid fractions, or by pyrolyzing it into biochar (De la Fuente et al. 2013; Insam et al. 2015).

Under Finnish conditions, the degradation of digestate in the soil has been investigated in the Mahtava project conducted by Natural Resources Institute Finland (funding: MMM Makera 2016–2018), where the persistence of carbon in different soil amendments was investigated in soils using a litter bag test, laboratory incubation and chemical fractionation. The results were also compared with the simulation results given by the soil carbon model Yasso07. Based on the results, there is more chemically stable carbon in the digestate compared to unprocessed biomass after the biogas process (Heikkinen et al. 2021). Based on the litter bag test, the proportion of permanent carbon was 49 % in raw biomass and 75 % in digestate. However, the biogas process was not found to affect the carbon stock of the soil (Figure 19), when the conversion of carbon into biogas caused by the biogas process is considered. The result is in line with the estimates presented by Möller (2015) and Insam et al. (2015).

Figure 13. Carbon accumulation in the soil when either unprocessed or digested slurry is applied. In the example calculation, it is assumed that in the biogas process 40 % of the carbon contained in the digestate is converted into biogas. The figure is adapted from Heikkinen et al. (2021).



The persistence of carbon in the soil is facilitated by the binding of carbon to the soil's fine particulate matter and aggregate structures (Six et al. 2002; Kögel–Knabner et al. 2008), which determine the maximum carbon sequestration potential of the soil. When the amount of carbon exceeds the maximum carbon sequestration potential, the accumulated carbon is not bound to the mineral matter and is therefore more susceptible to degradation (Poeplau et al. 2018; Cotrufo et al. 2019). In terms of the carbon stability and the achievable climate effects, it would be advantageous if the digestate were applied on field parcels where the amount of carbon in relation to the amount of fines is low. The influence of soil properties on carbon sequestration potential is being studied in more detail in the Hiiletin project of Natural Resources Institute Finland, which is ongoing at the time of writing.

According to Möller (2015), the secondary effects of biogas production can be more important for the soil than the direct effects of applying the digestate on the soil. In monotonous cropping, biogas production can diversify crop rotation and increase the share of perennial grasses in them by offering them a use as a feed for biogas production. Crop rotations that are diverse and include grass have been found to sequester soil carbon (Bolinder et al. 2010; Heikkinen et al. 2022; King & Blesh 2018). In the same way, the use of digestate (or other organic material) as a soil amendment can improve the health of the soil (soil structure, water management, nutrient status), increasing the biomass and thereby also the amount of carbon ending up in the soil. At least in organic farming, the use of digestate has been found to increase above-ground biomass and yield (Stinner et al. 2008), but in a field experiment in Norway, for example, no effect on productivity was observed (Løes et al. 2013).

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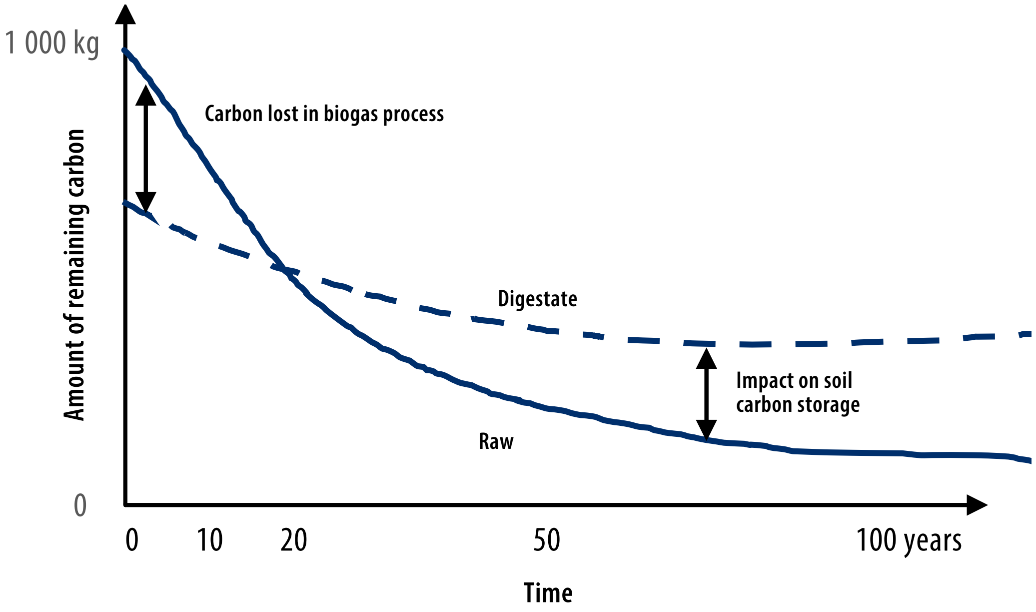
4.2 Modeling

The goal of the implemented modeling was to evaluate the effects of the biogas process of cattle and pig slurry and its hydraulic retention time (HRT) on the carbon balance of the soil when the slurry-based digestate is used as fertilizer. The modeling was done using the Yasso07 soil carbon model. In the Yasso07 model, soil carbon is divided into five fractions with different decomposition rates. Climatic conditions, temperature, and precipitation, regulate the decomposition rate of the fractions. The Yasso07 model can be used to evaluate the effect caused by the biogas process on the chemical stability of plant masses and manure in the soil. The model has been found to predict the breakdown of soil amendments in the soil relatively well (Heikkinen et al. 2021). However, the Yasso07 model does not include factors that describe the properties of the soil, and therefore the model cannot consider the effects of the soil on the stability of the carbon contained in the digestate. The Yasso07 model is used when calculating soil carbon stock changes in the national Finnish greenhouse gas inventory (Statistics Finland 2020; Statistics Finland 2021; Tuomi et al. 2009). An effort was made to make the modeling as consistent as possible with the calculation methods used in the national greenhouse gas inventory, so that the calculation could be transferred to form a part of the inventory's calculations.

Modeling was used to estimate the decomposition rate of unprocessed slurry and digested slurry in the soil, based on which the effect of biogas process on soil carbon was calculated. The principle of the calculation is described in Figure 14. In the biogas process, part of the carbon bound to the slurry is converted into biogas when the organic matter breaks down, which is why less carbon ends up in the soil as digestate compared to the use of raw slurry. On the other hand, the carbon remaining in the digestate from the slurry is slower to decompose, depending on the original properties of the slurry and the operation methods of the biogas process. In this work, it was assumed that either 40 % or 60 % of the carbon in the slurry is converted to biogas during digestion. A smaller proportion describes an estimate of a short HRT and a larger proportion of a longer HRT. The effect on the soil's carbon stock is the difference between the remaining portions of digestate and raw slurry, which depends on the time considered (see Figure 14).

The modeling was done using the average (2000–2020) temperatures and rainfall in Southern Finland. The chemical qualities of digestate and raw slurry were extracted from the results of the Mahtava project (Heikkinen et al. 2021). Modeling was done separately for pig and cattle slurry. In addition to slurry, the effect of grass biomass as a feed material was considered in the calculation.

Figure 14. The calculation principle used in assessing the soil carbon impact of digestate fertilizer use.



The decomposition of both raw slurry and digestate in the soil is fastest in the initial phase of decomposition and slows down over time (Figure 15). In the initial phase, the decomposition of raw slurry is clearly faster than that of digestate. Even after a hundred years, there is still slightly more carbon left in raw cattle slurry than in digested slurry. However, the differences are very small. With pig slurry, the raw slurry initially decomposes so quickly that after ten years, more of the carbon in the digestate (60 %) is left. Even with pig slurry, when looking at a longer period, the differences between raw slurry and digestate are small. The effects on the carbon stock are shown in Table 17.

Figure 15. The decomposition of cattle and pig slurry in soil assuming that 40 or 60 % of carbon is converted to biogas during the digestion process.

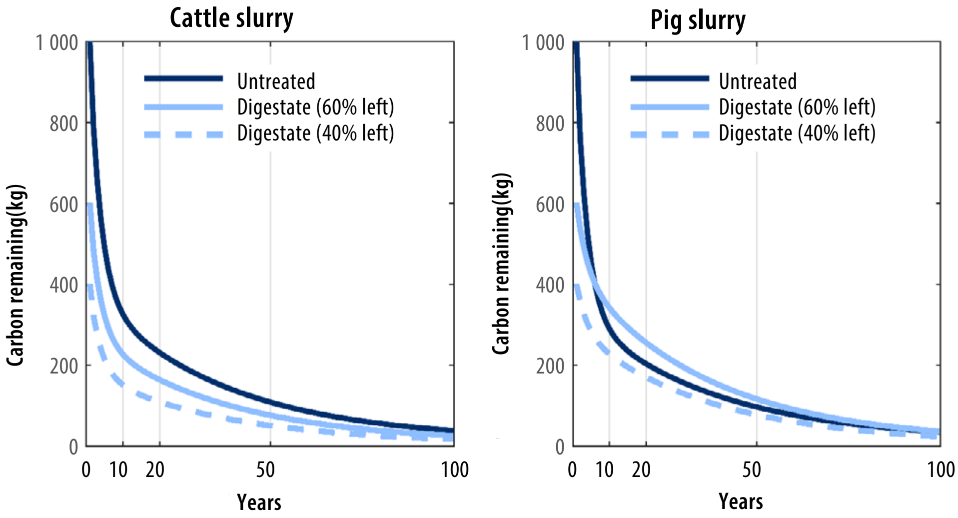


Table 17. The effect of biogas process on soil carbon stock in 0, 10, 20, 50 and 100 years. The results have been calculated for 1 000 kg of unprocessed slurry (as carbon). A negative value means that there is less carbon in soil as compared to unprocessed slurry. The unit is kg.

Period (years)	Pig slurry (40 % of carbon to biogas)	Pig slurry (60 % of carbon to biogas)	Cattle slurry (40 % of carbon to biogas)	Cattle slurry (60 % of carbon to biogas)
0	-600	-400	-600	-400
10	-55	55	-165	-93
20	-32	51	-119	-65
50	-19	19	-57	-32
100	-11	1	-21	-12

The modeling results confirm the conclusion of the literature review that biogas production does not have a clear effect on the amount of carbon in the soil in the long term. The result is in line with the calculation presented by Heikkinen et al. (2021), which was based on the decomposition of raw slurry and digestate observed in the litter bag experiment. Due to the lack of research data and applicable methods, the indirect effects of easily degradable carbon on the amount of permanent carbon in the soil were not evaluated in this context.

In the national Finnish greenhouse gas inventory, carbon stock changes in mineral soils are estimated using the Yasso07 soil carbon model. In the inventory, the amount of carbon ending up in the soil from plant residues is estimated based on crop yield data and cultivated areas. The carbon from manure is estimated based on the number of domestic animals. At the time of writing, the effect of digestate has not been considered in the greenhouse gas inventory but the consequential effects of biogas production on, for example, crop rotations and crop yields are included. The current calculation corresponds to a situation where the use of agricultural biomass for biogas production has no effect of increasing or decreasing carbon in the soil. Technically, the inclusion of digestate in the calculations of the inventory would mainly require information on the extent to which digestate is used as soil amendment. However, based on the literature review and the modeling done in this report, the current calculation can be considered justified.

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5 The inclusion of manure-based biogas in the greenhouse gas inventory

Tarja Silfver (Luke)

In 2021, the majority of Finnish biogas was produced from biowaste and sewage sludge. However, production based on agricultural feed materials such as manure and various grasses has been on the rise throughout the 2010s. The goals for increasing biogas production heavily rely on the utilization of agricultural biomass. Compared to 2011, the number of farm facilities has increased from ten operating facilities (Huttunen & Kuittinen 2012) to a total of 25 facilities in 2021 (*preliminary data, OSF 2021). In addition to farm-scale biogas plants, agricultural feed materials are processed in centralized plants, and processing volumes are expected to continue growing this decade.

The greenhouse gas inventory emission calculation is based on the guidelines of the Intergovernmental Panel on Climate Change (IPCC). The latest 2019 update of these guidelines provides instructions and a range of emission factors to include manure-based biogas production in calculations concerning emissions associated with manure management (IPCC 2019). The utilization of manure in biogas production can reduce methane and nitrous oxide emissions compared to traditional manure management methods. However, emissions depend significantly on the technical and operational implementation of biogas plants and the storage methods of digestate (IPCC 2019; Miettinen et al. 2022). In Finland, more accurate estimates are needed to determine the extent to which manure is directed to biogas plants, because the data from Finland's biogas registry is often incomplete regarding feed materials. In addition, more detailed information about the operational practices of manure-handling biogas plants is required to select the most appropriate emission factors for national calculations according to IPCC guidelines. Emission factors for emission-reducing practices are notably lower compared to less efficient practices. These factors vary from around one percent for the best practices (best available technology, minimal process leaks and gas-tight digestate storage) to an over twelve percent for the weakest practices (low-quality technology, significant process leaks and open digestate storage; IPCC 2019).

Due to its increasing significance, the inclusion of manure-based biogas in the national greenhouse gas inventory is being prepared in Finland. Additional insights into the aforementioned data needs are being obtained through, e.g., the biogas survey conducted by Statistics Finland, surveys related to manure management conducted on farms, and data collection specifically related to manure-based biogas carried out by Natural Resources Institute Finland. As of current knowledge, the inclusion of digestate spreading in the greenhouse gas inventory is not considered appropriate, as the emissions from digestate spreading and its effects on the soil carbon stock do not significantly differ from conventional manure, as stated in chapters 2 and 4.

As the use of manure in biogas production increases and becomes a part of the national greenhouse gas inventory, the emission impacts of the production practices will also become visible. This presents an opportunity for the industry and its management to recognize and invest in practices that minimize emissions during biogas plant operation.

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6 Review of policy instruments

Helena Valve (Syke)

The review of policy instruments focused on the regulations and schemes seeking to guarantee the environmental sustainability of biogas production. Both existing instruments, and those under preparation at the of writing, were mapped. The aim was to scrutinize the coverage and functionality of the existing legal, financial, and voluntary instruments in relation to the identified emission sources and the conditions for achieving the sustainability goals. The feasibility of the regulation, and its capacities to generate legal certainty, were also considered. Based on the findings, development needs of policy instruments were defined.

The review aimed to answer the following questions:

- Which policy instruments influence the sustainability of the biogas production chain and how the emission reductions take shape?
- How do the instruments regulate the different sustainability aspects of the biogas production chain (Figure 1)? Which stages of the production chain are regulated and what is left out?

The report was based on the analysis of documents and interview data. Legal instruments were mapped with the help of legal texts and research reports. In this work, the assumption was that in addition to environmental regulation (such as the Environmental Protection Act) that falls within the scope of the administrative branch of Ministry of the Environment, biogas production is controlled by the conditions set for public subsidies, and indirectly by, for example, regulating digestate application on fields.

The documentary material was supplemented with thematic interviews, which were carried out between November 2021 and March 2022. All four interviewed persons were private sector operators who had been working with biogas production and its development for a long time. They have a broad view of the industry and its regulation through customer contacts and industry advocacy. Two of the interviewees work in companies that supply biogas plants for decentralized and/or centralized biogas production. In addition, a consultant, who works versatile in the industry, and a representative of a company planning an investment in a biogas plant were interviewed.

The on-line interviews lasted 1–1.5 hours. The interviews were recorded, the recordings were transcribed, and the documents were analyzed using the NVivo program, so that the comments on the issues relevant to the sustainability of biogas production and their regulation could be grouped together.

In the following subsections, the results of the review are presented first per policy instrument and then by evaluating the policy mix as a whole.

6.1 Economic policy instruments

6.1.1 Type of support

The energy subsidy from the Ministry of Economic Affairs and Employment of Finland has been granted to industrial-scale biogas plants for 20–30 % of the costs (Alm 2022). The energy investment subsidies in accordance with Finland's Recovery and Resilience Plan can also be granted for biogas projects (Government Decree 1112/2021 on support for energy investments in accordance with Finland's Recovery and Resilience plan in the years 2022–2026). In the first support round (2021–2022), energy investments exceeding 5 million euros were financed.

The Finnish Ministry of Agriculture and Forestry's Rural Development Programme, which ended at the end of 2022, and Finland's CAP plan, which entered into force at the beginning of 2023, contain investment subsidies for both farms and rural companies. Since May 2021, agricultural investment support has been granted up to half of the eligible investment costs of a biogas plant (50 %), and the support will continue in the new CAP plan. Receiving the subsidy requires that the subsidized energy is consumed on the farm. The selection criteria for energy investment subsidy emphasize the project's effects on the environment and climate. Investors can also apply for a government guarantee for the investments.

Rural business support, partly funded by the EU, has been granted to biogas plants from the Rural Development Programme 2014–2020; transition period 2021–2022. In addition, during the transition period, the recovery instrument of the European fund for rural development was used to allocate support for biogas investments. Finland's CAP plan 2023–2027 can continue to support investments in biogas plants (50 % of eligible costs). Micro and small businesses operating in rural areas can apply for support. In addition, during the funding period 2023–2027, energy investments, including biogas investments, are eligible for national subsidies.

In the years 2022–2026, the so-called Security of Supply Package provides support for alternative energy sources and other investments and experiments in security of supply. For investments in nutrient recycling, the Ministry of Agriculture and Forestry has earmarked 14.5 million euros for its own administrative branch, and the Ministry of the Environment respectively 25 million euros. In addition, the administrative branch of the Ministry of Agriculture and Forestry is introducing a nutrient recycling subsidy to be distributed through tendering. The new subsidy encourages biogas plants to receive manure as feed material and to process the digestate into more advanced fertilizer products.

The production of biogas as vehicle fuel will also be supported through the national distribution obligation of sustainable biofuels renewed in 2021. According to the scheme, a biogas plant producing vehicle fuel, for instance, from manure can sell a so-called ticket share to other transport fuel distributors to help them to fulfill the distribution obligation.

6.1.2 Sustainability criteria for subsidized measures

Sustainability Act

The sustainability criteria and assessments included in the subsidy systems aim to ensure that public resources are used to finance projects that are sustainable and capable of supporting the achievement of carbon neutrality goals. The Sustainability Act (393/2013), which implements the sustainability criteria of the Renewable Energy Directive (2018/2001, RED II), stipulates that state support for biogas production can only be granted if the production is based on raw materials defined as sustainable and bioenergy achieves sufficient reductions in greenhouse gas emissions. The conditions have been initially applied to biogas plants with a total output of more than 2 MW (change in preparation at the time of writing). If a state subsidy has been granted to produce biogas as a vehicle fuel, the recipient must demonstrate the sustainability of the raw materials used, regardless of the size of the project (Energy Authority 2021). In addition, only biogas produced within the framework of an approved sustainability system can be included as a vehicle fuel fulfilling the distribution obligation.

The sustainability of biogas production is generally demonstrated based on a sustainability system drawn up by the operator and verified by an impartial body. The Finnish Energy Authority is responsible for the approval in the national sustainability system. The operator must check compliance with the sustainability system regularly and provide an annual report on the fulfillment of the sustainability criteria to the Energy Authority (2021). Biogas production is defined as sustainable if the feed materials used are sustainable in origin and if the process produces a sufficient amount of emission reductions according to the preliminary calculation. The calculation is affected by the feed materials used in biogas production. For example, when manure is used as a feed in the process, the production can get a negative emission value, i.e., it is estimated to generate emission reductions (manure bonus), while production based on surplus grass does not result in calculated reductions.

Aspects related e.g. to the operation of the biogas plant and the utilization of digestate are excluded from the sustainability criteria according to the Sustainability Act. Methane leaks and emissions from the biogas production chain are not considered in the calculation of emission reductions. Verification takes place within the framework of calculated material balances, without paying attention to operating practices and leakage possibilities. However, based on the interviews, the calculation process can play a significant role in the planning of operations.

> *"I have never had to do that verification. But those are reasonably harsh demands. That yes, you must really, at least on paper, look at it quite carefully. But whether it can be done, hardly, there probably won't be any such verification or some sort of checking, if you have some kind of leaks at the plant, so that it's a matter of verifying it on paper." (Biogas plant operator)*
>
> *"But I talked to one operator in the summer, and they stated that the sustainability issue struck them when they went to the Energy Authority to make those reports and calculations. And to break it through. That at that point it became concrete for them what it actually means in practice." (Consultant)*

The rules for calculating GHG reductions according to the Sustainability Act encourage the use of manure as a feed material for biogas production. The definition of manure as zero emissions supports better utilization of the energy potential of manure and creates a basis for promoting the processing and recycling of manure nutrients. In addition, the inclusion of manure in the feed mixture produces a calculated emission reduction compared to the fossil reference value for the emission reduction calculation submitted to the Energy Authority (Rasi et al. 2019).

However, the Renewable Energy Directive's manure bonus can also have unwanted side effects. Biogas plants that use energy-rich plant biomass as feed, such as surplus grass, may be tempted to supplement the feed mixture with manure to achieve a calculative emission reduction. The result may be a situation where an excessive amount of feed material is received in relation to the plant's digestion capacity. The situation can be sought to solve by shortening the reactor HRT, which increases the risk of methane emissions (see chapter 2).

The principle of 'do no significant harm'

The biogas plants supported by the Recovery and Resilience Plan must comply with the technical instructions (2021/C58/01) regarding the "do no significant harm" (DNSH) principle (Forsius et al. 2022). In the DNSH assessment, the process chain can be considered thoroughly and extensively (Forsius et al. 2022). For example, the risks of accidental emissions and the effects caused by digestate application should in principle be taken into account. The self-assessment is carried out by the biogas plant operator applying for funding. The funding body also makes its own assessment of the effects and takes a position on the applicant's self-assessment. However, regarding the DNSH evaluation, it is unclear how detailed evaluation is required of biogas plant projects and how the evaluations affect decisions regarding the production process. It should be noted that there is no mention of the DNSH evaluation in the subsidy guidelines of the Ministry of Agriculture and Forestry or the Finnish Food Authority.

6.2 Environmental permit and environmental impact assessment

6.2.1 Application of regulation and their impacts

Based on the Environmental Protection Act, biogas investments require an environmental permit. If more than 20,000 t/y of biomass are processed, a permit is sought from the regional administrative authority (AVI). The municipality grants permission for the operation of smaller biogas plants. Permits of on-farm biogas plants can be integrated to the permit of the animal shelter. If the permit for the animal shelter has been granted by AVI, the permit for the biogas plant is also applied for from AVI. When the animal shelter and the biogas plants are both new, a joint permit should be applied (Ministry of the Environment 2021). However, there are variations in permit practices across different parts of the country.

An environmental permit can be granted if the biogas plant fulfills the permit conditions. Specific demands about the construction and operation of the installation are also given. A permit can be granted if the plant is not considered to pose a threat to the environment. The granting of a permit is based on legal sources, such as laws, regulations, and court rulings. In its consideration, the permitting authority must consider how the permit criteria are met in the given case and in relation to the special features of the environment. In 2023–2026, permit applications for investment projects that are important for green transition may receive priority in permitting based on the Environmental Protection Act and the Water Act.

The environmental permitting practices of biogas plants have not been systematically studied, but based on the newest permit solutions, the role of the environmental permit in the regulation of biogas production chains can be estimated. For example, the biogas plant investment that Valio Ltd planned in Nivala was planned to be located relatively close to housing. This raised questions about the potential odor nuisance (Maaseudun Tulevaisuus 27.04.2018). In the interviews, the environmental permit was considered to serve specifically the minimization of the harm caused to the immediate neighborhood. From the point of view of the person assisting permit applicants, the meaningfulness of the permitting processes has nonetheless improved in recent years:

> *"The environmental permit has perhaps been the most challenging phase, or the slowest – it [the permit decision] always arrives at some point, but it has been such a restrainer. Without it there might be more plants. But it has changed for the better all the time. It still seems that it is constantly moving in a better direction, and it is, shall we say, that what is expected and required is more reasonable. Nonetheless, there is perhaps good grounds to change the thinking in the direction that it, biogas, is a good thing, and not an environmental crime…" (Biogas plant supplier)*

Environmental permits set stipulations, among other things, about the permitted raw materials and their amounts; about the utilization of energy and digestate, preparing for disruption situations and wastewater treatment (Pajala 2022).

In the case of so-called directive facilities, processing over 100,000 tons per year, regulations on the application of the best available technology (BAT) are given in the permit.

It is worth noting that GHG emissions are not a legal basis for abandoning an environmental permit, and, in the permit, stipulations cannot be set about the minimization of GHG emissions (Silvo et al. 2021). Consequently, stipulations cannot be issued regarding the factors affecting the probability of methane emissions. However, the HRT of a biogas plant must be stated in the permit application (Pajala 2022). The insignificance of GHG emissions caused surprise among the interviewees: the general assumption was that the calculations concerning GHGs and the capacity of the digestion process would have had an impact on permit decision-making.

The environmental impact assessment procedure produces information for permitting decision-making. The procedure must be carried out if the planned biogas plant processes feed materials over 35,000 t/year or if the project is likely to have significant environmental impacts. In the procedure, the definition of environmental impact is broad, covering the direct and indirect effects of the project on the environment and human health. In addition, the operator must indicate and evaluate various project alternatives and organize citizen participation. The latter task was seen as difficult:

> *"Here, in principle, the same things are considered three times, if we think about the permitting, environmental impact assessment and spatial planning processes. So maybe in the assessment process, I haven't experienced it so heavy because in practice it produces to a large extent the materials required for the environmental permit. You can, almost after you have the assessment process done, submit the environmental permit and you have those materials ready for it as a background. So almost the same work would probably have to be done in the case of large projects without the assessment procedure. But, of course, it takes its own time. But what is perhaps the saddest thing about the assessment procedures, is that no-one wants to take part in the hearings. They are pointless. It feels a bit like that, that they are quite pointless. People wake up to complain only at the permit stage when the environmental permit is being applied for. Although the purpose of that assessment procedure was perhaps to tackle this problem as well. That there are development needs in that." (Biogas plant operator)*

6.3 Nitrate decree and regulation on fertilizer products

Nitrate decree (1250/2014) regulates biogas production by setting requirements for the storage of manure (also that processed on the farm) and urine, and the application of organic fertilizer products such as digestate. The regulation determines the maximum amounts of total nitrogen (170 kg/ha) that can be applied in the annual use of organic fertilizer products, as well as the maximum amounts of soluble nitrogen that can be applied depending on crops produced and soil types (30–250 kg/ha).

The Government Decree on the use of phosphorus-containing fertilizer products and manure (64/2023), issued based on the Fertilizer Product Act (711/2022), defines the limits for the maximum amounts of phosphorus fertilization that apply to all farms. With the phosphorus regulation, the fertilization limits set in the voluntary Agri-environmental Scheme were removed.

The limits set for maximum nitrogen and phosphorus use in fertilization are very important for ensuring the sustainability of biogas production. The restrictions aim to ensure that digestate or fertilizer products processed from it are not spread on the fields in excess of the nutrient requirement of the crops. This is necessary to prevent development of water eutrophying nutrient loading.

The restrictions on the use of nutrients are also important because they encourage manure processing when more manure is produced than is needed as fertilizer in the farm's own crop production or in the nearby area. Unprocessed manure is generally not worth transporting far. When manure is used as feed for the biogas process and the resulting digestate is processed into more easily transportable nutrient products, their use can be tailored to the needs of the crops. Adjusting the fertilization amounts to the needs of the crops reduces the nutrient loading ending up in waters over time. Digestate and the end products of its processing can, in turn, replace the use of industrial mineral fertilizers in nutrient-poor fields.

Fertilizer legislation guides phosphorus fertilization, but also sets requirements for the quality of organic fertilizer products. In the quality decree being prepared at the time of writing, requirements can be set for the biogas process by requiring that the resulting digestate is stable. This is the case when methane has been captured during biogas production and there is little methane production potential left in the digestate. Through the requirements placed on the digestate, the length of the HRT of the biogas process could therefore be indirectly regulated. However, at the time of writing, it is unclear how widely the requirement would apply to different biogas plants and business models.

6.4 Voluntary measures and quality protocols

Sweden has a voluntary system for measuring methane emissions from biogas plants (Egenkontroll metanemissioner), which is coordinated by Avfall Sverige and Svenskt Vatten. Within the framework of the system, feed storage, pre-treatment, mixing, digestion, and post-digestion, as well as digestate storage at the plant are monitored. Measurement and observation sites are selected based on plant-specific inventories. The plants monitor possible leaks based on a procedure checked by an external consultant. If leaks are found, they should be repaired immediately. In addition, an external consultant measures the emissions at the plants every three years.

In the interviews with the representatives of the biogas industry, the operating model based on voluntariness received very little support. The system would probably be burdensome and thus would not be particularly suitable for self-regulation of small units without an additional incentive. On the other hand, large companies or, for example, municipalities, could make use of a voluntary system in implementing their corporate and social responsibility. Voluntary measures, however, mean that precisely those plants whose operations would require a critical review would be excluded from the system.

> *"Well, basically a good [idea]. In the case of voluntary systems, it always comes up that the plant operators, they will think that most likely the big municipal operators will join,*

> *but surely many plant operators immediately think that there must be some benefit to me, or at least that some harm must be avoided [laughs], if it is not useful. That probably comes first. But really, as I said, it's not-, for a plant that is managed well, it's not necessarily a big workload and cost if there is a-, once or twice a year this kind of analysis is done. But the challenge will certainly be precisely at these gate-fee-based plants, who know that the digestate produces a lot of gas, so that's where the challenge will certainly come, and then if it's voluntary, the plants for whom it's a challenge are hardly going to do it voluntarily, and so there's really no point in it anymore, if only those who are already doing things well do it." (Biogas plant supplier)*

Biogas plant suppliers have also their own quality systems. Some foreign plant manufacturers offer quality control services to their customers. A sample can be sent to them for analysis. Based on the result, the plant manufacturer provides instructions for actions.

> *"We have a centralized control room, that is, if we think that we are going to build bigger plants or some plant is running where production activities are carried out, then there is usually a control room where a person sits in three shifts or at least two shifts, so we have that control remotely for those small plants and, that single supervisor monitors all the plants." (Biogas plant provider)*

6.5 The views of the interviewees on regulatory gaps endangering sustainability

In the conducted interviews with representatives of the industry, the interviewees were asked for their views on what kind of issues can endanger the sustainability of biogas production and thus cause reputational harm to the entire industry. In this context, the interviewees reminded us of the importance of considering the transportation distances of feed materials and the conditions for the sustainable use of digestate. In addition, there was a discussion about the operation of biogas processes and particularly about the capacity of the biogas plants and the HRT of the process.

Minimizing methane emissions requires careful planning and operation of the entire biogas production chain, but above all that the feed materials are digested in the biogas reactor for long enough (sufficient retention time). In this way, the largest possible proportion of methane from the feed is recovered and utilized and the risk of methane emissions during digestate storage is reduced. From the entrepreneur's point of view, this is profitable, except for those situations where the investment in a smaller reactor is clearly more affordable or the company gets a significant part of its income from receiving waste materials. In these cases, it may be tempting to keep the retention time short instead of investing in a large enough reactor or reducing the biomasses received. Also, in batch-operated dry digestion processes, the goal of maintaining a stable biogas production can lead to shortening the retention time of the batches.

> **Q:** *If we turn to the topic of sustainably produced biogas and start with a broad question, what would you raise as critical, and what are the key questions regarding the sustainability of biogas production?*
>
> **A:** *"Well, I was thinking about that a little bit in advance, which questions might be the most critical, so actually your previous question about the gate fee-based feeds, so it already leads to digestate use and maximizing gas production in a way... because it's quite clear that in the gate-fee-based plants, the aim is to maximize the amount of feed that passes through and the digestate then still contains [methane]. First of all, they don't necessarily want to further process it, they just want to get rid of it as quickly as possible." "...And if you now compare, for example, to the few trips that have been made to biogas plants in Central Europe, there is a pretty clear difference that no one there runs biogas plants with such short HRTs as what they largely do in Finland at the moment. So, it's probably one clear factor, the digestate then, its monitoring, is probably very important for sustainability." (Biogas plant supplier)*

Although feed materials with gate fee are received especially in centralized biogas plants, the question of the size of the plant investment is a matter that, according to the consultant, is discussed with many of the customers, regardless of the size of the plant investment being planned:

> *"Too small reactors are made, the retention time is too short. Then, the point of view of sustainability is lost. And why this has been done, because there has been some saving in that investment phase…" (Consultant)*

Based on the interviews and the review of the regulation, it seems clear that the HRT in biogas production is insufficiently regulated. The current policy instruments do not take HRT into account. From the companies' point of view, the small size of plant investments in relation to the amount of biomass directed to biogas production – or the too much feed materials in relation to the size of the plant – can be profitable, especially in the short term. An imbalance can lead to a shorter retention time and the generation of methane emissions.

More specific conclusions from the assessment of policy instruments and recommendations for further actions are summarized in the conclusion chapter of the report.

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7 Example biogas plants

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7.1 Description of the biogas plants

To calculate the emissions of the biogas production chain and the environmental and economic effects of emission minimization, four theoretical biogas plant examples were created (Table 18). The scale, feed mixture, operation and digestate treatment of each example plant were set to describe typical Finnish biogas plants. The goal was to produce examples for various plant and input options. Finnish Biocycle and Biogas Association participated in the definition of the example plants.

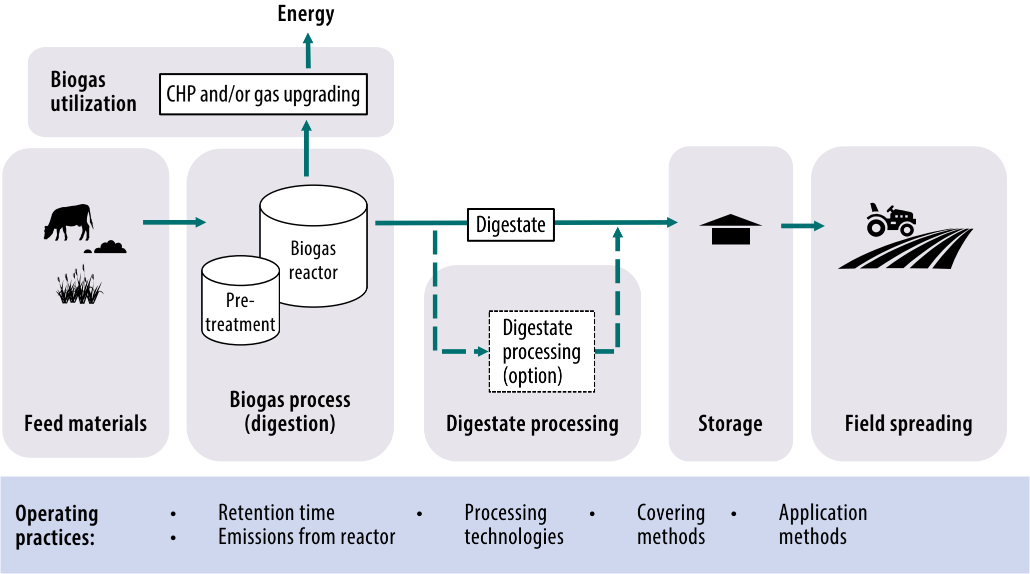
Table 18. The example biogas plants and their capacity and feed materials.

Scale	Technology	Capacity (t/a)	Feed materials
Farm-scale plant	Wet digestion	10 000	Cattle slurry (90 %) Grass silage (10 %)
Farm cooperative plant		30 000	Pig slurry (100 %)
Centralized plant		200 000	Pig slurry (40 %) Poultry manure (15 %) Solid fraction of pig and cattle slurry (15 %) Grass from fallows (10 %) Side stream from food processing (20 %)

Scale	Technology	Capacity (t/a)	Feed materials
Farm-scale or farm cooperative plant	Dry digestion	2 000	Grass silage (25 %) Grass from fallows (50 %) Horse manure (15 %) Poultry manure (10 %)

The example plants were used to examine the effect of different management practices on the gaseous emissions from biogas plants (Figure 16). The practices were divided into two categories, which are called here a) conventional practices and b) advanced practices (Table 19). The effort was to highlight the most significant differences in the emissions of the biogas production chain, focusing on solutions for operating biogas reactors and processing, storing, and spreading digestate. The impact of practices on the operation of example plants was examined through their mass and energy balances as well as environmental and economic impacts.

Figure 16. Measures and practices affecting gaseous emissions from different phases of biogas production process.



Biogas plants have varying practices that have an impact on the emissions resulting from the operation of the plant (see Chapter 2). In the example plants, the effect of retention time, reactor operation (incl. emissions from feed processing, leaks, maintenance) and digestate storage on gaseous emissions was examined. Since the processing of digestate can also affect the emissions of the production chain (and the utilization of digestate nutrients), depending on the scale of the plant, separation with a screw press or decanter centrifuge was included in the advanced practices. In addition, the further processing of the separated fractions by means of thermal drying and evaporation was also considered as an advanced practice at the large, centralized plant. In this case, the nutrients in the fractions are in a more concentrated form and thus better transportable for utilization. In the centralized plant, the liquid fractions formed during the processing of the digestate were also utilized for the dilution of the plant's feed mixture to make it suitable for wet digestion technology.

In the example biogas plants located on farms or in connection with farms, electricity and heat were produced from biogas in a CHP unit either for the farm's own use or also for sale (farm-scale and farm cooperative wet digestion plants, dry digestion plant). At the centralized plant, the option where the biogas was purified and pressurized in its entirety into biomethane for use in traffic was the main energy option considered. In this case, the plant bought the electricity and heat it needed in the process from elsewhere. In the environmental impact assessment (Chapter 7.3.2.3) for the centralized plant, an alternative was also considered, in which the centralized plant produced electricity and heat in a CHP unit.

Table 19. Conventional and advanced practices defined for each example biogas plant. Methane emissions in the production chain are described in Appendix 1, Table 35.

Example plant	Practice	HRT	Digestate processing	Digestate storage
Farm-scale (wet)	Conventional	20 d	-	Open
-	Advanced	50 d	Separation with screw press	Liquid fraction: tightly covered Solid fraction: covered
Farm co-operative (wet)	Conventional	20 d	-	Open
-	Advanced	50 d	Separation with screw press	Liquid fraction: floating cover Solid fraction: covered

Example plant	Practice	HRT	Digestate processing	Digestate storage
Centralized (wet)	Conventional	20 d	Separation with decanter centrifuge	Liquid fraction: open Solid fraction: open
-	Advanced	50 d	Separation with decanter centrifuge, evaporation of liquid fraction, thermal drying of solid fraction	Concentrated liquid fraction: tightly covered Thermally dried solid fraction: covered
Dry digestion	Conventional	2 months	-	Open
-	Advanced	4 months	-	2/3 direct spreading, 1/3 storage in covered pile

7.2 Methods

7.2.1 Mass, nutrient and energy balances

The mass, nutrient and energy balances of the example biogas plants were calculated as the basis for the environmental and economic impact assessments for both conventional and advanced practices. A total of eight different cases were thus examined. The balances were used to describe the transformation of the feed materials and their organic matter and nutrients fed to each plant during the biogas process and further processing of the digestate. At the same time, the effect of conventional and advanced operating methods on the production of biogas and digestate was considered. The methods for balance calculation are described in Appendix 1.

The methane losses of the production chain were also considered in the calculation of the energy balances. Estimates for methane emissions were set based on the literature review (see Chapter 2) and expert assessments. Since the literature review showed that the variation in emissions was large and their evaluation is subject to significant uncertainty, ranges were determined for methane emissions. Methane emissions for the different phases of the process are described in Table 35 of Appendix 1. Methane leaks were considered in the balance calculation in such a way that assumed leaks during the process, leaks through compressed air control valves and emissions from maintenance were subtracted from the amount of biogas produced. In addition, the methane loss of the process was considered in the production of transportation fuel. The methane loss of CHP units was not included as such in the balance calculation, as it was assumed to be included in the efficiency of CHP production.

7.2.2 Environmental impacts

Life cycle climate impacts of the biogas production chain were examined using a standardized method (ISO 14040) based on Life Cycle Assessment (LCA). It can be used to study the climate impacts of the different phases of the biogas production chain and to identify factors which climate impacts are the most significant during the life cycle of the operation. The goal of the work was to evaluate the climate impacts of operating practices using systems based on the example biogas plants. The life-cycle climate impacts were assessed for all four example plants and their conventional and advanced practices.

Global warming is caused by an increase in the concentration of greenhouse gases in the atmosphere, due to which the removal of thermal radiation from the atmosphere is reduced. The most typical greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The specific heating effect and lifetime of greenhouse gases in the atmosphere vary. In terms of biogas production, the most important greenhouse gas is methane, which is a shorter-lived but more powerful greenhouse gas than carbon dioxide. In Life Cycle Assessment, climate impacts are typically measured using the GWP method (Global Warming Potential). The method converts the heating effect of unit emissions of different greenhouse gases into carbon dioxide equivalent, considering the heating effect during the selected time. The uncertainty of the method increases, the longer the review period is. A period of 100 years (GWP100) is typically considered, as it is consistent with the UN Climate Agreement and the Kyoto Protocol under it. In this study, the GWP coefficients of the IPCC's fourth assessment report (IPCC 2007) for a period of 100 years were used in the characterization of emissions in accordance with the reporting and method guidelines for the greenhouse gas inventory (OSF 2020).

The climate impacts were calculated for each example biogas plant for one year of operation. The goal of the calculation was to evaluate the impacts of the plant's operating practices on the climate at different scales and with different feed materials. The initial data used in the calculation are presented in Appendix 4. Due to the uncertainties related to the initial data and to find out the emission reduction potential of different practices, the calculation was made using minimum and maximum values for both conventional and advanced practices. The results of the calculation are presented as a range of minimum values for advanced practices and maximum values for conventional practices in graphs. In addition, the emission reduction potential of advanced practices was examined by life cycle phase.

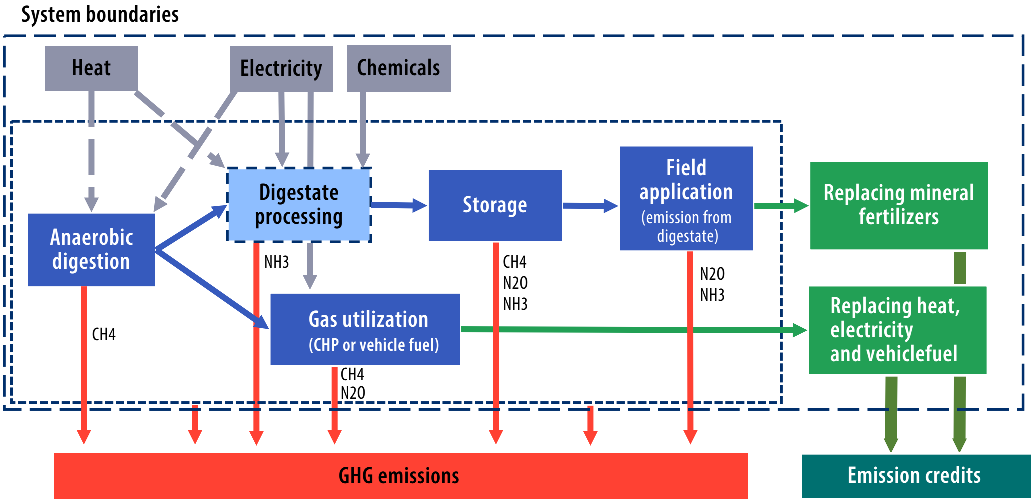
The calculation boundary used is shown in Figure 17. The direct (blue boxes) and indirect emissions (gray boxes) of the different life cycle phases were considered in the calculation. All feed materials for biogas plants were assumed to be side streams and waste from agriculture and food industry. Consequently, the emissions resulting from their production were not included in the calculation. Regarding the final use of digestate, only the greenhouse gas emissions released during field spreading were considered. The effects of operating practices on the emissions of operating practices concerning the spreading and transport of digestate or fractions processed from it were not evaluated. Emissions from the construction of biogas plants and the production of materials used in construction were also not included in the study.

To be able to evaluate the effects of different practices considering the possible consequences, possible emission credits, i.e. substitutions for the products formed in the process (green boxes) were also included in the assessment. These include the energy produced and the nutrients (phosphorus and nitrogen) contained in the digestate. The end products produced in all example plants were assumed to replace the existing production and use of electricity and heat or transport fuels and inorganic fertilizers in full. In addition, the results were examined without possible emission credits.

In addition to the different operating practices of the biogas plants, the traditional processing and utilization of biomass as feed materials for each example system was examined, i.e. the reference situation without biogas production. Life-cycle climate impacts were also calculated for the reference situation. The reference works as a bench mark for evaluating the impacts of different operating practices of a biogas plant. The reference included possible biomass storage, composting, greenhouse gas emissions resulting from utilization, and nutrient substitutions depending on the biomass.

The life-cycle environmental impacts of the example plants were evaluated for both greenhouse gases and ammonia emissions. Since the effects of different practices on ammonia emissions differ with the used boundaries mainly only regarding storage and spreading, the results of ammonia emissions were presented mainly non-numerically.

Figure 17. The system boundary of Life Cycle Assessment. Blue boxes: direct emissions from the process phases. Grey boxes: indirect emissions for the life-cycle phases. Green boxes: credits.



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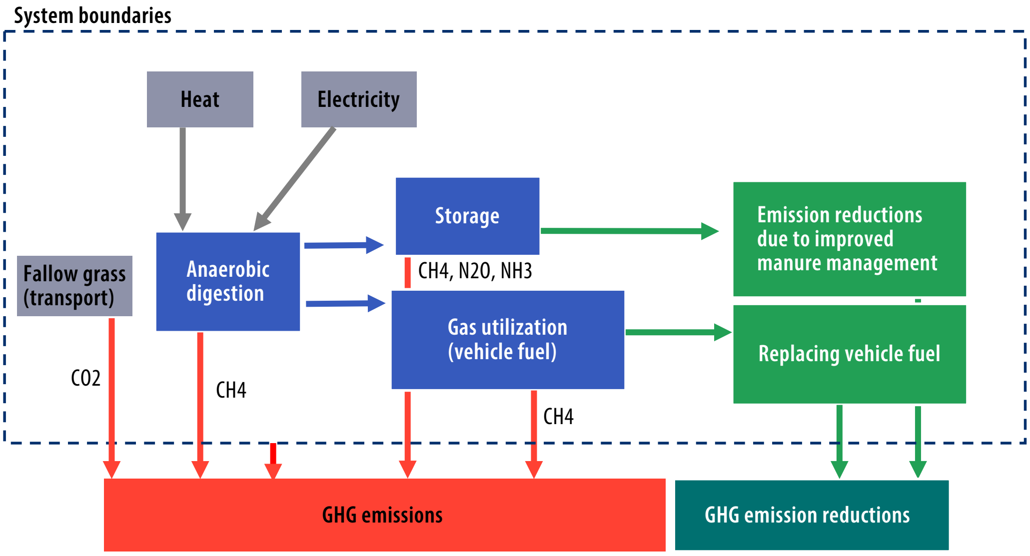
7.2.3 Emission calculation according to the Renewable Energy Directive

The emission reduction calculation according to the Renewable Energy Directive (EU 2018) was done for the centralized example plant (Energy Authority 2022) producing transport fuel. The calculation was made only for the largest example plant, because at the time of writing the report, the other example plants are not large enough in terms of scale to require verifying sustainability (min. 2 MW total heat output, when biogas is used for electricity and heat production). There may be changes to the plant size limit, because according to the Excise Tax Act on Fuels (Act amending the Act on Excise Tax on Electricity and Certain Fuels, 958/2022) the biogas producer is liable for excise duty if biogas production is over 1 GWh/year (incl. heating which was included in taxation at the beginning of 2023).

The calculation boundaries differ slightly from those of the LCA calculation made (Chapter 7.2.2), because the emission calculation according to the Directive does not consider the processing or use of digestate. However, the assumed GHG emission reduction from improved manure management (reduced storage time) is included (Figure 18). In addition, the harvesting and transport of uncultivated, fallow grass is included in the calculation, unlike in the LCA calculation.

Figure 18. System boundary in the emission calculation of the centralized example biogas plant according to the Renewable Energy Directive. Manure and side stream from food processing are considered zero emission and thus do not show up in the figure.



The starting point for the calculation was the emissions from the different phases of the biogas production chain obtained from the LCA calculation (Chapter 7.3.2) (calculation 1). In addition, the calculation used the default values of GHG emissions given in the Renewable Energy Directive for the different phases of the production chain (calculation 2 and 3) to compare the emission data. The Directive gives default emission values for only a few feed materials (slurry, maize, biowaste) in the different phases, and for four different technology options, which include digestate storage and the treatment of methane from the exhaust gas of biogas upgrading (e.g. by burning). Of these, the advanced practice in this project was to cover the digestate storage and treat the exhaust gas from upgrading unit, and the conventional practice was to use an open storage tank and not treat the exhaust gas. In addition to emissions, the Directive also gives default values for emission credits from raw manure management. The calculation is described in more detail in Appendix 2.

References

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Energy Authority 2022. Biopolttoaineita, bionesteitä ja biomassapolttoaineita koskeva toiminnanharjoittajan kestävyyskriteeriohje (Sustainability criteria guideline concerning biofuels, bioliquids and biomass-based fuels, in Finnish). https://energiavirasto.fi/documents/11120570/12778928/OHJE-Toiminnanharjoittajan-kest%C3%A4vyyskriteeriohje.pdf/6eafa3a2-4c7e-adea-c955-4959a54a8b6d

7.3 Results

7.3.1 Balance calculations for the biogas plant examples

The mass, nutrient and energy balances were calculated for the four example biogas plants, for each of which advanced and conventional practices in terms of gaseous emissions were considered. The results should not be compared between the example plants, but a comparison is possible between the conventional and advanced operating practices of each plant.

7.3.1.1 Energy balances

The energy production of a biogas plant is based on the energy content of the plant's feed materials, which determines the biogas production potential. However, the continuous feeding of the plant and the retention time of the feed mass in the reactor affect the fact that the theoretical potential is not fully reached, but only a part of it is realized. The longer the retention time is, the more of the potential is achieved, as the feed material has more time to degrade due to the microbial activity in the reactor.

Figure 19 summarizes the effects of the considered factors on reaching the energy production potential with the farm-scale wet digestion plant. The result is similar regardless of the example plant.

The longer retention time of advanced practices enables higher recovery of the energy content of the feed material. The production of biogas, or more precisely methane, is also affected by methane leaks, i.e. the biogas that is released into the atmosphere, for example, during the plant operation (leaks, safety valves) or as a result of maintenance procedures and equipment breakdowns. For plants with conventional practices, higher methane leaks than in advanced practices were assumed. If the plant produces electricity and heat with the help of a CHP unit, the efficiency of CHP production and its effect on the realization of energy production must also be considered. The efficiency is often around 90 % depending on the CHP unit. Efficiency is also considered in the production of transport fuel, and it is higher than the efficiency of a CHP unit, about 98 %. Overall, in the example of a farm-sized wet digestion plant (Figure 19), with advanced practices (longer retention time and minimization of methane leaks), 73 % of the energy production potential was realized, while the corresponding figure for conventional practices was 56 %.

The plant's retention time was the most significant factor affecting the energy balance. However, the amount of methane leaks also matters. The energy production of example plants was calculated by considering the range of leakages (minimum and maximum), to be able to describe the importance of methane leaks in the plant. In the LCA calculation (Chapter 7.3.2), the range of methane loss was considered, but in the economic calculations (Chapter 7.3.4), an average of the minimum and maximum values was used when examining the energy yield of the example plants (Table 20).

Figure 19. The effect of emissions on the achieved energy yield in the example of farm-scale wet digestion plant. The yield includes the impact of retention time, methane leaks in the process and the efficiency of the CHP unit. The result is similar in all example biogas plants studied.

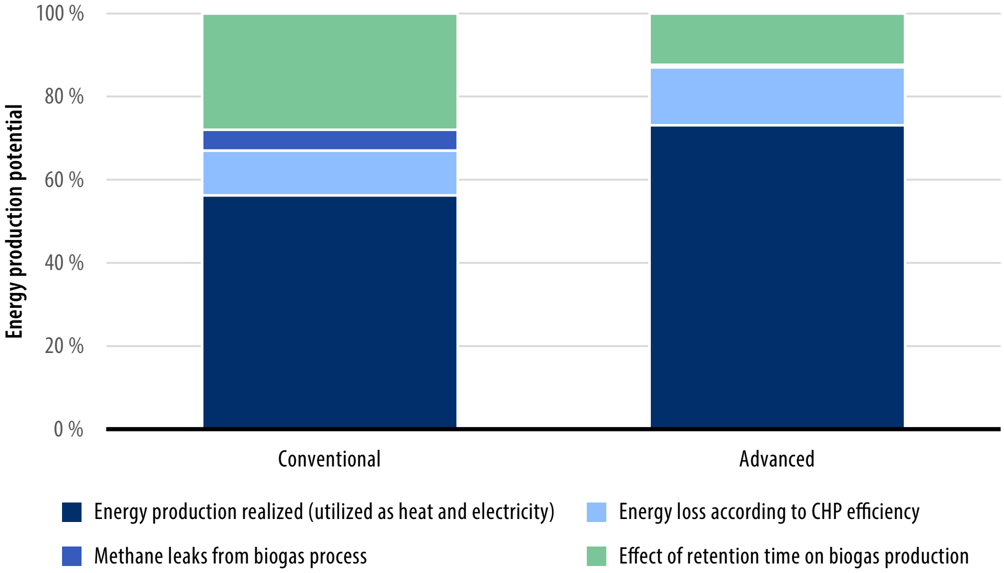


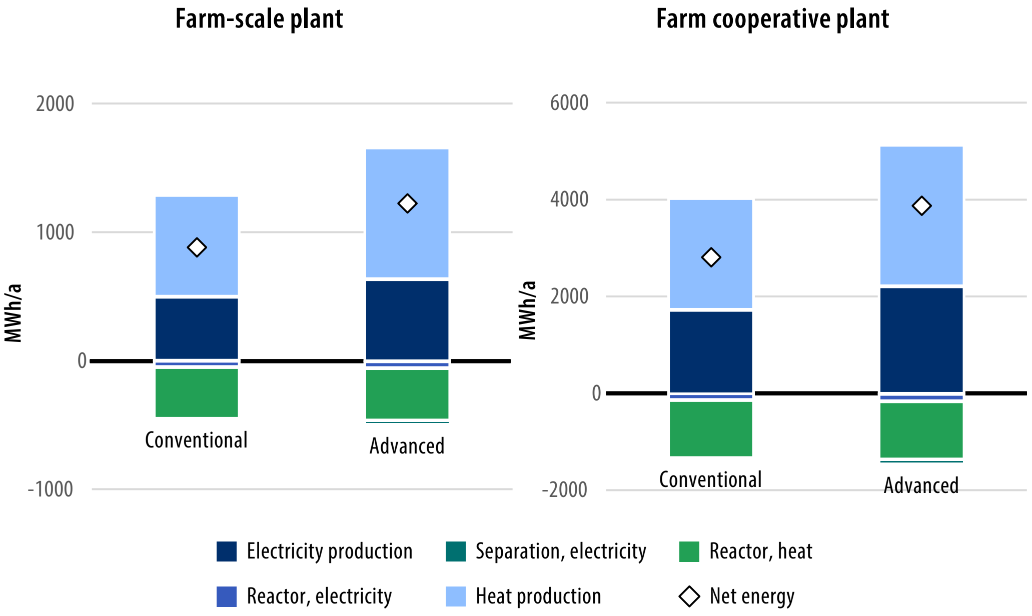
Table 20. The energy content of the biogas in the example biogas plants when using conventional and advanced practices. Minimum and maximum consider the range of methane leaks and their impact on the energy production of each plant. The range was included in the LCA calculation, while in the economic calculation an average of the leaks was used.

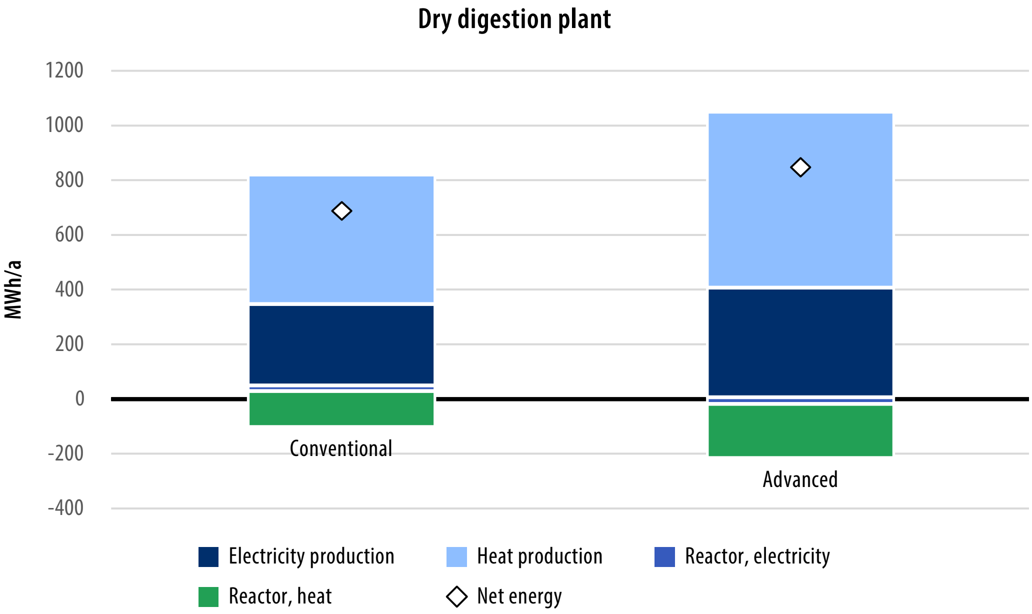
Example plant	Practice	Min-max of energy production (MWh/a)	Average of energy production (MWh/a)
Farm-scale	Conventional	1 466–1 521	1 494
	Advanced	1 883–1 904	1 893
Farm cooperative	Conventional	4 554–4 705	4 630
	Advanced	5 722–5 786	5 754
Centralized	Conventional	66 566–68 478	67 522
	Advanced	81 038–81 862	81 450
Dry digestion	Conventional	919–966	942
	Advanced	1 183–1 209	1 196

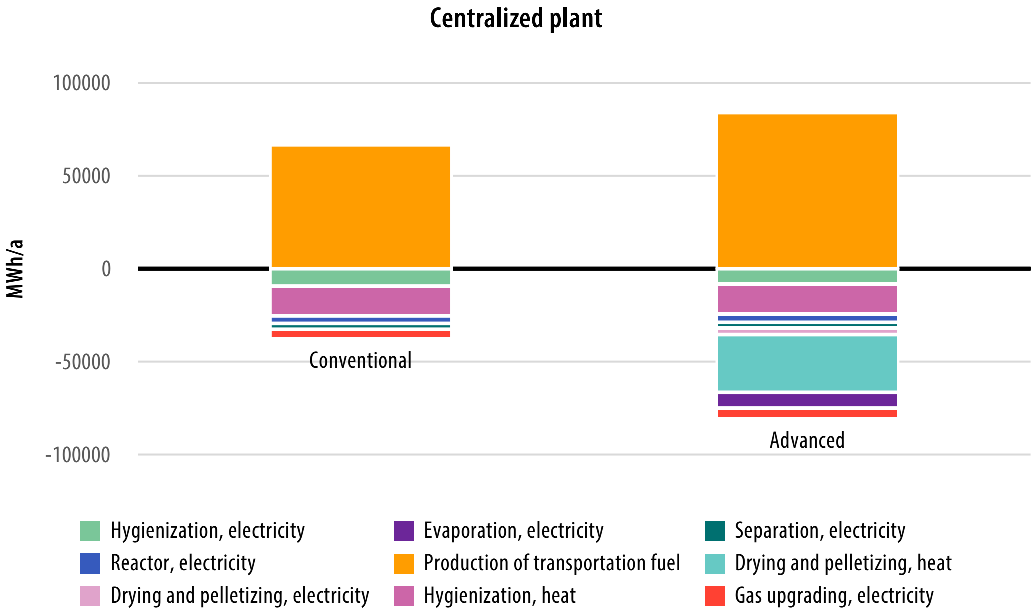
The biogas produced in the example plants was utilized in different ways. Smaller plants (farm-scale wet digestion, farm cooperative and dry digestion) produced electricity and heat from their biogas in a CHP unit. Electricity and heat were mainly used to cover the plant's own energy consumption. The energy remaining after the plant's consumption (so-called net energy) could be used, for example, for other uses on the farm or it could be sold outside. The centralized example plant purified the biogas into a transport fuel (biomethane). The assumption was that the entire biogas volume was used to produce transport fuel and the plant's own electricity and heat needs were covered with purchased energy. Figure 20 summarizes the energy production of different example plants as well as the plant's own consumption as electricity and heat. In addition, in plants where own energy consumption was covered by the energy produced by the plant, the amount of net energy is presented. Regarding the centralized plant, the situation where the plant fully utilizes the biogas it produces in a CHP unit for electricity and heat is presented in Appendix 3 (considered in the LCA calculation).

On the basis of Figure 20, it can be stated that in the example plants using advanced practices, energy consumption is increased by digestate processing methods compared to conventional practices. In farm-scale and farm cooperative wet digestion plants, digestate was separated into liquid and solid fractions, which slightly increased the total electricity consumption. In the centralized plant, separation was also part of the conventional practices, while the advanced practices included a more extensive digestate processing, consisting of thermally drying and pelletizing the separated solid fraction and concentrating the liquid fraction by evaporation. Thermal energy was assumed to be used for drying the solid fraction of the digestate, while evaporation and pelleting used electricity. Despite the increased energy consumption for the more extensive processing of digestate, the benefit is more concentrated fertilizer products with a low transport cost per ton of nutrients.

Figure 20. Energy production and consumption of the example biogas plants. Positive values present the produced electricity, heat or transport fuel and negative values present the energy consumption in the process phases.







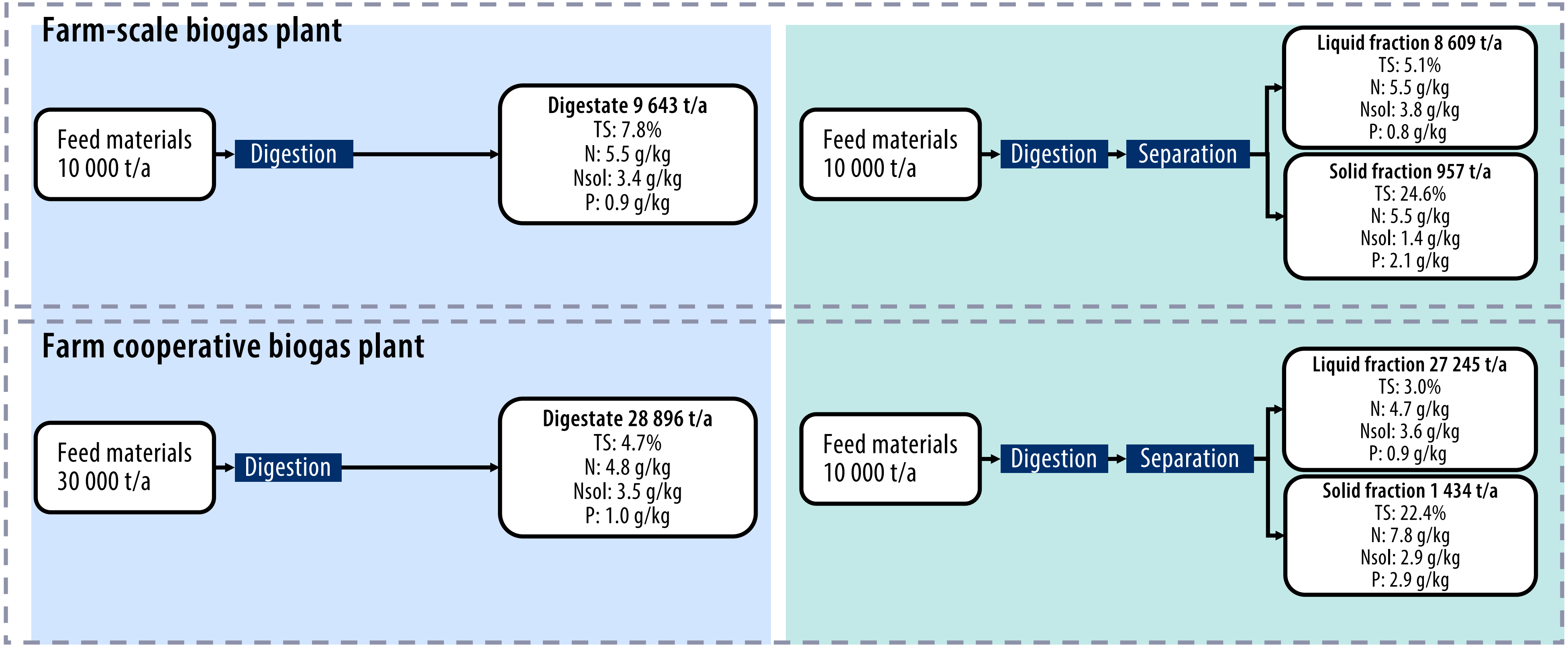
7.3.1.2 Mass and nutrient balances

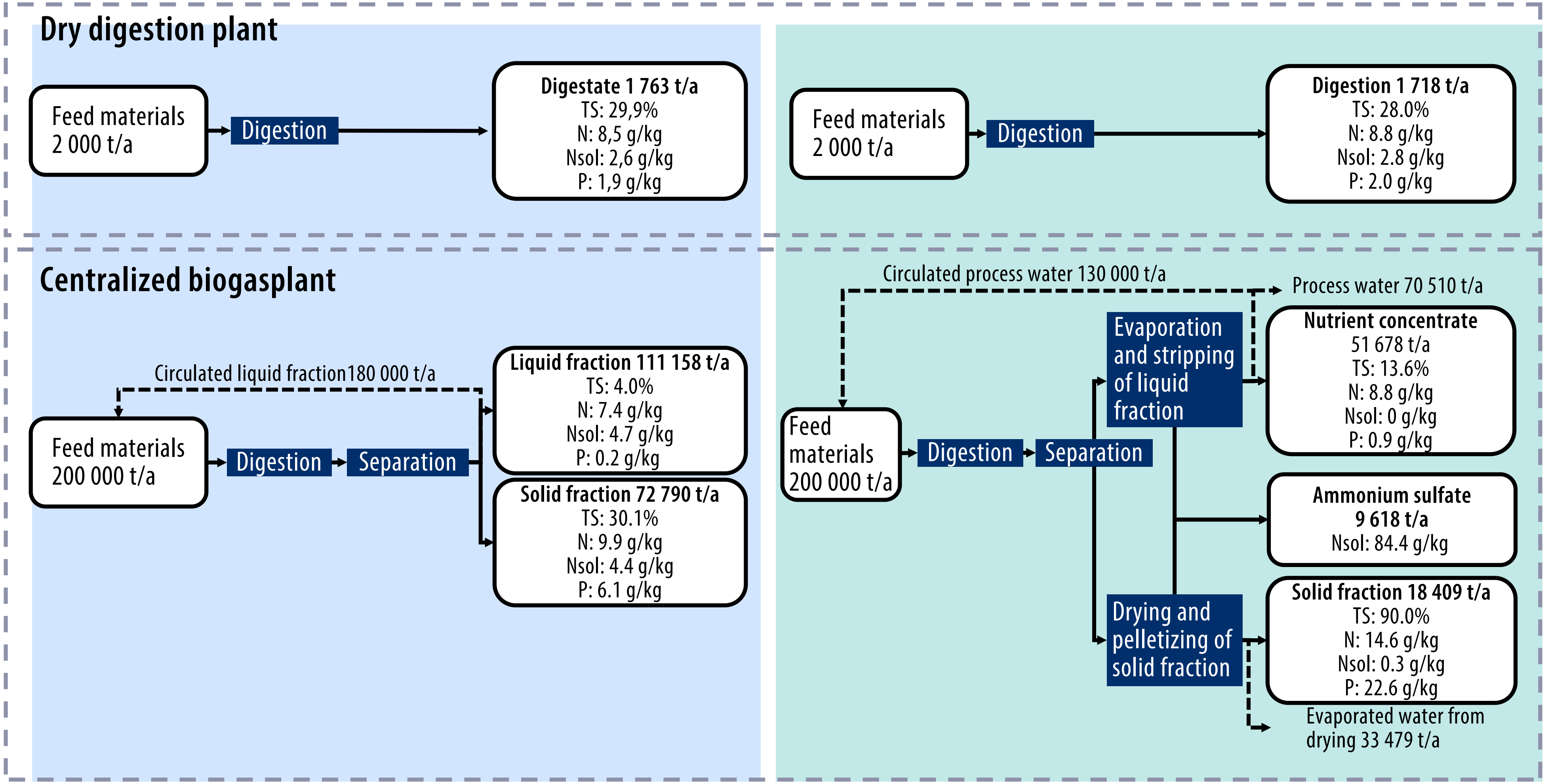
The retention time of the feed material in the biogas process affects the efficiency of its decomposition; the longer the retention time is, the better the organic matter decomposes into biogas. Decomposition also affects the mass and nutrients, which is why the amount of digestate is slightly lower than the total amount of feed materials. In the biogas process, the relative proportion of soluble nitrogen also increases, which is due to the decomposition of nitrogenous organic matter and the mineralization of nitrogen. The solubilization of nitrogen depends on the degree of decomposition of the organic matter, and therefore a longer retention time also affects the amount of soluble nitrogen in the digestate. Since a longer retention time was considered in the advanced practices of the example plants, the amount of soluble nitrogen in the digestate according to the advanced practice was higher than in the conventional practices (Figure 21). A higher proportion of soluble nitrogen is an advantage when using digestate as a fertilizer. Total nitrogen and total phosphorus remain unchanged in the digestate during the biogas process. Still, the concentration of these nutrients (g/kg) increases slightly, because the mass of the digestate is slightly lower than the original feed mass due to the decomposition of organic matter, i.e. the formation of biogas.

Advanced practices in farm-scale and farm cooperative wet digestion plants involved processing the digestate using a screw press separator. Separation divides the digestate into two fractions, a liquid and a solid fraction. Most of the water-soluble nitrogen ends up in the liquid fraction, and phosphorus binding into organic matter ends up in the solid fraction. Separation thus enables phosphorus to be partially separated into the solid fraction, which is easier and more profitable to transport. The partial separation of nitrogen and phosphorus into different fractions and the change of N/P ratios can also ease the fertilizer use of the fractions and the distribution of nutrients on the farm. The separation consumes electrical energy, but this did not influence the total energy balance of the plants compared to the situation of conventional practices, because the energy yield was higher in the example plants using advanced practices.

As an advanced practice, the centralized example plant included an advanced further processing chain of the digestate, where the digestate was separated with a decanter centrifuge and the formed fractions were further refined. The solid fraction was dried and pelletized, resulting in a dry pellet-shaped product with a high total nitrogen and phosphorus content (14 gN/kg, 23 gP/kg; Figure 21). The product is efficient for transporting long distances and its production contributes to balancing the regional phosphorus surplus. The liquid fraction was concentrated with an evaporator into a nutrient concentrate and further stripped to recover soluble nitrogen as ammonium sulfate. Concentration removes water from the products reducing their volume, which also enables enhanced transportation. The nutrient concentrate contained most of the nitrogen in the digestate, but also a small amount of phosphorus (9 gN/kg, 1 gP/kg). The concentration of soluble nitrogen in ammonium sulfate was high (84 gNH_4-N/kg). The further processing of the digestate consumed a significant amount of energy, but also due to the advanced practices in the centralized plant (long retention time, minimization of emissions from the process), energy production was significantly higher than when using conventional practices. Thus, the plant using advanced practices produced more traffic fuel for sale. Due to the energy consumption of digestate processing, the plant using advanced practices bought more electricity and heat for its own use, but the plant's total energy net balance was positive (Figure 21).

Figure 21. Mass balance of the example biogas plants and the end products and their composition.




Dry digestion plant
Feed materials 2 000 t/a
Digestion
Digestate 1 763 t/a
TS: 29,9%
N: 8,5 g/kg
Nsol: 2,6 g/kg
P: 1,9 g/kg
Feed materials 2 000 t/a
Digestion
Digestion 1 718 t/a
TS: 28.0%
N: 8.8 g/kg
Nsol: 2.8 g/kg
P: 2.0 g/kg
Centralized biogasplant
Circulated liquid fraction180 000 t/a
Feed materials 200 000 t/a
Digestion
Separation
Liquid fraction 111 158 t/a
TS: 4.0%
N: 7.4 g/kg
Nsol: 4.7 g/kg
P: 0.2 g/kg
Solid fraction 72 790 t/a
TS: 30.1%
N: 9.9 g/kg
Nsol: 4.4 g/kg
P: 6.1 g/kg
Circulated process water 130 000 t/a
Process water 70 510 t/a
Feed materials 200 000 t/a
Digestion
Separation
Evaporation and stripping of liquid fraction
Nutrient concentrate 51 678 t/a
TS: 13.6%
N: 8.8 g/kg
Nsol: 0 g/kg
P: 0.9 g/kg
Ammonium sulfate 9 618 t/a
Nsol: 84.4 g/kg
Drying and pelletizing of solid fraction
Solid fraction 18 409 t/a
TS: 90.0%
N: 14.6 g/kg
Nsol: 0.3 g/kg
P: 22.6 g/kg
Evaporated water from drying 33 479 t/a

7.3.2 Life cycle environmental impacts

7.3.2.1 Farm-scale wet digestion plant

The effects of operating practices on the net life cycle GHG emissions of a farm-scale example plant digesting cattle slurry and grass silage vary greatly (65–737 t CO_2-eq/y), when the emission reductions (substitutions) resulting from the replacement of energy and nutrients are considered. If substitution impacts are not considered, the biogas plant's life cycle total net GHG emissions are higher and vary between 404–1 001 t CO_2-eq/year. Most of the emissions are caused by the operation of the biogas process, the CHP unit, and the storage and spreading of the digestate (Figure 22). With advanced practices, emissions from the biogas production chain are lower than with conventional practices. According to the results, advanced practices can reduce emissions from all operations by approximately 76–91 %, when substitutions are considered (Table 22). Without considering substitutions, advanced practices can reduce operational emissions by approximately 44–60 %.

When comparing to the traditional manure management without a biogas plant, it was assumed that slurry is stored and spread on the field and grass silage is composted. In total, when the substitution impacts are considered, the inclusion of the biogas process reduces the climate impacts of slurry and silage management by 63–735 t CO_2-eq/year, depending on the operating practices. If the substitutions assumed in the calculation do not materialize as such, or the produced products (energy and nutrients) replace products with lower emissions, the benefit achieved will decrease. If the substitutions are not considered, the biogas process reduces the emissions of managing the feed materials by 527 t CO_2-eq/year with advanced practices but increases them by 70 t CO_2-eq/year with conventional practices. In this case, the climate impact of managing the feed materials is reduced by approximately 57 % with advanced practices in the biogas process, while following conventional practices leads to an increased climate impact by 7 % compared to traditional manure management. If substitutions are considered, the climate impact is reduced by 8–92 %.

Figure 22. The variation in life cycle GHG emissions (t CO_2-eq/year) in the farm-scale wet digestion plant per life cycle phase. The results are presented as the range of advanced and conventional practices (minimum, maximum). Additionally, the graph gives an estimate of the emissions in a reference situation, i.e. managing the feed materials without biogas process.

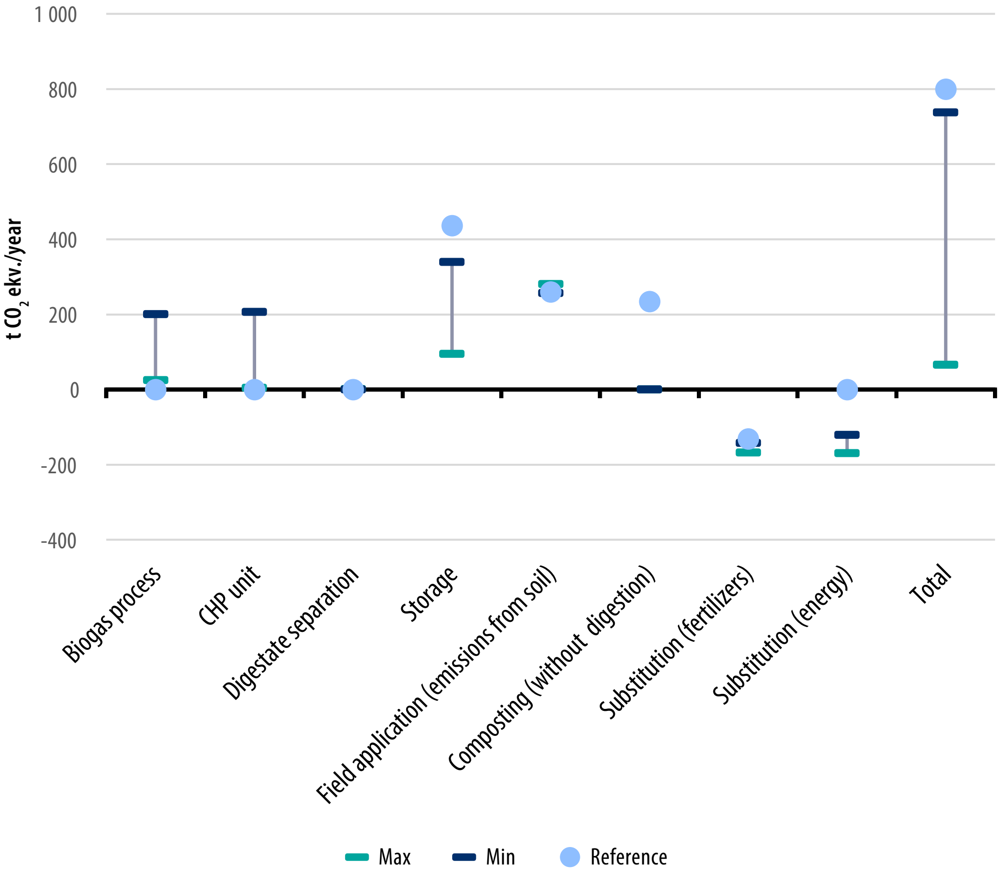


Table 21. The impact of advanced practices on GHG emissions in the farm-scale wet digestion plant in relation to conventional practices per life cycle phase. Negative values depict emission reduction and positive values increased emissions.

	The impact of advanced practices on emissions per life cycle phase
Biogas process	-37 % … -88 %
CHP-unit	-80 % … -98 %
Digestate separation	+100 %*
Digestate storage	-71 % … -72 %

	The impact of advanced practices on emissions per life cycle phase
Digestate spreading (emissions from soil)	+9 %
Fertilizer substitutions	-18 %
Energy substitutions	-30 % ... -40 %
Total (without substitutions)	-44 % . . . -60 %
Total (including substitutions)	-76 % . . . -91 %

*Digestate is not separated in conventional practices

7.3.2.2 Farm cooperative wet digestion plant

The impacts of the operating practices of the farm cooperative biogas plant on the net GHG emissions vary greatly (-52 ... +1 845 t CO_2-eq/year), when substitutions are considered. If substitution impacts are not considered, the plant's life cycle total net GHG emissions are higher and vary between 1 013–2 726 t CO_2-eq/year. The biggest impact on the generated emissions comes from the operation of the biogas process, the CHP unit, and the digestate storage and spreading (Figure 23). With advanced practices, the GHG emissions are lower than with conventional practices. Advanced practices can reduce net operational emissions compared to conventional practices by approximately 89–103 % when substitutions are considered (Table 23). Without considering substitutions, advanced practices can reduce operational emissions by around 48–63 %.

In the reference situation without a biogas plant, it was assumed that slurry is stored and spread on the field as it is. In the example plant, the biogas process reduces the climate impacts of slurry management by 974–2 871 t CO_2-eq/year, when substitutions are considered, with both advanced and conventional practices. If the substitutions assumed in the calculation do not materialize as such or the products replace products (energy, nutrients) with lower emissions, the benefit achieved will decrease. In other words, the benefit is greatest when replacing fossil energy. If, on the other hand, substitutions are not considered at all, the biogas process reduces the emissions of slurry management by 560–2 273 t CO_2-eq/year. In this case, the climate impact of slurry management is reduced by approximately 17–69 %, depending on the practices. If substitutions are considered, the climate impact is about 35–102 %.

Figure 23. The variation in life cycle GHG emissions (t CO_2-eq/year) in the farm cooperative wet digestion plant per life cycle phase. The results are presented as the range of advanced and conventional practices (minimum, maximum). Additionally, the graph gives an estimate on the emissions in a reference situation, i.e. managing the feed materials without biogas.

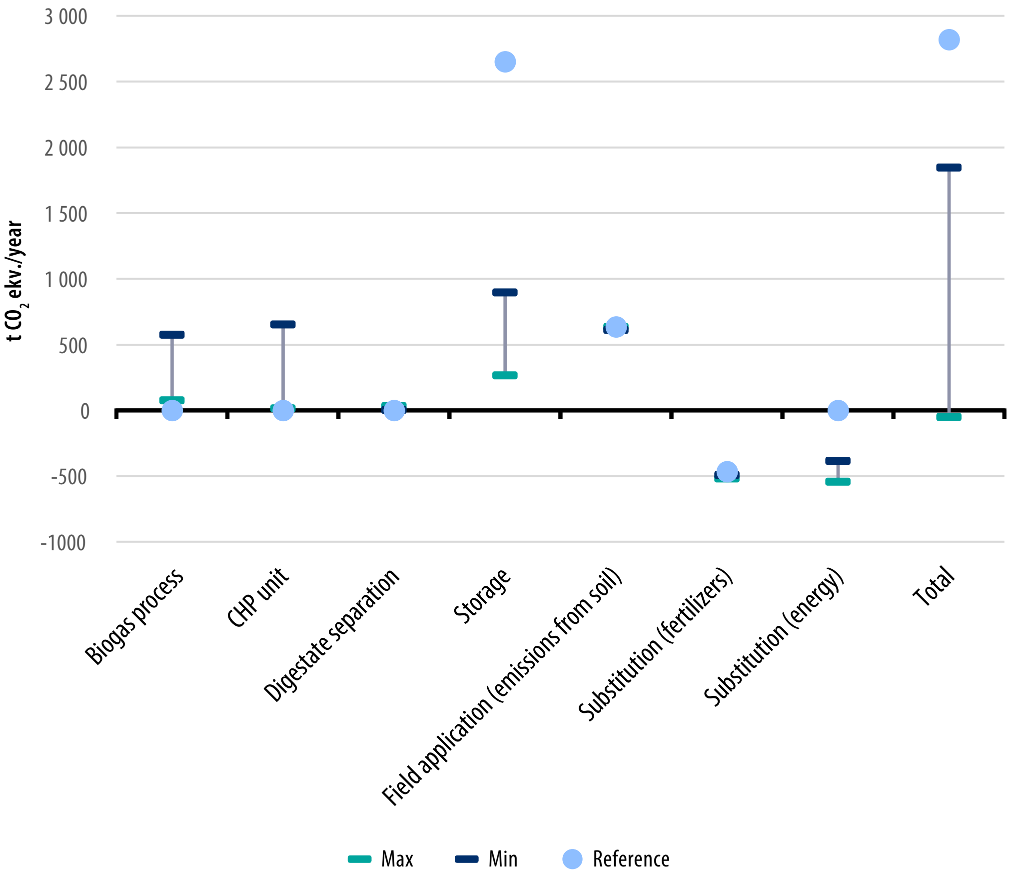


Table 22. The impact of advanced practices on GHG emissions in the farm cooperative wet digestion plant in relation to conventional practices per life cycle phase. Negative values depict emission reduction and positive values increased emissions.

	The impact of advanced practices on emissions per life cycle phase
Biogas process	-37 % … -87 %
CHP-unit	-80 % … 98 %
Digestate separation	+ 100 %
Digestate storage	-70 %

	The impact of advanced practices on emissions per life cycle phase
Digestate spreading (emissions from soil)	+4 %
Fertilizer substitutions	-6 %
Energy substitutions	-32 % … -41 %
Total (without substitutions)	-48 % … -63 %
Total (including substitutions)	-89 % … -103 %

* Digestate is not separated in conventional practices

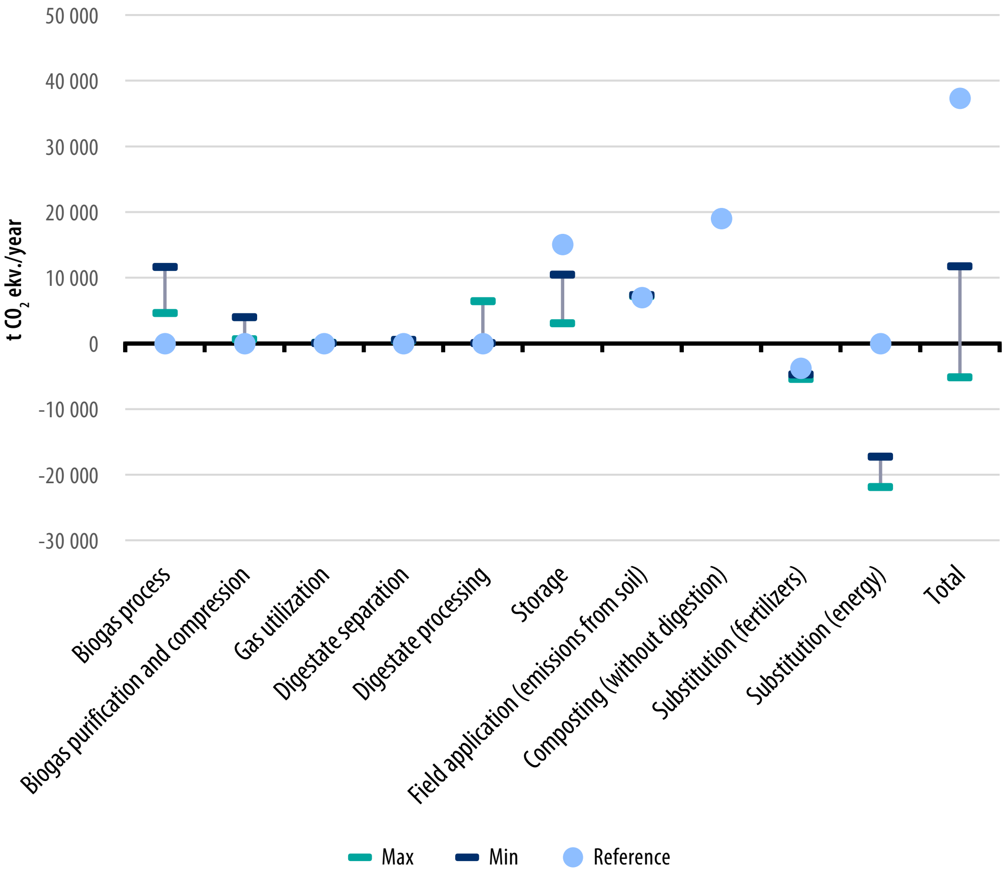
7.3.2.3 Centralized wet digestion plant

Slurry, solid fraction separated from slurry, poultry manure, grasses from fallows, and side stream from the food processing were used as feed materials for the centralized example biogas plant. The calculation of climate impacts was made for two cases, in one of which biogas is utilized as transport fuel (A) and in the other, electricity and heat are produced (B). As a result of the differences between advanced and conventional practices, correspondingly different end products were formed (more detailed plant descriptions, Chapter 7.1).

When the biogas is fully purified into transport fuel and the energy used for the further processing of the digestate is purchased from outside the plant (A), the impacts of the practices on the total net GHG emissions of the plant vary greatly (around -5 229 t ... +11 705 t CO_2-eq/year), when substitution impacts are considered. If substitution impacts are not considered, the corresponding GHG emissions are higher and vary between 22 136–33 762 t CO_2-eq/year. The highest impacts on emissions come from the operation of the biogas process, the upgrading and pressurization of the biogas, the digestate processing, and the storage and spreading of the resulting fertilizer products (Figure 24). With advanced practices, emissions from the biogas production chain are lower than with conventional practices. Advanced practices can reduce emissions by approximately 145–168 % when substitutions are considered (Table 23). Without considering substitutions, advanced practices can reduce emissions by approximately 16–34 %.

In the reference situation, the management chain of the different feed materials without the biogas plant was considered (additional information in Appendix 4). The inclusion of the centralized biogas plant in the management chain reduces the climate impacts by approximately 25 603–42 536 t CO_2-eq/year, i.e. 69–114 %, if substitutions are considered. If the substitutions assumed in the calculation do not materialize as such or the products replace products (energy, nutrients) with lower emissions, the benefit achieved by the biogas process will decrease. If the substitution impacts are not considered at all, the biogas process reduces the emissions from managing the feed materials by approximately 7 335–18 961 t CO_2-eq/year, i.e. approximately 18–46 %.

Figure 24. The variation in life cycle GHG emissions (t CO_2-eq/year) in the centralized wet digestion plant per life cycle phase when transport fuel is produced and the energy needed for plant operation and digestate processing is bought from outside the plant. The results are presented as the range of advanced and conventional practices (minimum, maximum). Additionally, the graph gives an estimate on the emissions in a reference situation, i.e. managing the feed materials without biogas.



When electricity and heat (B) are produced from biogas instead of transport fuel and part of the energy is utilized for the plant's own energy need, the impact of different practices on the plant's net total GHG emissions vary between 7 586–27 822 t CO_2-eq/year. If substitution impacts are not considered, the corresponding emissions vary between 14 492–35 355 t CO_2-eq/year. The biggest impact on emissions comes from the operation of the biogas process and the CHP unit, the digestate processing, and the storage and spreading of the resulting fertilizer products (Figure 25). With advanced practices, emissions from the biogas production chain are lower than with conventional practices. With advanced practices, emissions can be reduced by approximately 54–73 %, when substitutions are considered (Table 23). Without considering substitutions, advanced practices can reduce emissions by about 43–59 %.

With the assumptions used in the calculation, the inclusion of the biogas process in managing the feed materials reduces the climate impacts by at least 9 485–29 721 t CO_2-eq/year, i.e. 25–80 %, if substitution impacts are considered. If the substitutions assumed in the calculation do not materialize as such or the products replace products (energy, nutrients) with lower emissions, the benefit to be achieved will decrease. If substitution impacts are not considered at all, the biogas process reduces climate effects by approximately 5 742–26 605 t CO_2-eq/year, i.e. 14–65 % depending on operating practices.

Figure 25. The variation in life cycle GHG emissions (t CO2-eq/year) in the centralized wet digestion plant per life cycle phase when electricity and heat are produced. The results are presented as the range of advanced and conventional practices (minimum, maximum). Additionally, the graph gives an estimate of the emissions in a reference situation, i.e. managing the feed materials without biogas.

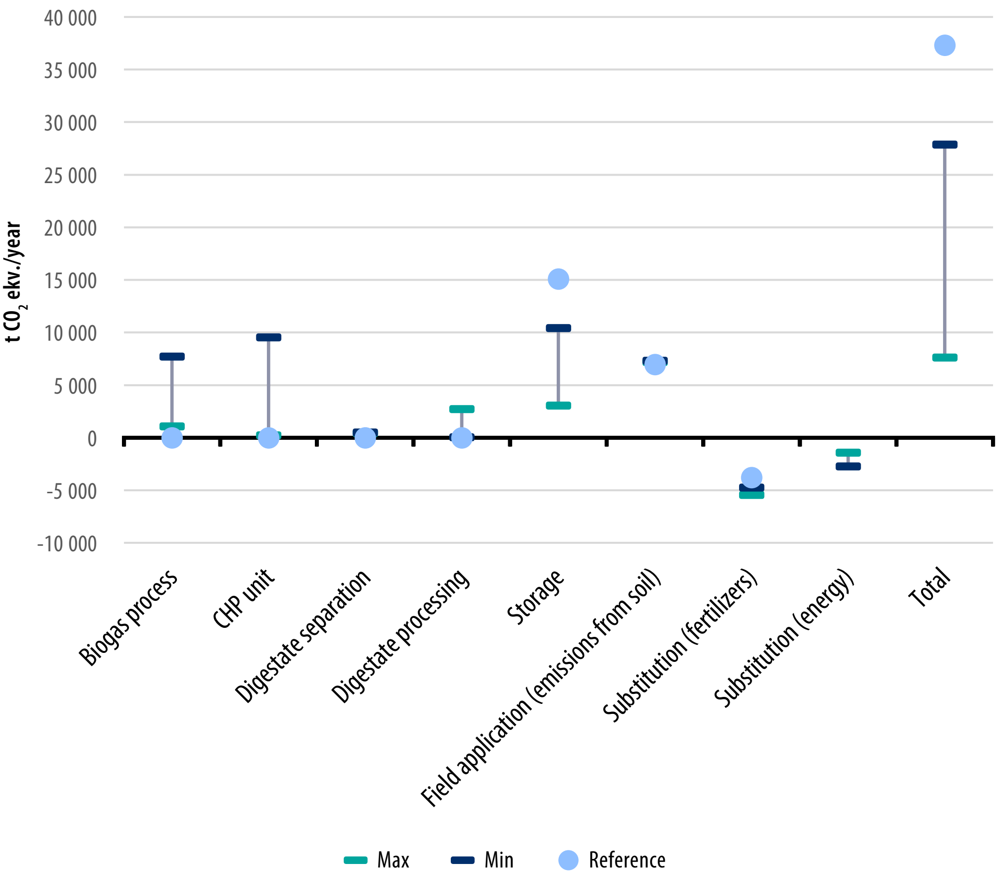


Table 23. The impact of advanced practices on GHG emissions in the centralized wet digestion plant in relation to conventional practices per life cycle phase in case A (transport fuel) and case B (CHP). Negative values depict emission reduction and positive values increased emissions.

	Case A: Impact of advanced practices on emissions per life cycle phase	Case B: Impact of advanced practices on emissions per life cycle phase
Biogas process	-26 % … -61 %	-40 % … -86 %
Biogas upgrading and pressurization/CHP	-64 % … 85 %	-81 % … -98 %

	Case A: Impact of advanced practices on emissions per life cycle phase	Case B: Impact of advanced practices on emissions per life cycle phase
Use of transport fuel	-19 % … – 27 %	-
Digestate separation	-15 %	-15 %
Digestate processing	+100 %	+100 %
Digestate storage	-71 %	-71 %
Digestate spreading (emissions from soil)	-2 %	-2 %
Fertilizer substitutions	-15 %	-15 %
Energy substitutions	-19 % … -27 %	-48 % … -50 %
Total (without substitutions)	-16 % … -34 %	-43 % … -59 %
Total (including substitutions)	-145 % …-168 %	-54 % … -73 %

7.3.2.4 Dry digestion plant

The impacts of different practices on the net total GHG emissions of the dry digestion biogas plant vary widely (47–496 t CO_2-eq/year), when substitutions are considered. If substitution impacts are not considered, the corresponding emissions are higher and vary between 232–642 t CO_2-eq/year. The biggest impact on the generated emissions comes from the operating methods of the reactor silo's emptying phase and the storage and spreading of digestate (Figure 26). With advanced practices, emissions from the biogas production chain are lower than with conventional practices. With advanced practices, operational emissions can be reduced by approximately 72–90 %, when substitutions are considered (Table 24). Without considering substitutions, advanced practices can reduce emissions by about 47–64 %.

Also, for the feed materials of the dry digestion plant, treatment without the biogas plant (composting and storage of the feed materials) was created for reference. The inclusion of a biogas plant with conventional practices can cause a 1 % (5.5 t CO_2-eq/year) greater climate impact than in a comparison situation without a biogas plant, when substitution impacts are considered. By following advanced practices, the climate impact can be reduced by 90 % (443 t CO_2-eq/year). If the substitutions assumed in the calculation do not materialize as such or the products replace products (energy, nutrients) with lower emissions, the benefit achieved compared to the reference situation will decrease. If the substitution impacts are not considered at all, the biogas process increases the climate impact of managing the feed materials by approximately 25 % (128 t CO_2-eq/year) with conventional practices. With advanced practices, the climate impact is reduced by about 45 % (281 t CO_2-eq/year).

Figure 26. The variation in life cycle GHG emissions (t CO_2-eq/year) in the dry digestion plant per life cycle phase. The results are presented as the range of advanced and conventional practices (minimum, maximum). Additionally, the graph gives an estimate of the emissions in a reference situation, i.e. managing the feed materials without biogas.

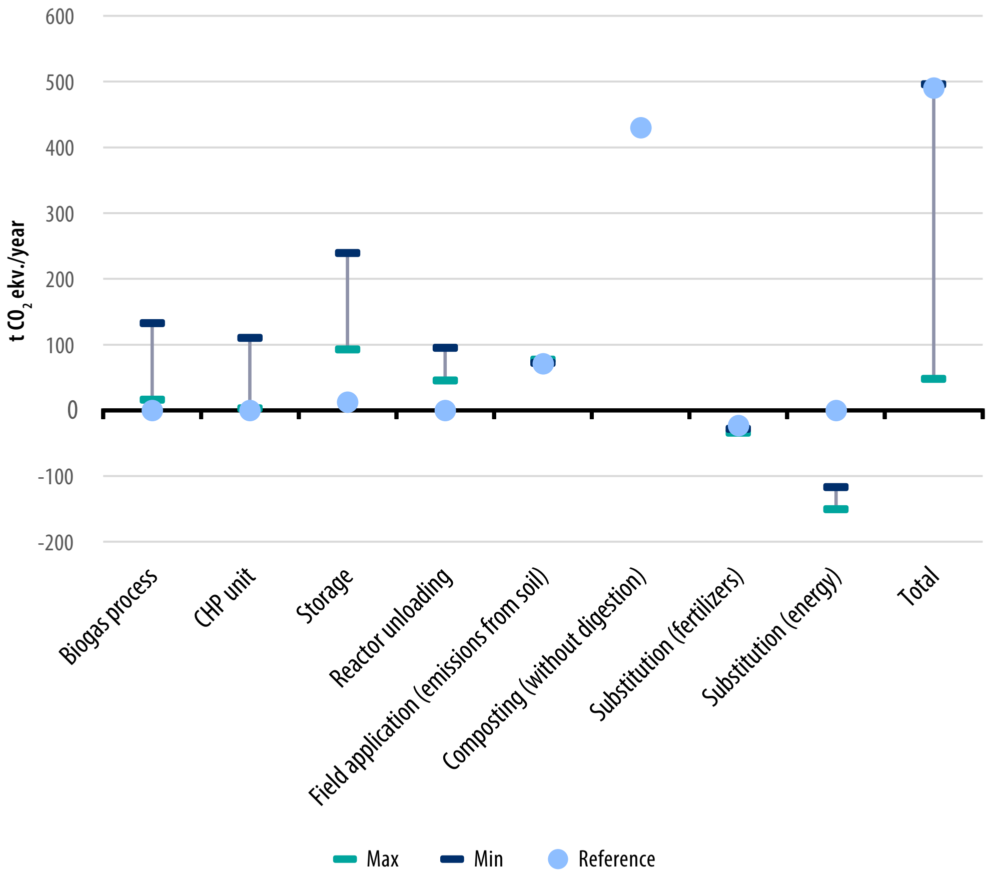


Table 24. The impact of advanced practices on GHG emissions in the dry digestion plant in relation to conventional practices per life cycle phase. Negative values depict emission reduction and positive values increased emissions.

	Impact of advanced practices on emissions per life cycle phase
Biogas process	-39 % … -88 %
CHP-unit	-80 % …-97 %
Emptying phase	-11 % … -52 %
Digestate storage	-61 %
Digestate spreading (emissions from soil)	-7 %
Fertilizer substitutions	-20 %
Energy substitutions	-23 % … -28 %
Total (without substitutions)	-47 % … -64 %
Total (including substitutions)	-72 % …-90 %

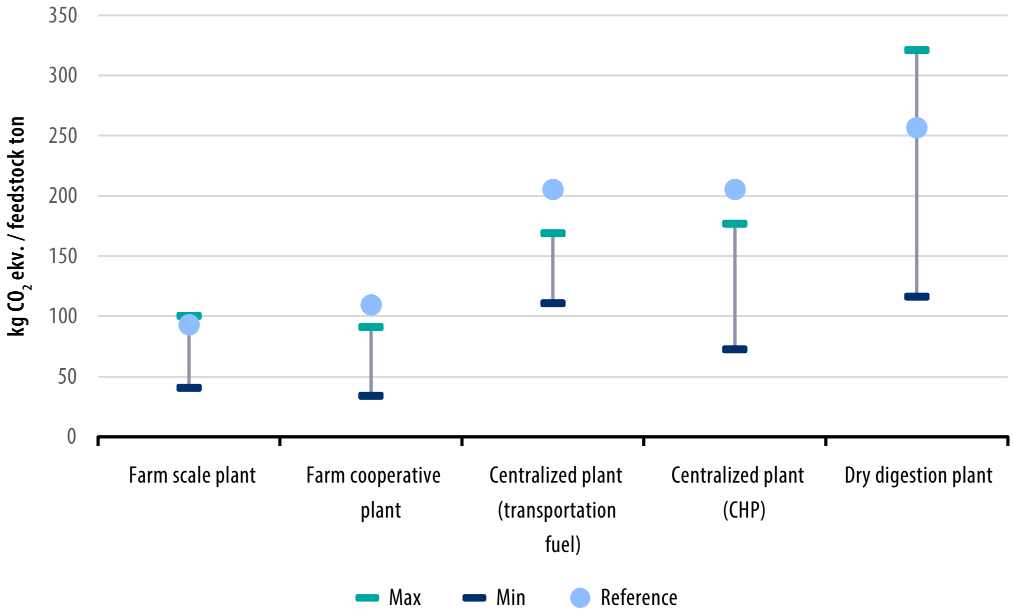
7.3.2.5 Discussion on the example biogas plants

In almost all examined examples of wet digestion plants, the biogas process reduces GHG emissions with both conventional and advanced practices compared to the reference situation defined for feed material management without biogas production (Figure 27). At a farm-scale wet digestion plant, GHG emissions may rise to the level of or even higher than in the reference situation with conventional practices and without considering substitutions.

The dry digestion plant can also increase the emissions if the plant is operated with conventional practices. The difference in emissions between the reference and the biogas process narrows if substitutions are considered. The higher emissions of biogas process than in the reference situation are mainly caused by lower emissions estimates from composting and storage of feed materials than what was estimated to be produced by the dry digestion plant operating with conventional practices. In dry digestion, for example, pockets containing methane may remain in the digestate and the methane escapes into the atmosphere when the reactor silo is emptied. Since the feed material of the dry digestion plant is mainly grass from fallows, grass silage, and only a small amount of manure, most of the emissions in the reference situation are from the composting chosen as an alternative management for grass. In practice, the methods of managing grasses and thus the resulting emissions on the farms vary. There are also uncertainties associated with the emissions from composting, and the emissions are also affected by the prevailing conditions.

In the farm-scale and farm cooperative wet digestion plants, the methane production potential per ton of feed material is about half of the methane production potential of the centralized wet digestion plant and the dry digestion plant. This is reflected in the results calculated per ton of feed and is therefore not due to the size of the plant but to the feed materials used.

Figure 27. GHG emissions from the example biogas plants and their reference situation per ton of feed without substitutions from energy and fertilizers. The results are presented as the range of advanced and conventional practices (minimum, maximum). In the centralized biogas plant TF means transport fuel (case A) and CHP means electricity and heat production (case B).



7.3.2.6 The impact of different practices on ammonia emissions

Ammonia emissions from the biogas process can generally only be released in connection with malfunctions and maintenance situations if the reactor must be opened. The biggest risk of ammonia emissions in biogas plants is related to the storage of feed materials and digestate and the possible further processing of digestate. Biogas production also increases the risk of ammonia emissions in connection with digestate field spreading. A large part of the ammonium nitrogen contained in the digestate can evaporate into the atmosphere as ammonia under suitable conditions. Evaporation is influenced, among other things, by the handling of the digestate, pH and weather conditions.

The biogas process increases the concentration of ammonium nitrogen in the digestate compared to the original feed material. Biogas production therefore both increases the risk of ammonia emissions and enhances the use of nitrogen as fertilizer. However, with advanced digestate management, storage and spreading practices, ammonia evaporation can be minimized and at the same time maintain the fertilizing value of the digestate or the fertilizer products processed from it.

The digestate formed at the biogas plant can be stored as is, as separated liquid and solid fractions, or as processed fertilizer products. During the separation of digestate, most of the soluble ammonium nitrogen ends up in the liquid fraction. The organic nitrogen in the solid fraction can break down due to spontaneous composting during storage, resulting in ammonia emissions. It is recommended to process the digestate into fertilizer products without intermediate storage to minimize nitrogen evaporation. Concentrated fertilizer products should be stored in tight storage, so that the fertilization effect does not weaken due to nitrogen evaporation. Their properties, for example low pH, can also prevent nitrogen evaporation.

At the time of writing, the air pollutant emission calculation guidelines (IPCC 2006; EMEP/EEA 2019; Grönroos et al. 2017) do not contain separate information on the effects of different practices on ammonia emissions from digestate. However, coefficients derived for manure management can be used in the emission evaluation as they are based on the concentration of ammonium nitrogen contained in the manure. According to them, when stored in open storages, about 30 % of the ammonium nitrogen contained in manure (and therefore digestate) can evaporate. Storing the solid fraction in a covered storage reduces ammonia evaporation by about 10 %. The tightest roof and wall structures, as well as tent-like and gastight roofs can reduce the ammonia evaporation from slurry-like and liquid digestate considerably, by 60–95 % (EMEP/EEA 2019; Grönroos et al. 2017).

The risk of ammonia emissions in the field spreading of digestate and fertilizer products processed from it depends on both the ammonium nitrogen content of the product being spread, the spreading method used, and the weather conditions. When spreading slurry-like and liquid digestate, approximately 30–60 % of the ammonium nitrogen can evaporate as ammonia. With injection, evaporation can be reduced by about 80 % and with spreading hoses by about 35 %. About 80 % of the ammonium nitrogen can evaporate when spreading digestate solid fraction. Nitrogen losses caused by spreading can be reduced by mulching the digestate quickly after the spread either by plowing or harrowing. If mulching takes place less than four hours after application, nitrogen loss can be reduced by up to 50–70 % (EMEP/EEA 2019; Grönroos et al. 2017).

7.3.2.7 Discussion and uncertainties

The practices of biogas production chains have a significant impact on GHG emissions for all example biogas plants. Advanced practices can significantly reduce the life cycle GHG emissions of the entire production chain, and at best, biogas production can achieve considerable climate benefits. This requires that good (here called advanced) practices are followed in the entire production chain, the energy produced in the process reduces the use of fossil energy sources, and the nutrients in the digestate are utilized, reducing the use of mineral fertilizers. In some cases, the practices named as conventional here, which are weaker in terms of emissions, may lead to a situation where the GHG emissions of the production chain are almost as large, if not even larger, than when managing the feed materials without biogas production.

The biogas plant technology, the feed materials used, the form of biogas utilization, and the possible further processing of the digestate affect the GHG emissions of the example plants. Since these differ between the example plants studied, the plants' emissions are not comparable with each other, and the shares of emissions per each plants' life cycle phases should not be compared to each other. In the interpretation of the results, it should also be considered that the emissions of different life cycle phases are partly connected to each other and dependent on the assumptions made for the plants. Therefore, a change in one practice can also affect emissions during other life cycle phases.

In all the examined example plants, the impact of methane emissions from the biogas process was considerable with conventional practices. Most of the emissions were estimated to be from the pressure reduction valves. In addition, GHG emissions consisted of methane emissions during maintenance and methane leaks escaping from process structures. In practice, however, the number and proportions of emission sources in the biogas process are always case-specific and there is considerable variation, even between years.

At the dry digestion plant, methane emissions were also estimated to be formed after the process, in connection with emptying the reactor silo, when methane from the gas pockets of the digested mass is released into the air. The size of the resulting emission depends on the properties of the digestate and the practices of filling and emptying the silo. It can be difficult to completely prevent the formation of gas pockets that enable methane emissions in this type of plant. The magnitude of the emissions varies and their assessment is challenging, as there is little available research information on the emissions from the emptying phase of the dry digestion silo. In this project, in connection with emission measurements made at a real dry digestion plant (Chapter 3.3), methane was found to be released during the emptying phase, although the actual process phase of the batch digestion with its leaks was estimated to be a larger source of emissions.

Based on the results, it can be stated that the emissions caused by the storage of digestate can be considerable in all example plants when the retention time in the process is short. Since the conditions in the biogas process have been optimized to produce biogas, biogas production can continue during storage if there is methane production potential left in the digestate due to a short retention time and the conditions, such as temperature, are favorable for methane production. Therefore, for example, heat recovery from digestate is recommended, as microbial activity and thus the risk of methane emissions decreases as the temperature of the digestate decreases.

The emissions from the storage of digestate are affected not only by the retention time, but also by the duration of the storage period, and possible separation and further processing of the digestate. However, due to lack of information, it was not possible to include the effects of digestate separation and further processing on the GHG formed during storage in the calculation. In practice, storage emissions are affected not only by the operating practices reviewed, but also by storage conditions, such as temperature, storage method and duration, and the quality of stored digestate or fractions or fertilizer products processed from it.

In the balance calculation of the example plants and in the evaluation of the emission impacts of the plants, the impacts of possible pre-storage of feed materials and its duration were not considered. During the storage of feed materials, GHG emissions can be formed, which can also lead to the partial loss of their methane production potential in the process. In terms of the sustainability of biogas plants, it is important that the feed materials are directed into the process as soon as possible after they are formed.

The production of transport fuel in the centralized plant studied is more favorable from a climate perspective than the combined production of electricity and heat if the use of fossil fuels in transport can be replaced by the produced transport fuel. However, the benefit to be achieved is affected by what type of electricity and heat needed for the biogas process and further processing of the digestate is purchased. In this work, no sensitivity analysis was done in that respect. If, on the other hand, substitution impacts are not considered, the production of electricity and heat is more profitable than the production of transport fuel in terms of the climate effects of the example plant, because there is no need to buy energy from outside the plant to process the digestate.

In the climate impact assessment, it was assumed that the transport fuel or electricity and heat produced from biogas fully replace the production and use of transport fuel or electricity and heat in all example systems. Recycled nutrients were also assumed to fully replace mineral fertilizers. In practice, the substitution benefit does not necessarily materialize as expected, because the regulation of consumption and emissions and the changes that occur in it affect the substitution benefit that can be achieved. If the compensation benefit assumed in the calculation were realized to be smaller, the net climate effect would be greater than the presented result (for more information, for example, IPCC 2014). For example, manure nutrients mainly end up in the field even without biogas production, thus reducing the need for mineral fertilizers even today. On the other hand, nutrients are not necessarily applied according to crops' needs, which makes it difficult to evaluate the substitution impacts of recycled nutrients, especially in the reference situations.

In the evaluation of GHG emissions of the example biogas plants, the focus was on comparing the effects of different practices. The reference situation calculated alongside them describes the GHG emissions of feed materials without the biogas process. The amount of GHG emissions in the reference situation affects the climate benefit achieved by the biogas process. In practice, even in the reference situation, there are different practices and conditions that affect the amount of emissions formed. In this report, no sensitivity analysis was performed for the reference situations.

The temporal occurrence of GHG emissions and sinks is a key factor when evaluating the climate effects of the management and utilization of different biomasses. In terms of the warming of the atmosphere, it is important when the emission occurs in time. In the life cycle of the biogas production chain, slowly released emissions occur after the digestate is spread on the field, as the organic matter of the digestate gradually breaks down in the soil. In addition to the properties of the feed materials themselves (degradability of organic matter), their retention time in the process and the storage period after the process affect the amount and composition of the carbon in the digestate spread on the field. In terms of the sustainability of the biogas production chain, it is essential to look at how the carbon balance and emissions change within the period under review, when biomass ends up in the biogas process instead of some other management option, and how different practices in the biogas production chain affect the carbon cycle.

In the biogas process, the amount and composition of the carbon contained in the feed materials change, reducing the carbon input to the soil compared to the original mass. Most of the material's easily degradable carbon is released as biogas, while without biogas process, carbon could be released as gaseous compounds, for example, from manure during storage and partly after spreading due to the activity of the soil microbiota within a short period of time (see Chapter 4). Changes in soil carbon inputs also affect carbon balances through soil microbiota. The soil microbiome has been found to be an important factor in the formation of soil carbon. The microbiome utilizes easily degradable carbon, turning it into part of the soil's permanent carbon storage, forming the so-called carbon pump (Liang et al. 2017). However, the effects of soil processes on the carbon cycle are still incompletely known (Liang et al. 2017; Chenu et al. 2019).

The retention time of the biogas process affects the carbon content of the digestate and especially the ratio of fast and slow decomposing carbon. However, the overall effect is presumably small. If methane production from the digestate continues during storage, the difference may not be significant. In practice, however, whether manure or digestate is spread to the soil is probably more important in terms of the carbon pump formed by soil microbes. Also, for example, the harvesting of grasses from fallows affects the carbon balance of the field, even if the carbon contained in the grasses is returned to other fields for utilization after biogas production. The research data and methods for evaluating the decomposition of different digestates with different residence times and inputs were found to be insufficient in the expert assessments of the project and the uncertainties regarding them to be considerable, so that it would have been possible to make sufficiently reliable assessments in this project. Consequently, impacts on soil carbon were not assessed from a life cycle perspective.

7.3.2.8 Conclusions

The practical implementation of biogas production chains has a great impact on the GHG gas emissions from biogas plants and on the climate benefits sought by the operation, as confirmed by the LCA. The results were similar in all the inspected example biogas plants, despite their different scale (plant size) and implementation method and practices. GHG emissions can vary considerably between different practices. Practices that insufficiently consider the emissions lead to a deterioration of the climatic sustainability of the biogas production chain, and the climate benefits sought by biogas production are not necessarily achieved in the management of the examined agricultural side streams. Climatically sustainable biogas production requires that the entire production chain is implemented and operated carefully in all its phases. In addition, solutions for storing and spreading digestate can minimize ammonia emissions and ensure that nitrogen is used by crops. In reducing gaseous emissions, special attention should be paid to the retention time in the biogas reactor, plant scaling and proper maintenance, digestate storage methods, intact plant structures, and advanced methods for utilizing biogas.

The management of agricultural side streams in biogas plants produces good practices in compliance with the climate benefits compared to the selected reference management solutions. In the future, it will be important to include the assessment of soil carbon input and the resulting carbon stock to the assessment of climate impacts.

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7.3.3 Emissions and emission reductions according to the Renewable Energy Directive

Emissions and emission reductions based on the Sustainability Act and in accordance with the Renewable Energy Directive were calculated for the centralized example plant, considering the same conventional and advanced practices as in the LCA calculation. When the calculation is carried out using the emission data of the LCA calculation presented above (Table 25, calculation 1), the biomethane produced as a transport fuel in the centralized plant produces significant emission reductions compared to the fossil reference value with advanced (123 % reduction) practices. However, with conventional practices, the emission reduction target required (65 % reduction compared to the fossil reference value) is not met, although emission reductions are achieved (52 % reduction).

When the calculation uses the Directive's default values (Table 25, calculation 2) for emissions from slurry and side stream from food processing, and other feed materials use the LCA calculation data, an emission of 23 gCO_2-eq/MJ (of energy that ends up being sold) is generated with advanced practices. This is nearly the same as achieved when using solely LCA emission data (28 gCO_2-eq/MJ). When using the Directive's default values, there is a slight difference in the calculated emission credit received from digesting slurry (Directive's credit for cattle slurry -111.9 gCO_2-eq/MJ; credit in LCA calculation for pig slurry -149.6 gCO_2-eq/MJ). The reason for this is probably a different assumption made in this project about the amount of energy obtained from manure and ending up for sale than in the background calculation of the Directive. However, the emission reduction achievable with biogas production with advanced practices is still significant, 121 %. With conventional practices, emissions increase significantly (104 gCO_2-eq/MJ) and the achievable emission reduction is lower, 41 %.

If the default emission values of the Directive are used for all feed materials used (Table 25, calculation 3), emissions are significantly lower with advanced practices than with other calculation methods (17 gCO_2-eq/MJ). The amount of calculated emission credits from manure will also increase and the emission reduction compared to fossil fuel will increase to 159 %. The larger credits from manure are due to the large, calculated credits for the solid fraction separated from pig slurry manure and the poultry manure (Appendix 5), when using the default value based on the methane yield of cattle slurry. In the case of solid manures, the relative share of the emission credit will increase due to the relative share of the total energy amount based on their energy content is larger than for slurry. For the same reason, the emissions caused by conventional practices, especially from the shares of solid manure in the different stages of the production chain (Appendix 5), are so large that even after the emission credit for manure, the emission reduction remains at 55 % and the emission reduction target of the Directive (65 %) is not met.

In the same calculation (3), using default values for maize in the calculation of grassland emissions did not significantly change the result. A closer look (Appendix 5) shows that the default values for maize in different production chain phases differ slightly from the LCA calculation values in this report, but the total emissions are almost the same for both advanced and conventional practices. It should also be noted that the amount of grass fed to this example plant was very small (9 % of the energy content of the feed materials) and the emissions during grass cultivation were not considered. Thus, the emissions from the use of the grass feed remain small.

The results of the calculation examples show that care must be taken with the background assumptions of the Renewable Energy Directive's manure emission credit. Compared to the LCA calculation reported here for manure storage emissions without the biogas process (15,100 tCO_2-eq), it can be stated that the calculated manure emission credit according to the Directive with the biogas process is moderate (8,100 tCO_2-eq). Using the Directive's default value for slurry can reduce the calculation burden for biogas plants, but for solid manures, the Directive's default value is not suitable as such. However, the manure emission credit can be calculated for solid manure as well when the dry matter content and methane production potential of the manure are considered (Appendix 2). In the calculation, it is also important to clearly indicate the emission data used, because the standard emission coefficients given in the calculation instructions (Energy Authority 2022), based on the Directive, are only suitable for slurry, maize and biowaste. Standard coefficients regarding the composition of feed materials commonly used in Finland (e.g.

standard humidity) should be attached to the plant operator instructions of the Energy Authority. This would enable uniform treatment of the biogas plant operators when comparing calculations. In addition, the instructions should more clearly state which type of reactor technology and mode of operation the Directive's default emission coefficients have been calculated for.

The Directive's default values for the emissions of advanced practices are smaller than the emissions used in the LCA calculation of this project. On the other hand, in conventional practices, the emission values, especially for biogas upgrading, are higher than those used in the LCA calculation. One significant difference between the advanced and conventional practices of the LCA calculation is the process retention time according to which the biogas yields were calculated for the example plants. The calculation of the default emission values of the Renewable Energy Directive is based on the fact that the methane yield for certain feed materials does not change, whether the plant uses advanced or conventional practices. However, the Directive's calculation considers that the biogas generated in the gastight storage is recovered (the storage is in practice a postdigestion tank). In this case, the amount of methane produced for sale when using advanced practices is greater than when using conventional practices without a gastight storage, where the biogas generated from the storage is supposed to escape into the air. In the LCA calculation of this project, it was assumed that the long retention time of the reactor was sufficient to achieve a methane yield corresponding to the advanced practices of the Directive (reactor + postdigestion). In addition, lowering the temperature of the digestate, for example by heat recovery, was in the LCA calculation assumed to decrease microbial activity and thus possible methane production during storage. In this case, the storage does not have to be gastight and within the scope of methane recovery, even if small amounts of methane eventually end up in the atmosphere. This difference due to methane emissions from digestate storage explains why the Directive's default values for emissions are significantly lower than the emissions estimated in this work in advanced practices (Appendix 5, Tables 5.1 and 5.3). In conventional practices, the differences in the calculation are smaller.

It is therefore important to look carefully at the underlying assumptions of the Directive's default emission values. Default values should not be used if the practices at the biogas plant differ from the background assumptions of the default values. For example, if the retention time of the reactor in the plant is short and the gas is not recovered in storage or in postdigestion tank, the assumed emission reduction will not be achieved (even if the storage is covered). Therefore, the default emission values should not be used.

Table 25. GHG emissions and emission reduction in the centralized biogas plant with different calculation choices (more detailed emissions per processing chain in Appendix 5).

Advanced practices

Calculation	Total GHG emissions without manure credit [gCO_2-eq/MJ]	Total GHG emissions with manure credit [gCO_2-eq/MJ]	Emission reduction as compared to the fossil fuel [%]
1	28	-22	123
2	23	-20	121
3	17	-55	159

Conventional practices

Total GHG emissions without manure credit [gCO_2-eq/MJ]	Total GHG emissions with manure credit [gCO_2-eq/MJ]	Emission reduction as compared to the fossil fuel [%]
103	45	52
104	55	41
123	42	55

1 Emission data according to the LCA calculation of the project for all feed materials
2 Directive's default emission values for slurry and side stream for food processing, but emission data of the LCA calculation for other feed materials (grass from fallows, Rasi et al. 2019)
3 Directive's default emission values for all feed materials (exception: grass from fallows, Rasi et al. 2019)

7.3.4 Economic assessment of the example biogas plants

The profitability of the example biogas plants was examined through the economic performance of the plants and the payback period of the investment. Detailed information on the economic assessment can be found in Appendix 6. Background calculations for farm-scale and farm cooperative wet digestion plants were also done using the Finnish web-based Biogas Tool (https://maatalousinfo.luke.fi/en/laskurit/biogas) to ensure comparability of the results. Still, for the actual calculations reported here, an economic model developed at Natural Resources Institute Finland was used. The model was also used for the economic assessment of the dry digestion plant and the centralized wet digestion plant. It is important to note that the profitability of different plant sizes should not be compared. A comparison can be made between the economic profitability of the advanced and conventional practices per example plant.

The background assumption of the calculations was that the net electricity and heat produced by the CHP unit of the farm-scale, farm cooperative and dry digestion plants is sold in full outside the plants and, for example, part of the heat is not condensed, which can happen in practice. This assumption had a positive effect on the profitability of the example plants. However, it is essential that the profitability comparison between advanced and conventional practices was otherwise made from the same starting points, but the investment cost of plants using advanced practices is higher due to the additional investments required. Regarding the centralized plant, it was assumed that the raw biogas produced by the plant is upgraded and pressurized in the plant and sold as biomethane as transport fuel from a fueling station located next to the plant.

The investment costs of the plants using advanced practices were 15–93 % higher than those with conventional practices due to the structures and functions required to minimize emissions. However, the higher investment support received for them in terms of euros improved the annual economic profit compared to the plants using conventional practices. With advanced practices, the reactor's long retention time also increased the biogas yield, thanks to which the net energy yield and income were higher in all example plants. The annual profit was better when using advanced practices than when using conventional practices in the dry digestion plant and in the farm cooperative wet digestion plant. However, only in the dry digestion plant the payback period with advanced practices was shorter than with conventional practices (Table 26).

Table 26. Summary of the economic assessment. Plant 1 = farm-scale wet digestion plant, plant 2 = farm cooperative wet digestion plant, plant 3 = centralized wet digestion plant and plant 4 = dry digestion plant. A = advanced practices, C = conventional practices.

	Plant 1 A	Plant 1 C	Plant 2 A	Plant 2 C	Plant 3 A	Plant 3 C	Plant 4 A	Plant 4 C
Investment (€)	1 387 000	747 000	1 623 000	1 057 000	21 135 000	10 964 000	955 000	832 000
Investment support (%)	50 %	50 %	50 %	50 %	30 %	30 %	50 %	50 %
Supported investment (€)	694 000	373 000	811 000	529 000	14 795 000	7 675 000	477 000	416 000
Total income (€/yr)	129 000	97 000	400 000	310 000	11 123 000	9 593 000	94 000	74 000
Total costs (€/yr)	63 000	49 000	66 000	47 000	9 206 000	7 270 000	45 000	41 000
Gross margin (€/yr)	66 000	49 000	334 000	263 000	1 918 000	2 323 000	48 000	33 000
Annuity of investment (€/yr)	65 000	37 000	79 000	53 000	1 314 000	657 000	45 000	39 000
Profit (€/yr)	1 000	12 000	256 000	210 000	603 000	1 666 000	4 000	-6 000
Payback period (years)	10.5	7.6	2.4	2.0	7.7	3.3	9.9	12.8

7.3.4.1 Farm-scale biogas plant

With the advanced practices, the investment cost of the farm-scale example plant was 86 % more expensive than when using conventional practices (1.4 vs. 0.75 million euros). The price was increased by the larger reactor size required for a longer retention time (274 000 euros more expensive) and the investments related to digestate separation and storage of the resulting fractions: screw separator, storage for solid fraction, and tent-like cover (tensioned cover) of the liquid fraction storage tank cost a total of 366 000 euros (the storage tank itself was assumed to already exist at the farm, thus it was not included as a biogas plant investment cost).

With the advanced practices, the plant received income from electricity sales of 69 000 euros (12 cents/kWh VAT 0 %) and heat sales of 43 000 euros (7 cents/kWh) per year. Costs incurred for both practices were 20 000 euros/year (20 euros/t) for grass silage production, 2 000 euros/year (2 euros/t) for loading the silage into the crusher, plant maintenance, daily work, and insurance (see Appendix 6). The nitrogen mineralized in the biogas process was also calculated as income for the plant (17 000 euros/year, 2.35 euros/kg). With the conventional practices, the plant's total income was a quarter lower (income: electricity 55 000 euros/year, heat 28 000 euros/year and nitrogen 14 000 euros/year).

With advanced practices, the plant's profit was 1 000 euros/year and the payback period was 10.5 years. With the conventional practices, the profit was better, 12 000 euros/year, and the payback period was 7.6 years (Table 27).

Table 27. The profitability of the farm-scale wet digestion plant with advanced and conventional practices.

Farm-scale plant	Advanced practices	Conventional practices
Biogas plant without digestate-related investments	1 021 000	747 000
Screw press separator (€)	50 000	-
Tent-like cover for liquid fraction storage tank (€)	127 000	-
Storage for solid fraction (€)	189 000	-
Total investment without support (€)	1 387 000	747 000
Supported investment (€) (support 50 %)	694 000	373 000
Total income (€/yr)	129 000	97 000
Total cost (€/yr)	63 000	49 000

Farm-scale plant	Advanced practices	Conventional practices
Gross margin (€/yr)	66 000	49 000
Annuity of investment (€/yr)	65 000	37 000
Profit (€/yr)	1 000	12 000
Payback period (yrs)	10.5	7.6

7.3.4.2 Farm cooperative biogas plant

With the advanced practices, the investment cost of the farm cooperative wet digestion plant was 54 % more expensive than with the conventional practices (1.6 vs. 1.1 million euros). The price was mainly increased by the larger reactor size required by the longer retention time, digestate separator, storage for solid fraction located next to the plant, and covering of the liquid fraction storage tank. With advanced practices, the plant received income from electricity sales of 244 000 euros (12 cents/kWh VAT 0 %) and heat sales of 119 000 euros (7 cents/kWh) per year. The nitrogen mineralized in the process was calculated as income of the biogas plant (37 000 euros/year, 2.35 euros/kg). With the conventional practices, the plant's total income was 23 % lower than with advanced practices (income: electricity 198 000 euros/year, heat 80 000 euros/year and nitrogen 31 000 euros/year).

With the advanced practices, the profit of the plant was 22 % better due to the higher energy yield, but the payback period was 20 % longer than with the conventional practices due to the higher investment cost (2.4 vs. 2.0 years; Table 28). Calculations did not consider the costs of transporting feed materials and digestate between the biogas plant and the farms.

Table 28. Profitability of the farm cooperative wet digestion plant with advanced and conventional practices.

Farm cooperative plant	Advanced practices	Conventional practices
Biogas plant without digestate-related investments	1 455 000	1 008 000
Screw press separator (€)	75 000	-

Farm cooperative plant	Advanced practices	Conventional practices
Storage tank for liquid fraction (advanced) / storage tank for digestate (conventional)	48 000	49 000
Floating cover for liquid fraction storage tank	3 000	-
Storage for solid fraction (€)	42 000	-
Total investment without support (€)	1 623 000	1 057 000
Supported investment (€) (support 50 %)	811 000	529 000
Total income (€/yr)	400 000	310 000
Total cost (€/yr)	66 000	47 000
Gross margin (€/yr)	334 000	263 000
Annuity of investment (€/yr)	79 000	53 000
Profit (€/yr)	256 000	210 000
Payback period (yrs)	2.4	2.0

7.3.4.3 Centralized biogas plant

The investment cost of the centralized wet digestion plant with the advanced practice was about double compared to the usual practice (21 million vs. 11 million €; Table 29). With the advanced practices, the plant price as significantly higher caused not only by the larger reactor size required by the longer retention time and the higher biogas yield (4 million euros), but also for the investments in recycling of digestate nutrients via further processing (6 million euros).

With both practices, the centralized plant received a gate fee income of 2 million euros (50 euros/t) due to the side stream from food processing per year. No price was calculated for grasses from fallows and the fertilizer products produced. In addition, the plant using advanced practices received 8.47 million euros (1.452 euros/kg, VAT 0 %) from the sale of biomethane and 649 000 euros (2.35 euros/kg) from nitrogen mineralized in the biogas process per year. The plant using advanced practices also paid 2.6 million euros for the electricity needed by the plant (12 cents/kWh) and 3.1 million euros for heat (7 cents/kWh) per year. The transportation distance of the feed materials to the centralized plant was assumed to be 20 km for both practices. The cost of slurry transportation was 219 000 euros/year (2.43 euros/t, density 1 t/m^3), while the cost of transportation of solid feed materials was 341 000 euros /year (2.43 euros/t, density 0.5 t/m^3) and their loading to the crushing and feeding equipment 220 000 euros/year (2 euros/t). Costs are also caused by plant maintenance, daily work, and insurance (see Appendix 6). No price was specified for the fertilizer products produced from digestate, but their transportation costs were considered. With conventional practices, the plant received lower total income (biomethane 6.9 million euros/year and nitrogen 677 000 euros/year), but also the costs for electricity (1.6 million euros/year) and heat (1.1 million euros/year) were lower than when using advanced practices.

The further processing of digestate into concentrated fertilizer products as part of the advanced practices caused significant savings in transportation. This was due to the significantly lower mass of fertilizer products produced by evaporation and thermal drying (80 000 t/y) in comparison to the mass of the liquid and solid fractions formed when using conventional practices (364 000 t/y). The advanced practices saved 1.9 million euros in transportation per year, while with both practices the transportation distance of liquid fertilizers was assumed to be 25 km and that of solid fertilizers 125 km.

Despite the higher biomethane sales of the advanced practices and the savings from fertilizer transportation, the income is not enough to compensate for the expensive investments if no income is available from the fertilizer products. The payback period of the advanced practices is more than double (7.7 vs. 3.3 years) and the profit remains 1.06 million euros/year lower than with the conventional practices (Table 29). To achieve the same annual profit for the centralized plant, the fertilizer products produced via the advanced practices should receive an income of around 13 euros/t (VAT 0 %), while assuming no income from the separated fractions produced by conventional practices (with the advanced practices, the profit is 1.06 million euros lower / fertilizer products 80 000 t are produced per year = 13 euros/t).

Table 29. The profitability of the centralized wet digestion plant with advanced and conventional practices.

Centralized plant	Advanced practices	Conventional practices
Biogas plant without digestate-related investments	13 855 000	9 647 000
Decanter centrifuge	600 000	600 000
Concentration of liquid fraction by evaporation	4 600 000	-
Thermal drying of solid fraction	1 500 000	-
Ammonia scrubber for drying	150 000	-

Centralized plant	Advanced practices	Conventional practices
Storage for ammonium sulphate and nutrient concentrate (advanced) / Storage tank for liquid fraction (conventional)	100 000	182 000
Tent-like cover for storages	44 000	-
Storage for solid fraction	286 000	535 000
Total investment without support (€)	21 135 000	10 964 000
Supported investment (€) (support 30 %)	14 795 000	7 675 000
Total income (€/yr)	11 123 000	9 593 000
Total cost (€/yr)	9 206 000	7 270 000
Gross margin (€/yr)	1 918 000	2 323 000
Annuity of investment (€/yr)	1 314 000	657 000
Profit (€/yr)	603 000	1 666 000
Payback period (yrs)	7.7	3.3

7.3.4.4 Dry digestion plant

In the dry digestion plant, the unsubsidized investment cost with advanced practices including digestate storage was 955,000 euros, and that of the conventional practices 832 000 euros. The price with advanced practices was 15 % more expensive due to the longer retention time of the batches requiring larger reactor silos. The exception was the manure storage (concrete slab), which was 32 000 euros more expensive with conventional practices due to storing digestate generated throughout the year. With advanced practices, only a third of the digestate is stored on a concrete slab, while the remaining 2/3 goes directly to field spreading.

With the advanced practices, the plant received income from electricity (45 000 euros; 12 cents/kWh, VAT 0 %) and heat sales (43 000 euros; 7 cents/kWh) per year. The nitrogen mineralized in the process was also calculated as income (5 300 euros/year; 2.35 euros/kg). With the conventional practices, the plant's total income was 21 % lower (income: electricity 35 000 euros/year, heat 34 000 euros/year and N 4 500 euros/year). Costs for both practices were 10 000 euros/year (20 euros/t) for grass silage production, 8 000 euros/year (4 euros/t of silage) for loading the feed materials into the reactors and removing digestate from the reactors, as well as plant maintenance, daily work, and insurance (see Appendix 6). The advanced practices had an additional cost of covering the digestate pile on fields (500 euros/year).

The profitability of the plant using advanced practices iswas better thanks to the higher energy yield: the result is +4 000 euros/year and the payback period was 9.9 years. The plant using conventional practices is unprofitable (profit -6 000 euros/year) and the payback period is 12.8 years (Table 30).

Table 30. The profitability of the dry digestion plant with advanced and conventional practices.

Dry digestion plant	Advanced practices	Conventional practices
Biogas plant without digestate storage (€)	939 000	785 000
Digestate storage (€)	15 000	47 000
Total investment without support (€)	955 000	832 000
Investment support (%)	50	50
Supported investment (€)	477 000	416 000
Total income (€/yr)	94 000	74 000
Total cost (€/yr)	45 000	41 000
Gross margin (€/yr)	48 000	33 000
Annuity of investment (€/yr)	45 000	39 000
Profit (€/yr)	4 000	-6 000
Payback period (yrs)	9.9	12.8

7.3.4.5 Conclusions

Minimizing emissions in biogas plants increases investment costs and, depending on the size of the plant and the use of end products, also operating costs. However, they also increase the amount of biogas and therefore energy produced, as well as the proportion of soluble nitrogen in the digestate, which increases the plants' income in terms of energy and nutrients. Thanks to inexpensive equipment, simple mechanical separation of digestate is possible even on a relatively small scale at the current level of financial support. The cost of digestate processing is partly compensated by the decrease in transportation costs, which was only included in the calculation for a centralized plant. This could also apply to other plant sizes.

The advanced processing of digestate into fertilizer products (thermal drying, evaporation, ammonia stripping, etc.) requires other support in addition to the current investment subsidies. This should be considered when developing incentives. The nutrient recycling support that is being prepared in Finland is needed and should be available in the long term, so that biogas plant operators dare to invest in processing equipment. Other possible incentives and regulation guiding nutrient recycling and water protection may also be necessary.

8 Sustainable practices and emission management in biogas production

Sustainable practices implemented in the biogas production chain can significantly affect the emissions and emission risk of the entire production chain, both as gaseous emissions into the air and nutrient loading into water. For this reason, they should be considered already in the planning phase of biogas plants and required in plant permitting and investment support decisions. In this way, the transition to the most sustainable solutions is promoted. Although this report focuses especially on gaseous emissions, biogas plants must also consider the effect of the properties and origin of different feed materials, for example on the need for hygienization, but also on the possibilities of further use of the end products. Furthermore, sustainable practices increase the safety of biogas production, when potential gas leaks are monitored and effectively prevented.

Considering sustainable practices during the planning, implementation and operation of biogas plants requires wide-ranging expertise from biogas plant operators as well as authorities that issue permits, monitor the plants, and evaluate support decisions. Since there are no comprehensive, clear instructions on the subject at the time of writing, a short guide to the factors to be considered has been put together in this chapter as a checklist (Table 31).

The most significant emissions in the biogas production chain are often caused by the storage of digestate and the utilization of biogas for energy. Storage emissions, on the other hand, are linked to the retention time of the feed materials in the biogas process. However, emissions also arise from other phases of the production chain, which depend not only on the design and operation of the plant, but also on the maintenance and life span of structures and equipment. The operator is able to influence e.g. the quality, feed ratios and quantity of feed materials within the limits of the plant’s capacity. In the planning phase of the plant, the size of the reactor should be chosen so that it is large enough even if there are changes in the feed mixture of the plant. It is also important to consider the storage and utilization capacity of biogas in the planning phase, to avoid unnecessary flaring (or other burning) of biogas and the resulting emissions thereof. The size of the digestate storage is also essential information already in the planning phase. In terms of emissions, they could be minimized with the emptying rhythm of digestate storages, but in practice the emptying rhythm often depends on the needs and schedules of farming. Covering the storages significantly reduces ammonia emissions.

Table 31. Measures with which emissions from biogas production chain can be managed and minimized.

Phase	Measures and their impacts
Scaling of the plant	Reactor size in relation to the quantity of the feed materials: ensuring sufficiently long retention time reduces gaseous emissions from digestate storages significantly Correct scaling helps to minimize emissions from reactor pressure valves Sufficiently large gas storage reduces the need for flaring
Maintenance	In terms of emission management, the planning and regularity of process maintenance measures essential Regular inspection of structures, locating and repairing emission leaks (e.g. tight gas hood fasteners, plugging tears and holes) as part of maintenance procedures Checking the functioning of the pressure control valves, avoiding their unnecessary opening Gas handling during the maintenance of gas handling equipment. Sufficient gas storage capacity
Biogas use	Treatment of exhaust gas from CHP unit and gas upgrading units (e.g. oxidation technology) to minimize methane emissions Avoiding flaring of biogas to prevent emissions from incomplete combustion
Management of feed materials	Minimizing the storage time of feed materials to prevent microbiological degradation A closed system to control emissions from the reception, storage, and transfer of feed materials to the reactor. Covering storages and/or exhaust air treatment. Actions required by the origin of the feed materials, such as consideration of the hygienization requirement
Handling and storage of digestate and fractions processed from it	Cooling the digestate before storage to reduce degradation and emissions Digestate handling in a closed space, with exhaust air treatment to minimize emissions Minimizing the storage time (e.g. immediate separation of the digestate) Covering liquid/sludge storages (tight cover most effective) Digestate separation can reduce the total emission, covered storage of the separated liquid fraction required In case of thermal drying of digestate, minimization of nitrogen emissions into the air by recovering the nitrogen from the drying gases

Phase	Measures and their impacts
Field spreading on digestate and fractions processed from it	Use of mulching methods during or immediately after spreading to minimize nitrogen emissions Timely fertilization to maximize the fertilization effect and minimize emissions A destination for digestate or fractions processed from it, where there is a real need for nutrients and organic matter

9 Conclusions

9.1 Key questions related to the sustainability of biogas production

The structures of biogas plants and the practices of their operation and maintenance have a significant impact on the gaseous emissions resulting from production, including greenhouse gases that accelerate climate change (methane, nitrous oxide) and ammonia that deteriorates air quality. Inadequate practices lead especially to a deterioration of the climatic sustainability of biogas production.

Methane emissions from biogas production reported in the literature vary from low to as much as 20 percent of the total methane yield obtained. Nitrogen emissions, especially in the form of ammonia, can also be large. Emissions of nitrous oxide mainly occur after the field use of the digestate or its fractions because of microbial activity in the soil. This happens with all nitrogen fertilization, and it is difficult to reduce the emissions. The processing of agricultural side streams, such as manure, in a biogas plant produces the most significant climate benefits compared to conventional management, when attention is paid to emission control. As emissions decrease, more valuable nitrogen ends up being used by crops. The need for emission-reducing practices in biogas plants is significant, regardless of plant size and feed materials.

The most important measures affecting the gaseous emissions from biogas production are the retention time of feed materials in the biogas reactor and the storage of digestate or processed fractions from it. Proper and properly scheduled maintenance of the plant, intact and durable structures, and minimizing the emission risks of biogas energy use are also important for controlling emissions in the production chain. On the other hand, there is little information on gaseous emissions from digestate processing. In connection with the field spreading of digestate, methods that minimize ammonia emissions must be used, but the use of digestate does not, for example, increase nitrous oxide emissions compared to unprocessed manure.

Biogas plants must be scaled in such a way that biogas is efficiently recovered from the feed materials. In practice, the amount of feed materials must be proportional to the size of the biogas reactor in such a way that the retention time of the feed materials in the process enables a good degradation of the organic matter and thus high production and recovery of biogas. If the retention time is short, not all available biogas (methane) will be recovered during the process, but easily degradable organic matter will remain in the digestate. It can be degraded to methane after the process during storage and cause a significant emission risk. A sufficient retention time can be ensured in two ways. If the reactor is small in relation to the amount of feed materials and the retention time is therefore short, the reactor must be followed by a post-digestion tank equipped with gas recovery. Alternatively, the reactor alone must be large enough to ensure a long retention time and thus a high degradation of the feed materials.

9.2 Changes needed in policy instruments

The inclusion of sustainable practices increases the investment costs of biogas plants and possibly also their operating costs. However, the additional cost can be partly compensated as increased income due to higher biogas yield and amount of soluble nitrogen directly usable for crops. In large, centralized plants, digestate processing increases the plant costs significantly, but reduces the transportation costs of the fertilizer products due to their higher nutrient concentration. Such advanced processing is often a prerequisite for sustainable nutrient utilization ending up in the fertilizer products. This is especially the case in areas where the need for nutrients in the vicinity of the plant is low and a longer transport distance is required.

Sustainable practices should be a requirement for investment support decisions and a starting point for cost calculations. In addition, as the plant size increases, support is also needed for the more advanced processing of digestate, especially in those areas where recyclable nutrients are in surplus to need.

The conclusion of the review of policy measures carried out in the project is clear: the current regulations and incentives do not guarantee the sustainability of biogas production. In addition to the controlled acceleration of investments, regulatory changes are also needed. Furthermore, it must be ensured that regulation is predictable in the long-term and clearly guided.

The current policy measures do not consider the length of retention time of the biogas plant, even though it is one of the most important factors affecting emissions. This is a clear shortcoming, because from the company's point of view, the small size of plant investment in relation to the amount of feed materials – or the oversizing of received feed materials in relation to the size of the plant – can be profitable, especially in the short term. An imbalance can lead to a shorter retention time and methane emissions. Therefore, setting a minimum time or a similar criterion for the retention time of the biogas process is necessary. Alternative routes can be followed in setting the obligation. Indirect regulation could take place either through the quality requirements governing fertilizer products (the maximum limit of digestate biogas production as a stability requirement) or, for example, as part of the expansion of the practices of the sustainability legislation. However, neither apply to all plants. Direct regulation in the environmental permit would therefore provide a clear instrument for regulating the retention time, regardless of plant size, but its use would require a change in the legislation. In any case, overlap should be avoided.

The default emission coefficients of the Renewable Energy Directive are available for only a few feed materials. In addition, their calculation is based on Central European conditions and assumptions about reactor technology and operating methods, which do not necessarily correspond to the Finnish implementation. The Finnish operating methods and the properties of feed materials should be considered better than at present. The Energy Authority's sustainability criteria guide for biogas plant operators should be updated so that it is clear to the operators when the directive's default values can be used. In addition, the emission calculation guidelines should consider the characteristics of typical input materials used in Finland. Only with the help of guidelines can it be guaranteed that operators are treated as equally as possible, and that regulation is predictable.

There is also a clear need for revising the guidelines for environmental permitting of biogas plants. The existing guidelines are out of date and do not serve permit applicants or permit authorities and fail to guarantee equal treatment of applicants. Environmental permit practices need unification, which is why the work on renewing the permit guidelines must be started in the environmental administration without delay.

There is plenty of regulation that encourages consideration of sustainability aspects. However, some of the obligations and support conditions are recent or just being prepared, and there is no clarity about their significance for the planning and implementation of biogas plants. To some extent, the ambiguities are the result of the vagueness of the legal status of the obligations. During this study, for example, the role of the "Do No Significant Harm" (DNSH) principle in the consideration of granting recovery funds was not clarified. The worst situation arises when regulations cause a regulatory burden, but do not significantly support ensuring the sustainability of biogas production.

Emission control solutions should also be considered in the criteria for the acceptable costs of investment subsidies, so that the criteria encourage sustainable practices.
In addition, incentives supporting the recycling of nutrients are still needed for the development of the market for recycled fertilizer products produced from digestate.

Targeting permit procedures and support measures in such a way that they encourage the adoption of sustainable practices at biogas plants requires wide-ranging expertise and understanding of the operation of biogas plants from permit authorities and assessors of subsidy applications. Insufficient and unclear instructions also trouble biogas plant operators. Training and increasing competence for support of decision-makers, authorities and operators is necessary. Advisory services must also be increased.

Summary of policy recommendations

- The sustainability of biogas production should be encouraged through regulatory changes, both by correcting and harmonizing regulatory practices. Only in this way can the risk of greenhouse gas and ammonia emissions related to production be minimized and the achievement of sustainability benefits maximized.
- The regulation of the retention time in biogas production must be included into the government program. Different regulatory routes can be used in this matter, the functionality of which must be determined separately. The clearest solution would be to regulate it as part of the environmental permit, which requires a change in the legislation. Merely a stability requirement of the quality regulation of the fertilizer product legislation or the expansion of the practices of the sustainability legislation are not enough, as they do not apply to all biogas plants.
- For the sake of legal certainty, the guidelines for the implementation of regulation and subsidies must be clear, uniform, and comprehensive.
- The Energy Authority must ensure the clarity of the guidelines supporting emission calculation as defined in the Renewable Energy Directive. Particularly the standard emission values to be used in calculations need to be clear.
- The environmental administration is responsible for improving the fluency and predictability of environmental permit processes. The environmental permit guidelines serving operators and licensing and regulatory authorities must be updated without delay.
- Financial support schemes targeting biogas plants must take into consideration the additional costs caused by sustainable practices. If necessary, eligible cost items should be defined so that the sustainable practices are treated as default assumptions in the system.
- To ensure sufficient expertise of the various parties and the understanding of biogas production as a whole, training is needed. Advisory services need also to be improved. The commitment of plant suppliers and industry consultants to sustainability promotion is important.

9.3 Research needs

Storages of digestate or fractions processed from it should be covered, especially to reduce ammonia emissions that impair air quality. At the same time, the fertilizer value of the digestate is preserved, as ammonia volatilization reduces the concentration of valuable nitrogen. Covering also prevents rainwater from entering the digestate or its fractions and thus their unnecessary dilution. In addition, heat recovery from the digestate when it leaves the reactor reduces the risk of ammonia evaporation and slows down the microbial activity that causes methane emissions during storage. At the same time, it improves the plant's energy balance.

Even though the emission measurements carried out in the project from the storage tank of the farm-scale wet digestion plant and the reactor silo of the dry digestion plant confirm the information gathered from the literature, more emission measurements should be done under Finnish conditions. The temperature of the digestate or the fractions processed from it during storage affects the emissions, and in particular, additional information is needed on the emissions during the entire batch process of dry digesters.

The use of digestate as a fertilizer product adds organic matter to the soil. Based on the literature review and modeling, the biogas process has no long-term effect on the share of more permanent carbon when compared to the use of unprocessed manure. However, more research is needed on the effects of faster decomposing carbon on the more permanent carbon in the soil, also from a life-cycle perspective.

Appendices

Appendix 1. Calculation of mass, nutrient and energy balances of the example biogas plants

The characteristics of the feed materials of the example biogas plants used to help outline the emission effects of biogas production were compiled from the literature (Table 32), and with their help, the annual feed mass of the example plants with their characteristics was calculated.

Table 32. Characteristics of the feed materials. Manure (ex housing, Luostarinen et al. 2017a, Luostarinen et al. 2017b), grass silage (Crop production statistics of Natural Resources Institute Finland and Mavi 2008), side stream from food processing (average waste according to a literature review, Luostarinen et al. 2019), methane production potentials (manure: Luostarinen et al. 2019; separated slurries: Biogas Tool 2020; grass biomasses and side stream from food processing: TEM 2020).

Feed materials		TS (%)	VS (%)	Ntot (g/kg)	NH4-N (g/kg)	Ptot (g/kg)	CH_4-potential (m^3/t_{VS})
Manure	Cattle, slurry	9.0	6.9	5.0	2.9	0.9	200
	Cattle, separated solid fraction from slurry[1]	22.4	11.5	4.5	1.4	1.0	190
	Pigs, slurry	8.2	6.9	4.6	2.9	1.0	320
	Pigs, separated solid fraction from slurry[2]	22.2	18.5	3.7	1.2	1.4	305
	Horses and ponies	34.7	25.0	4.2	1.7	0.8	150
	Poultry, average	54.7	44.9	23.8	7.8	9.6	201
Other	Grass silage	30.0	27.0	7.7	0.3	0.9	350
	Grasses from fallows	40.0	27.0	5.2	0.4	0.8	280
	Side stream from food processing	20.0	17	6.0	0.3	1.0	350

[1] Separation of cattle slurry by a screw press, separation efficiency in solid fraction: mass 20 %, TS 50 %, VS 33 %, N 18 %, NH4-N 18 %, P 22 % (Biogas Tool 2020, Pyykkönen 2019)

[2] Separation of pig slurry by a screw press, separation efficiency in sold fraction: mass 10 %, TS 27 %, VS 27 %, N 8 %, NH4-N 4 %, P 14 % (Møller et al. 2000, Paavola et al. 2016)

Calculation of mass and nutrient balances

In addition to the feed materials, in the calculation of the centralized wet digestion plant (capacity 200,000 t/y), it was assumed that dilution water would be added to the plant's feed mixture (Table 33) to keep its dry matter content at a level suitable for wet digestion (about 12–13 %). The properties of the dilution water depended on the plant's practices. The centralized plant in accordance with advanced practices included a far-reaching processing of the digestate, where the centrifuged liquid fraction of the digestate was concentrated by evaporation. The almost solid-free process water obtained from evaporation was then used as the dilution water (130 000 t/y). On the other hand, in the centralized plant according to the conventional practices, the digestate was only separated and the liquid fraction formed was used for dilution (180 000 t/y). The properties of the water fractions used for dilution were calculated by assuming the mass balance of the first year to be calculated with completely pure water (nutrient and dry matter concentrations 0 g/kg). The process water resulting from this calculation was used as process water in the next round of calculations, and the calculation was repeated until equilibrium was reached, i.e. the properties of the process water no longer changed.

Table 33. Characteristics of the process waters used for diluting the feed mixture in the centralized biogas plant (capacity 200 000 t/y). Process water originates from the digestate processing. TS = total solids, VS = volatile solids.

	TS (%)	VS (%)	Ntot (g/kg)	NH_4-N (g/kg)	Ptot (g/kg)
Centralized plant, advanced practices	0.07	0.07	0.03	0.03	0.00
Centralized plant, conventional practices	4.38	3.09	7.32	4.39	0.17

Based on the feed materials of the example plants (Table 32), the methane production potential of each plant was also calculated. However, the potential describes the result that can be achieved under optimal conditions and does not fully correspond to the biogas production of a continuously operating reactors. The achievable methane yield was modeled using a simple mathematical formula presented in the literature, which has originally been applied to materials of animal origin, such as in digestion of manure (Chen & Hashimoto 1978; Hill 1983). In the model, the amount of organic matter in the feed materials affects the actual methane production, feeding speed and plant retention time. The longer the retention time is, the better the organic matter decomposes, and a greater share of the methane production potential can be achieved. The modeling looked for differences between different retention times so that the importance of different practices for methane production could be compared. However, the modeling did not consider feed materials separately, but the calculation was simplified by using the same formulas and coefficients for all feed materials in the calculation of the growth rate and kinetic parameter.

The speed of methane production G ($m^3_{CH4}/d/m^3$) was calculated with the following formula:

(Formula 1) $G= B_0*L*(1-K/(\mu_m*\theta-1+K))$,

where B_0 *= methane production potential* (m^3/t_{VS})

L *= organic loading rate* (kg_{VS}/m^3d)

K *= kinetic parameter*

μ_m *= maximum growth rate*

θ *= retention time (days)*

Maximum growth rate of the microbes was based on the formula previously reported in literature $\mu_m = 0.013*T-0.129$, where T is temperature as Celsius degrees (35 °C) (Hashimoto et al. 1981). The growth rate is therefore 0.326.

The kinetic parameter (K) was calculated using the following formula for wet digestion processes (2: farm-scale and farm cooperative plants; 3: centralized plant) and for dry digestion process (4).

(Formula 2) $K=2+(0.0016)^{(0.06*S)}$

(Formula 3) $K=1+(0.0016)^{(0.06*S)}$

(Formula 4) $K=0.88+(0.0016)^{(0.06*S)}$

where S *= feed of organic matter* ($kgVS/m^3$)

The daily methane production (m^3_{CH4}/d) of each plant was calculated by multiplying methane production rate G ($m^3_{CH4}/d/m^3$) with the liquid volume of the reactor (m^3). The realized methane production (%) was then calculated by dividing the daily methane production (m^3_{CH4}/d) with daily methane production potential (m^3_{CH4}/d). Daily methane production potential was obtained by dividing the methane production potentials of the feed mixture (m^3_{CH4}/t_{VS}) with the amount of organic matter fed to the reactor daily ($kg_{VS}/m^3/d$).

The amount of mass converted from feed materials to biogas and the amounts of dry matter and organic matter were calculated using the density of methane and carbon dioxide (0.72 and 1.96 kg/m^3, NTP conditions) and the assumed biogas composition (56 % CH_4, 44 % CO_2). The mass of the digestate was calculated as the difference between the total amount of feed materials and the amount of mass going into biogas.

In the calculation of the nutrient balances, it was assumed that the total nutrients of the feed materials are fully preserved in the digestate. The solubilization of nitrogen originally bound to organic matter during the biogas process was calculated by considering the degradation of organic matter. It was assumed that the solubilization of nitrogen follows the degradation of organic matter. For the farm-scale plant fed mostly with cattle slurry, the value 0.73 was used as the ratio of organic nitrogen to organic matter degradation (Frost & Gilkinson 2011), while the ratio for the farm cooperative plant and centralized plant fed mostly with pig slurry was set to 0.63 based on the organic matter of pig slurry to degradation (Marcato et al. 2008). For the grass-based dry digester, the value was set to 0.60 based on Luke's previous experiments.

In the calculation of the mass and nutrient balances of the further processing of the digestate, separation efficiencies based on the literature were used (summarized in Table 34). Separation efficiency means the proportion of the original biomass that is transferred to the product. During thermal drying of the solid fraction, the separation of biomass and dry matter was calculated by assuming that the dry matter content of the dried fraction is 90 %, in which case it corresponds to the instructions of the Finnish Food Authority on the processing of productized manure (Finnish Food Authority 2019). The digestate processing chain of the centralized plant also included pelleting of the dried fraction, but that is not supposed to affect the mass or nutrient balance of the fraction.

Table 34. Separation efficiencies of the digestate processing technologies. The separation efficiency of the screw press was based on literature (Møller et al. 2000; Frost & Gilkinson 2011; Hjort et al. 2010; Luostarinen et al. 2011) and additionally on Pyykkönen (2019) for digestate from cattle slurry and on Paavola et al. (2016) for digestate from pig slurry. The separation efficiencies of the centrifuge and evaporation were based on a previous literature review (Tampio et al. 2016). The separation efficiency on thermal drying was based on the information from equipment suppliers.

		Separation efficiency, % of original material					
Plant	**Technology**	**Mass**	**TS**	**VS**	**Ntot**	**NH_4-N**	**Ptot**
Farm-scale	Screw press (in solid fraction)	10	35	35	10	4	22
Farm co-operative	Screw press (in solid fraction)	5	28	28	8	4	14
Centralized	Centrifuge (in solid fraction)[1]	17	70	70	25	15	90
	Centrifuge (in solid fraction)[2]	20	65	65	25	15	90
	Evaporation (in concentrate)	20	98	97	-	0	100
	NH_4-N stripping (in ammonium sulfate)	3	0	0	-	99	0
	Thermal drying (in dry fraction)	-	-	98	-	5	100
	Offgas treatment (in ammonium sulfate)	-	-	-	-	98	-

[1] Advanced practices
[2] Conventional practices

Ammonia recovery in connection with both the evaporation process and thermal drying consumes sulfuric acid, whereby ammonia is recovered as ammonium sulfate. The consumption of sulfuric acid (93 %) was calculated in relation to the molar masses of sulfuric acid and ammonium sulfate.

Methane leaks were considered in the balance calculation in such a way that leaks during the process, leaks from pressure release valves (PRV) and emissions from maintenance were subtracted from the amount of biogas produced. In addition, the methane loss of the process was considered in the production of transportation fuel. With regard to CHP units or transportation fuel production, methane loss was not considered as such in the balance calculation but was assumed to be included in the efficiency ratio of the technologies. CHP unit and traffic fuel methane losses according to table 35 were included in the life cycle assessment.

Table 35. Maximum and minimum values for methane emission in the different phases of the biogas production chains in the example biogas plants using advanced and conventional practices (PVR = pressure release valves, TF = transportation fuel).

	Conventional (% of CH_4 produced)	Advanced (% of CH_4 produced)
Farm-scale plant		
Emissions during the process	0.5–2	0.1–0.3
PRV	2–3	0.5–1
Maintenance	1–2	0.1–0.5
CHP	1.5–3	0.1–1
Total	**5–10**	**0.8–2.8**
Farm cooperative plant		
Emissions during the process	0.4–1.5	0.1–0.3
PRV	2–3	0.5–1
Maintenance	1–2	0.1–0.5
CHP	1.5–3	0.1–1
Total	**4.9–9.5**	**0.8–2.8**
Centralized plant		
Emissions during the process	0.31	0.1–0.2
PRV	2–3	0.5–1
Maintenance	1–2	0.1–0.5
TF	1–3	0.1–0.8
Total (TF)	**4.3–9**	**0.8–2.5**
Dry digestion plant		
Emissions during the process	0.5–2	0.1–0.3
PRV	2–3	0.5–1

	Conventional (% of CH_4 produced)	Advanced (% of CH_4 produced)
Maintenance	1–2	0.1–0.5
Emptying the reactor silo(s)	4–5	2–3
CHP	1.5–3	0.1–1
Total	**9–15**	**2.8–5.8**

Calculation of energy balances

Methane gas was converted to kilowatt hours with 1 $m^3 CH_4$ = 9,97 kWh.

In calculating the energy consumption of the example plants, the energy needed for heating and the electricity consumption in the different phases of the biogas production chain were considered. The heat energy requirement of the biogas process was estimated in wet digestion plants using the energy used to heat the feed (Tampio et al. 2016, formula 5), while in the dry digestion plant the heat consumption was calculated using a coefficient (Table 36). According to the calculations, the mass was heated slightly above the target temperature (in the reactor approximately 37 °C, hygienization 70 °C), and thus the temperature was assumed to remain at the target during the treatment.

The heat demand of wet digestion was calculated using the specific heat capacity of water (formula 5).

(Formula 5) $\Delta E = c \times m \times \Delta t$,

where ΔE = *energy demand for heating*

c = specific heat capacity of a substance (kJ/kg°C) (c_{vesi} = *4,18 kJ/kg °C)*

m = mass (kg)

Δt = *temperature change (°C)*

Temperature change (*Δt)* was assumed to be 12 –> 40 °C in those plants that did not include hygienization of the feed materials (farm-scale plant, farm cooperative plant). Based on previous studies (e.g. Tampio et al. 2020, Tampio et al. 2016) and literature (Smyth 2009, Rapport 2011), the amount of heat loss in wet digestion processes was assumed to be 15 % of the heating need, while in dry digestion, the proportion of heat loss was assumed to be smaller (5 %), in which case the losses would mainly occur in the percolate liquid tank.

In the centralized plant, the hygienization of the feed materials was also included. The heating demand required by hygienization was calculated as above, but the temperature change was calculated from 12 to 72 °C. No separate heating need was considered for the recycled process water, but the heat from the hygienization was assumed to be sufficient for heating the process water as well. The use of heat exchangers and their effect on the heat balance were not considered.

The electricity consumption of the different phases of the biogas production chain and the heat consumption of the further processing of the digestate were based on the literature and the coefficients used are summarized in table 36.

Table 36. The data used in calculating the energy consumption of the example biogas plants.

Phase	Value	Unit or definition	Reference
Reactor electricity consumption, small plant (wet digestion))	1.3	% of biogas produced	Pöschl et al. 2010
Reactor heat consumption, small plant (wet digestion)	Calculated using specific heat capacity of water	Temp. change 12–> 40 °C	
Reactor electricity consumption, large plant (wet digestion)	3	% of biogas produced	Pöschl et al. 2010
Hygienization heat consumption, large plant (wet digestion)	Calculated using specific heat capacity of water	Temp. change 12–> 70 °C	
Reactor electricity consumption, small plant (dry digestion)	1	kW/1 000 m^3	Background data for Biokaasulaskuri (2021)
Reactor heat consumption, small plant (dry digestion)	0.4	kWh/d/m^3 reactor volume	
Electricity consumption of hygienization and other pre-treatment (maceration, mixing)	150	kWh/tTS	Pöschl et al. 2010
Electricity consumption of screw-press	0.6	kWh/t of digestate	Chuda & Ziemiński 2021, Pyykkönen & Ervasti 2019

Phase	Value	Unit or definition	Reference
Electricity consumption of decanter centrifuge	3	kWh/t of digestate	Chuda & Ziemiński 2022, Duan et al. 2020
Electricity consumption of evaporation	25	kWh/t of material	Vondra et al. 2019
Heat consumption of evaporation	The chosen technology does not consume heat		
Electricity consumption of thermal drying	0.0375	kWh/kg of water	Huber Technology 2022
Heat consumption of thermal drying	0.8	kWh/kg of water	Awiszus et al. 2018, Huber Technology 2022
Electricity consumption of N recovery (drying)	2.5	kWh/kgNH$_3$	Hadlocon et al. 2015, Havukainen et al. 2022
Electricity consumption of pelletizing	0.1	kWh/kg	Czekała 2021, Kratzeisen et al. 2010, Cathcart et al. 2021
Consumption of biogas upgrading (pressurization and upgrading)	0.45	m_3/m_3 biogas	Biomethane Regions 2012

In the calculation of the energy production of the example plants, the efficiency rates of the energy production forms were considered according to table 37. In the production of transportation fuel, the effect of methane leaks during process on the amount of transportation fuel produced was taken into account (see Table 35).

Table 37. Efficiency rates of CHP and biogas upgrading to biomethane.

Phase	Efficiency rate	Unit	Reference
CHP, electricity [1]	32	%	IET Energy 2021
CHP, heat [1]	52	%	
CHP, electricity [2]	37	%	
CHP, heat [2]	49	%	

[1] Plants with <30 m^3/h of biogas –> farm-scale plant, dry digestion plant
[2] Plants with >30 m^3/h of biogas –> farm cooperative plant, centralized plant

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Appendix 2. Emission calculation according to Renewable Energy Directive

Emissions and emission reductions were calculated for the centralized example biogas plant in accordance with advanced and conventional practices, primarily using the phase-specific emissions obtained from the LCA calculation carried out in the project. The emission credit obtained from better handling of manure was then deducted from the emissions (calculation 1). The emission reduction for manure was calculated considering the manure's methane production potential and dry matter content (formulas 1 and 2 below).

Calculating the emission credit for manure:

1. $e_{sca} = \frac{L_h}{P_n * \frac{BMPachieved}{100}}$

where e_{sca} [gCO_2eq/MJ] is manure bonus for substrate n, L_h is a coefficient for good manure management practices defined in the Renewable Energy Directive (-54.06 $kgCO_2eq/t_{ww}$), P_n is energy production from substrate n [MJ/kg_{ww}] and $BMP_{achieved}$ is the realized share of the methane production potential (in this study, 90 % with advanced and 78 % with conventional practices).

Calculating the energy production from substrate (feed material):

2. $P_n = BMP * VS * LHV_{biogas}$

where BMP is methane production potential of substrate n [m^3_{biogas}/kg_{VS}], VS is the amount of organic matter [kg_{VS}/kg_{ww}] and LHV_{biogas} is the lower heating value of biogas (18.30 MJ/m^3_{biogas}; JRC 2017).

The calculation was also made using the default values of the Renewable Energy Directive. Since the default values are given only for slurry, maize and biowaste, two different calculations were made. In the first one, default values were used only for pig slurry (default value of wet manure) and the side stream of the food industry (default value of biowaste), while for the other feed materials, the emission data obtained from the present LCA calculation were used (calculation 2). We additionally wanted to see if the default values can be used more widely for different feed materials (calculation 3). Thus, both the default value of slurry and the manure credits from the Directive were used for all manures (pig slurry, solid fraction of cattle manure, solid fraction of pig manure, and poultry manure) considering the different dry matter contents of the different manures. Similarly, the default value of biowaste was used for the food industry by-products and default value of maize for fallow grasses with the difference that the emissions during maize cultivation were replaced by Luke's earlier calculation (Rasi et al. 2019) considering only the emissions from collecting and transporting the grass to the biogas plant (Table 38). Emissions from the transportation of upgraded biomethane were not taken into account, as the biomethane fueling station was assumed to be located in connection with the biogas plant.

Table 38. Default values used in the emission calculation according to the Renewable Energy Directive [gCO_2eq/MJ] (EU 2018). Phase of production; 1) cultivation, 2) processing, 3) biogas upgrading, 4) biomethane pressurization.

Covered storage, treatment of offgas from biogas upgrading

Feed	1	2	3	4	Manure credit
Slurry	0.0	4.4	6.3	4.6	-111.9
Maize	7.6*	6.0	6.3	4.6	-
Biowaste	0.0	7.2	6.3	4.6	-

Open storage, no treatment of offgas from biogas upgrading

Feed	1	2	3	4	Manure credit
Slurry	0.0	117.9	27.3	4.6	-124.4
Maize	8.6*	28.1	27.3	4.6	-
Biowaste	0.0	42.8	27.3	4.6	-

*Emission of fallow grasses Rasi et al. 2019

In all calculations presented above, the distribution of emissions and credits for different feed materials was calculated according to their energy content, in accordance with the Finnish Energy Authority's sustainability criteria guidelines for operators regarding biofuels, bioliquids and biomass fuels (Energy Authority 2022). The weight factor of the substrate for solid manure and grass (Wn) was calculated by assuming that the annual average moisture content (AMn) of the substrate n (calculated from dry matter, Table

1.1, Appendix 1) is the same as the standard moisture content (SMn) of the substrate n, because the standard moisture content is given in the guidelines of the Directive only for wet manure, maize and biowaste.

The calculated emissions were compared to the fossil fuel emission of 94 gCO_2eq/MJ given in the Directive. According to the Directive, produced transportation fuel is renewable if the emission reduction compared to fossil transport fuel is more than 65 %.

References:

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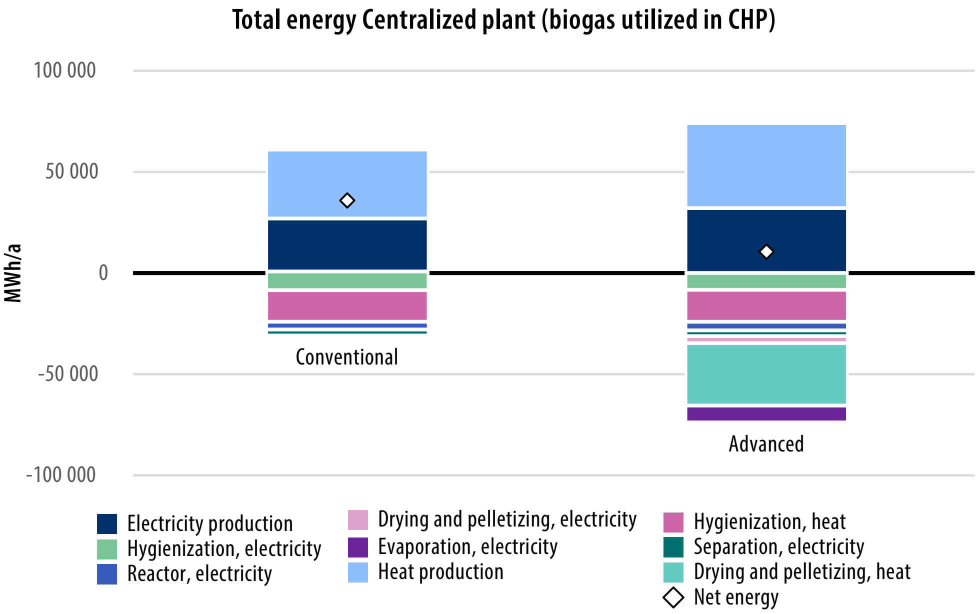
Appendix 3. The energy balance of centralized wet digestion plant when producing electricity and heat

For the LCA calculation, the energy balance of the centralized example plant was also calculated in a situation where the plant converts all the biogas it produces into electricity and heat with the help of a CHP unit. The plant covers its own energy demand from the heat and electricity produced. Chapter 6 presents a situation where the biogas produced by the plant is upgraded into biomethane for transportation.

If the centralized plant directs all the biogas it produces to the CHP unit, the efficiency of the CHP production affects the amount of electricity and heat energy produced. However, the efficiency rate is weaker compared to the production of transportation fuel, which is why the total energy production of a CHP is lower (70 400 MWh/year) than when the same amount of biogas is upgraded to transportation fuel (81 800 MWh/year). As in the case of transportation fuel production (see Chapter 6), also in CHP production using advanced practices, the energy consumption is higher than the consumption according to conventional practices due to the further processing of the digestate. However, when electricity and heat production are added together, the net energy balance is positive, in which case the plant produces more energy than it uses in its own processing chain (Figure 28).

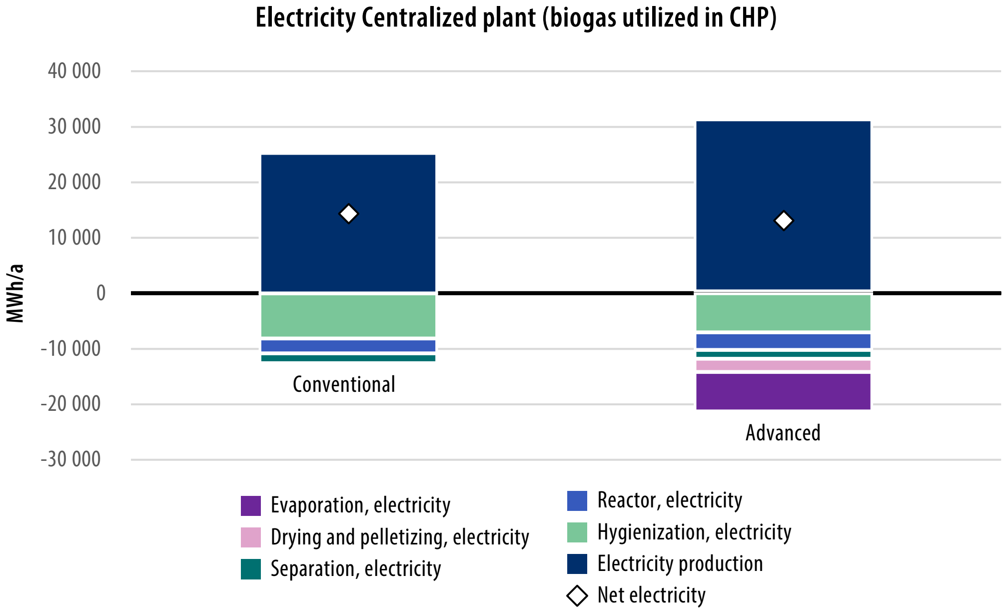
Figure 28. Energy balance of the centralized biogas plant when the biogas produced is used for electricity and heat production by a CHP.

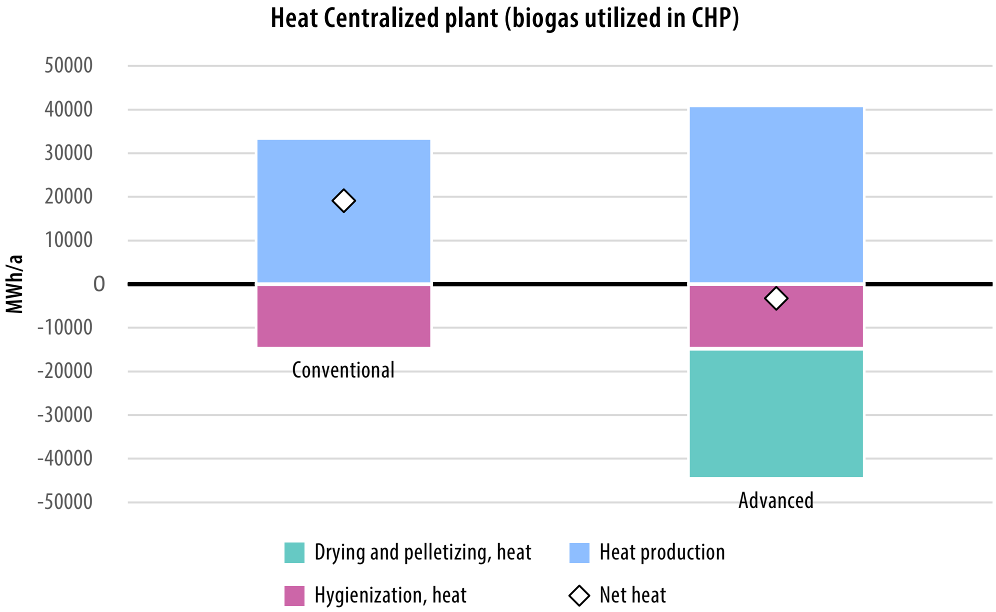


When the production and consumption of electricity and heat are examined more closely (Figure 29), the difference between electricity production and consumption (the so-called net electricity production) is positive, while the net heat balance is negative. The plant's heat consumption is high due to the thermal energy required for the further processing of the digestate, which is why the plant is not able to fully cover the demand with its own heat production. In practice, the plant then buys thermal energy from outside.

In this example, thermal drying, which utilizes thermal energy, was chosen for processing the digestate. However, there are also electricity-based drying methods on the market, in which case the plant's heat demand would decrease. Correspondingly, however, this would increase the plant's electricity demand. The heat balance of the plant can also be affected by the use of heat exchangers, which was not taken into account in this calculation example.

Figure 29. Electricity and heat production and consumption in the centralized example plant with a CHP.





Appendix 4. Life-cycle phases and background data used in the LCA calculation

In this appendix, the initial data and assumptions used in the LCA calculation are described in their main features by life cycle phase. Exact descriptions of example plants, characteristics of feed materials, biogas production, and assumptions related to plant practices are presented in detail in Chapter 6.1 and in Appendix 1.

Biogas process and biogas use

Methane leaks and emissions from biogas plants were assessed based on the literature review (Chapter 2) and expert assessments. To illustrate the variation in methane leaks and emissions, ranges were determined that consider different plant types and variation in practices. Methane leaks and emissions during the process were considered to reduce the amount of biogas produced in the balance calculation (Chapter 7.2.1). In addition, the emissions caused by dry digestion during the emptying phase of the silo were considered. The emission ranges used in the calculation for plant examples are presented in Appendix 1 (Table 35).

Utilization of biogas in combined electricity and heat production (CHP) produces methane and nitrous oxide emissions (Chapter 2.2). The upgrading and pressurization to produce transportation fuel also creates methane losses, but no nitrous oxide emissions. The minimum and maximum values presented in the literature review were used in the LCA calculation. The default values used for methane emissions related to gas utilization are shown by example plants in table 35 of Appendix 1. In CHP production, nitrous oxide emissions were assumed to be 0.002 g/kWh with advanced practices due to the low ammonia content of the gas and 0.345 g/kWh with conventional practices due to the high ammonia content (Liebetrau et al. 2013).

Digestate processing

The energy consumption of digestate processing, i.e. separation and possible further processing (drying and evaporation), was estimated according to the balance calculations made for the example plants (Chapter 6.2.1, Appendix 1). The polymers used in the separation and the sulfuric acid used in the further processing were included in accordance with Appendix 1. In addition, ammonia emissions from further processing were considered in the calculation, reducing the soluble nitrogen that ends up in the final product. Methane and nitrous oxide emissions were not included in the further processing of the digestate fractions of the centralized facility due to the lack of measurement and research data.

Storage and spreading of digestate and the processed fractions from it

The methane emissions resulting from the storage of the digestate, and the fractions separated and processed from it were estimated considering the retention time of the feed materials in the process and its effect on the remaining methane production potential of the digestate. In the calculation, it was assumed that in biogas plants with a shorter retention time, the digestate has more carbon that evaporates more easily as methane than in the more stable, digestate from processes with longer retention time. The actual emission factors were derived from the methane production potential of the digestate and from the calculation formula of IPCC (2019) so that the magnitude of the emissions corresponds to the range found in the literature review (Chapter 2). However, the differences in storage practices were not considered due to the lack of research data regarding methane emissions, but the same methane emissions were assumed to occur regardless of the chosen storage practice. Thus, in the farm-scale example plant (wet digestion), it was assumed that 1–4 % of the methane produced at the plant is released as methane in storage, while the assumptions for the other example plants were 2–10 % for the farm cooperative plant, 2–8 % for the centralized plant, and 4–13 % for the dry digestion plant.

Direct and indirect nitrous oxide emissions formed during the storage and spreading of digestate, and fractions processed from it were calculated based on the international calculation guidelines for manure and the Finnish calculation model (IPCC 2006, EMEP/EEA 2019, Grönroos et al. 2017). The spreading practices assumed in the calculation are shown in table 39.

Table 39. Field spreading practices in the example biogas plants.

	Conventional practices	Advanced practices
Farm-scale wet digestion plant	Digestate band spreading, mulching >12 h	Solid fraction broadcast spreading, mulching <4 h Liquid fraction injection
Farm cooperative wet digestion plant	Digestate band spreading, mulching >12 h	Solid fraction broadcast spreading, mulching <4 h Liquid fraction injection
Centralized wet digestion plant	Solid fraction broadcast spreading, mulching >12 h Liquid fraction band spreading, mulching >12 h	Dried fraction broadcast spreading, mulching <4 h Concentrated fraction (ammonium sulfate, nutrient concentrate) injection

	Conventional practices	Advanced practices
Dry digestion plant	Digestate broadcast spreading, mulching >12 h	Digestate broadcast spreading, mulching <4 h

Substitutions

The substitution impacts (substitution of mineral fertilizers) were calculated for the nitrogen and phosphorus contained in the digestate of the biogas plant, fully taking into account the nitrogen losses during the storage of the digestate. The emission factor for the production of mineral phosphorus was based on the ecoinvent database (ecoinvent v3) and the factor for the production of mineral nitrogen was based on literature (Brentrup et al. 2016). When replacing the mineral nitrogen fertilizer, only the proportion of soluble nitrogen that ends up in the field in the digestate or the processed fractions from it considered. In addition, the avoided nitrous oxide emissions from the application of mineral fertilizers were considered (IPCC 2006, EMEP/EEA 2019; Grönroos et al. 2017).

The energy produced by the example plants was assumed to replace either electricity and heat or transportation fuel (see plant descriptions, Chapter 6.1). The emission coefficients for consumed electricity and heat were taken from the A-Las model developed for municipal road emission calculation by the Finnish Environment Institute for 2018 (Lounasheimo et al. 2020). The heat emission coefficient was an average calculated for the regions of North Ostrobothnia, South Ostrobothnia, and Southwest Finland. In the replacement of transportation fuel, the ratio of fossil fuels (diesel, motor gasoline, natural gas) in road traffic energy consumption for the years 2018–2020 (Tilastokeskus 2022b), the emission coefficients set for them in the fuel classification (Tilastokeskus 2022a), and the emissions caused by the manufacture of fuels (ecoinvent v3) were considered.

Calculation assumptions for the reference cases (without biogas plants)

When assessing the climate impact, it was assumed that in the reference cases (no biogas plant for the processing of feed materials) the slurry storage has a floating cover, and the solid manure storage is uncovered. Solid manures are spread on the field with broadcast spreading and slurry with band spreading. It was assumed that grass silage formed as a surplus or otherwise unfit for feeding animals would end up being spread on fields after composting. The grasses from fallows were supposed to be composted. The side stream from food processing was assumed to end up in vessel composting and then be used for landscaping.

Composting considered the gaseous emissions caused by the decomposition of materials, machine work, and support materials. Gaseous emissions released during manure storage and composting of the side stream from food processing were estimated in accordance with the national greenhouse gas inventory (Statistics Finland 2021, IPCC 2006). The assessment of ammonia emissions from composting was based on the literature review carried out when building a tool for planning nutrient recycling in Finland (Luostarinen et al. 2019). The composting of grass silage and grass for fallows is not considered in the national greenhouse gas inventory, so the resulting methane and nitrous oxide emissions were estimated using literature (Zhu-Barker et al. 2017). The duration of composting was estimated to be 3 months. The needed machine work and the amount of support materials and greenhouse gas emissions were estimated based on the publications of Lehtoranta et al. (2020) and Manninen et al. (2016).

The nitrogen contained in the biomass was assumed to evaporate in connection with soil application as nitrous oxide 1 % in accordance with the IPCC (2006) calculation guidelines. Substitution impacts for manure nutrients were calculated in the same way as for digestate. Substitution impacts were not calculated for the nutrients contained in grass silage, grasses from fallows, and the side stream from food processing in the reference cases.

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Appendix 5. Greenhouse gas emissions and emission reduction per process phase in the emission calculation according to the Renewable Energy Directive

Table 40. Greenhouse gas emissions and emission reductions [gCO_2eq/MJ] divided to different feed materials according to their energy content. Emission data from the LCA calculation made in the present project (calculation 1). Phase of production; 1) cultivation, 2) processing, 3) biogas upgrading, 4) biomethane pressurization.

Advanced practices

Feed material	1	2	3	4	Manure credits
Pig slurry	0.00	4.72	0.19	0.17	-27.65
Solid fraction separated from cattle manure	0.00	0.00	0.63	0.03	0.02
Solid fraction separated from pig slurry	0.00	0.00	3.28	0.13	0.12
Poultry manure	0.00	0.00	7.84	0.32	0.28
Grass from fallows	0.68	0.68	2.28	0.09	0.08
Side stream from food processing	0.00	0.00	6.77	0.27	0.24
Total	**0.68**	**0.68**	**25.52**	**1.03**	**0.91**

Conventional practices

Feed material	1	2	3	4	Manure credits
Pig slurry	0.00	15.96	1.52	1.35	-31.91
Solid fraction separated from cattle manure	0.00	2.14	0.20	0.18	-4.31
Solid fraction separated from pig slurry	0.00	11.10	1.06	0.94	-8.62
Poultry manure	0.00	26.53	2.53	2.24	-12.93
Grass from fallows	0.77	7.72	0.74	0.65	
Side stream from food processing	0.00	22.90	2.18	1.94	
Total	**0.77**	**86.35**	**8.24**	**7.30**	**-57.77**

Table 41. Greenhouse gas emissions and emission reductions [gCO_2eq/MJ] divided to different feed materials according to their energy content. Emission data for slurry and side stream from food processing from Renewable Energy Directive (default values) and for other feed materials data from the LCA calculation made in the present project (calculation 2). Phase of production; 1) cultivation, 2) processing, 3) biogas upgrading, 4) biomethane pressurization.

Advanced practices

Feed material	1	2	3	4	Manure credits
Pig slurry	0.00	0.81	1.16	0.85	-20.68
Solid fraction separated from cattle manure	0.00	0.63	0.03	0.02	-3.74
Solid fraction separated from pig slurry	0.00	3.28	0.13	0.12	-7.47
Poultry manure	0.00	7.84	0.32	0.28	-11.21
Grass from fallows	0.68	2.28	0.09	0.08	0.00
Side stream from food processing	0.00	1.91	1.67	1.22	0.00
Total	**0.68**	**16.76**	**3.40**	**2.57**	**-43.10**

Conventional practices

Feed material	1	2	3	4	Manure credits
Pig slurry	0.00	21.79	5.05	0.85	-22.99
Solid fraction separated from cattle manure	0.00	2.14	0.20	0.18	-4.31
Solid fraction separated from pig slurry	0.00	11.10	1.06	0.94	-8.62
Poultry manure	0.00	26.53	2.53	2.24	-12.93
Grass from fallows	0.77	7.72	0.74	0.65	0.00
Side stream from food processing	0.00	11.35	7.24	1.22	0.00
Total	**0.77**	**80.63**	**16.82**	**6.09**	**-48.86**

Table 42. Greenhouse gas emissions and emission reductions [gC0_2eq/MJ] divided to different feed materials according to their energy content. Emission data from Renewable Energy Directive (default values) (calculation 3)). Phase of production; 1) cultivation, 2) processing, 3) biogas upgrading, 4) biomethane pressurization.

Advanced practices

Feed material	1	2	3	4	Manure credits
Pig slurry	0.00	0.81	1.16	0.85	-20.68
Solid fraction separated from cattle manure	0.00	0.11	0.16	0.11	-2.77
Solid fraction separated from pig slurry	0.00	0.57	0.81	0.59	-14.38
Poultry manure	0.00	1.35	1.94	1.41	-34.38
Grass from fallows	0.68	0.54	0.56	0.41	0.00
Side stream from food processing	0.00	1.91	1.67	1.22	0.00
Total	**0.68**	**5.29**	**6.30**	**4.60**	**-72.22**

Conventional practices

Feed material	1	2	3	4	Manure credits
Pig slurry	0.00	21.79	5.05	0.85	-22.99
Solid fraction separated from cattle manure	0.00	2.92	0.68	0.11	-3.08
Solid fraction separated from pig slurry	0.00	15.16	3.51	0.59	-15.99
Poultry manure	0.00	36.23	8.39	1.41	-38.22
Grass from fallows	0.77	2.51	2.44	0.41	0.00
Side stream from food processing	0.00	11.35	7.24	1.22	0.00
Total	**0.77**	**89.96**	**27.30**	**4.60**	**-80.29**

Appendix 6. Assumptions and methods for economic assessment

Price of energy and nitrogen

The price of electricity when selling it or using it on the plant (farm-scale and farm cooperative plants) and when buying it for the centralized plant was estimated at 0.12 euro/kWh and the price of heat at 0.07 euro/kWh VAT 0 %. The selling price of biomethane from the biogas plant's own filling station was assumed to be 0.1045 euro/kWh VAT 0 %, which as pure methane corresponds to the price of 1.45 euro/kg VAT 0 % and 1.8 euro/kg VAT 24 % (Mustankorkea 2023). The price of the nitrogen solubilized in the biogas process was estimated to be 2.35 euro/kg VAT 0 % (Rasi et al. 2022).

Calculation of logistic costs

Logistic costs were only considered for the centralized plant, where the transport distance of feed materials to the plant was assumed to be 20 km, and the transport distance of sludge-like digestate and liquid fertilizer products from the plant was 25 km and of solid fertilizer products 125 km. The loading and unloading times were estimated to be the same for all materials: sludge-like and solid feed materials as well as digestate and fertilizer products, a total of 0.25 h/truck load (32 m^3). The hourly cost of the truck for loading, unloading, and driving was 85 euro/h VAT 0 %. The driving speed of the truck was assumed to be 60 km/h. The return journey is taken into account in the driving time of the truck, i.e. the transport distance was multiplied by two (Mäkelä 2021). During transport, the density of sludge-like/liquid materials was assumed to be 1 000 kg/m^3, and the density of solid materials to be 500 kg/m^3.

Other costs and gate fee

The production cost of grass silage was assumed to be 20 euro/fresh ton (Rasi et al. 2022). No production cost was calculated for manure and grass from fallows. For all example plants, the daily working time was assumed to be 0.5 h/day (incl. daily inspections and minor repairs) and the employee's salary was 21 euro/h. At wet digestion plants, the price of loading solid feed into the crushing device was estimated at 2 euro/t. At the dry digestion plant, the cost of loading the feed into the reactor silo and the cost of removing the digestate from the silo was estimated at a total of 4 euro/t of feed material. The price of the insurance was assumed to be 0.5 % of the biogas plant's unsubsidized investment price cost per year (Hahn 2011). In dry digestion, the advanced practices had an additional cost of covering the piled digestate, estimated at 500 euro/year. The income of centralized biogas plants as a gate fee from the side stream from food processing was assumed to be 50 euro/t (Luostarinen et al. 2019).

Volumes of feed and digestate storages

In the farm-scale plants (wet and dry digestion), the volumes of the digestate storage were calculated in accordance with the manure storage requirement of 12 months, except for the advanced practice of the dry digestion plant, where only one third of the digestate produced was assumed to be stored (the remaining 2/3 directly spread on fields). In the farm cooperative and centralized biogas plants, it was assumed that the slurry feed storages are sized for a volume corresponding to three days' feed (the so-called buffer storage). The volume of storage tanks for liquid fractions processed from digestate and fertilizer products (separated liquid fraction, ammonium sulfate, nutrient concentrate) was assumed to be for an amount produced during seven days (then transported away from plant), and the volume of solid fertilizer products (separated solid fraction, dried solid fraction) was assumed to be a volume corresponding to 30 days' yield. In wet digestion, solid feed materials were assumed to be delivered directly to the feeder, so no storage volumes were calculated for them. The centralized plant using advanced practices required two storage tanks for separated liquid fraction, and separate tanks for ammonium sulfate and nutrient concentrate. In the calculation of the storage volume, the density of sludge-like/liquid materials were assumed to be 1 000 kg/m^3 and the density of solid materials to be 500 kg/m^3.

The volumes of the hygienization units of the centralized plant were calculated by dividing the volume of the yearly feed materials to be hygienized (m^3) by 365, i.e. it was assumed that only one "batch" is hygienized per day (it was assumed that the density of the material to be sanitized is 500 kg/m^3). The duration of one hygienized batch is 3 hours, so theoretically a maximum of 8 batches could be run per day.

Investment costs, lifetime and maintenance costs of wet digestion plants

The formulas for calculating the investment costs of various parts and equipment of wet digestion plants, as well as their lifetimes and basis for calculating their maintenance costs are presented in Table 43. For most parts of the plants, the maintenance costs are estimated as a percentage of the unsubsidized investment cost per year (% inv./year). The maintenance cost of the CHP unit is estimated per kilowatt hour of electricity produced. The maintenance costs of the decanter centrifuge, the evaporation equipment, the thermal drying equipment, and the ammonia scrubber of the centralized plants are stated in euros per ton of processed material in accordance with discussions with industry operators. The maintenance costs do not include the energy consumption of the equipment (consumptions indicated in Appendix 1, Table 36).

Table 43. Formulas for calculating investment costs of wet digestion plants, estimated lifetimes (LT) and the basis for calculating the maintenance costs (MC). V_R = reactor process volume (m^3). V_S = storage tank volume (m^3).

Part/device	Cost formula (€)	Ref.	LT (years)	MC
Reactor structures (incl. base slab)	$=84.55125*V_R+80{,}599.05$	1	20	1 % inv./y
Reactor mixer(s)	$=13.2132*V_R+7\ 150.185$, reactor-specific	1	10	5 % inv./y
Slurry feeding pump	=10 500 (constant). 1 /reactor	1	10	5 % inv./y
Digestate removal pump	=10 500 (constant). 1 /reactor	1	10	5 % inv./y
Other process technology	=56 600 (constant)	1	10	5 % inv./y
Other structures (technical spaces, pipelines, condensation wells)	$=3.34257*V_R+38\ 007.9$	1	20	1 % inv./y
Solid feeding device (TMR mixer and feeding into reactor)	=3.2051*F+40 313. where F is feed quantity (t/a)	1	15	5 % inv./y
Gas boiler	=20 000 (constant, in reserve at each plant)	1	20	2 % inv./y
Boiler, pipelines and automation	=46 000 (constant)	1	20	2 % inv./y
CHP-unit + gas blasting, activated carbon & removal of condensed water	$=2\ 388.225*e^{(-0.003*P)}*P+45\ 950$, where P is electric power (kW_{el})	1	10	1.8 €-cnt/kWh_{el}
Installation and deployment of the above mentioned	$=10.282125*V_R+71\ 452.5$	1	20	-
Designing and project lead	$=5.95371*V_R+41\ 373.15$	1	20	-
Flare	=10 000 (constant)	Estimate	20	-
Other (traveling, wreight, financial expense of plant designer et cetera)	$=1.011045*V_R+20\ 887.65$	1	20	-
Slurry feed storage with membrane cover, incl. installation	$=26.491*V_S+28\ 273+14.45*V_S+5\ 876.1$	1	20	1 % inv./y

Part/device	Cost formula (€)	Ref.	LT (years)	MC
Mixer of slurry feed storage, incl. installation	=6 000 (constant)	2	10	5 % inv./y
Uncovered storage tank, incl. installation	=26.491*V_S+28273	1	20	1 % inv./y
Tent cover of storage tanks, incl. installation	see: next chapter	3	20	1 % inv./y
Floating cover of storage tanks	=21 €/m^2 (only farm cooperative plant with advanced practices)	4	10	1 % inv./y
Mixer for storage tanks, incl. installation	=6 000 €/tank	2	20	5 % inv./y
Uncovered storage for solid fraction, incl. installation	=43.863*V_S+10435	1	20	1 % inv./y
Covered storage for solid fraction, incl. installation	=87.727*V_S+20870	1	20	1 % inv./y
Gas upgrading + pressurizing (250 bar) unit, incl. installation	=2 720.5*X+114 812, where X is the hourly flow of purified raw biogas (m^3/h)	5	20	3 % inv./y
Fueling station next to upgrading, incl. installation	=150 000 €/pc (centralized plant with advanced technology 6 pc, with conventional practices 5 pc)	6	20	3 % inv./y
Earthmoving	=45 €/m^2	1	20	-
Electrical connection to grid	=10 000 (constant)	Estimate	20	-
Hygienization unit	=2 680.2*V_S+44113	7	15	5 % inv./y
Screw press	=50 000 (farm-scale, advanced); 75 000 (farm cooperative, advanced)	Estimate	12	5 % inv./y
Decanter centrifuge	=600 000 (centralized)	8	12	2.46 €/t
Evaporation of liquid fraction	=4 600 000 (centralized, advanced)	8	15	2.85 €/t
Thermal drying of solid fraction	=1 500 000 (centralized, advanced)	8	15	2.0 €/t
Ammonia scrubber for drying	=150 000 (centralized, advanced)	8	15	1.5 €/t

References: 1) Saalasti 2022, 2) KTBL 2013, 3) Saalasti 2023, 4) MMM 2021, 5) Lehtonen & Luostarinen 2022, 6) Lehtonen 2023, 7) Ervasti ym. 2021, 8) discussions with Finnish biogas operators.

To estimate the earthmoving cost of the foundation phase of the biogas plant (45 euro/ m^2), the surface areas of the plant structures were calculated. In the calculation, the reactor height was assumed to be 6.9 m, the height of the storage tanks for slurry and sludge-like/liquid digestates was 4 m, and the height of the storages for solid materials was 2.5 m. The area of the technical buildings was assumed to be 200 m^2 (Saalasti 2022). The area of the gas upgrading container was assumed to be 60 m^2 (Lehtonen & Luostarinen 2022). The surface areas of the fueling stations were assumed to be 50 m^2/pc. The area of the passages was assumed to be 10 % of the area of the structures (Saalasti 2022).

Calculation of the price of tensioned cover of storage tank

The price of the tensioned (membrane) cover of the storage tank for separated liquid fraction (farm-scale, advanced; centralized) was calculated as follows. First, the surface area of the tank to be covered (A_{tank}, m^2) was calculated with formula 1:

1. $A_{tank} = \frac{V_{tank}}{h_{tank}}$

where V_{tank} is the tank volume (m^3) ja h_{tank} is the tank height (assumed at 4 m). Then the radius of the tank (r_{tank}, m) was calculated with formula 2:

2. $r_{tank} = \sqrt{(\frac{A_{tank}}{\pi})}$

Then the height of the membrane cone sheath situated directly above the tank (h_{sheath}, m) was calculated using formula 3:

3. $h_{sheath} = tan\ 30° \times r_{tank}$

Then the area of the cone-shaped, 30-degree membrane cover over the tank surface (A_{sheath}, m^2) was calculated with formula 4. Note that the base of the cone is not included in the result.

4. $A_{sheath} = \pi \times r_{tank} \times \sqrt{(h_{sheath}{}^2 + r_{tank}{}^2)}$

The height of the central poile holding the membrane cover (h_{pole}, m) was calculated with formula 5:

5. $h_{pole} = h_{tank} + h_{sheath}$

The membrane cover requires a 0.3 m hem for attachment. The height of the membrane cone including the hem ($h_{sheath\ incl.\ hem}$, *m*) was calculated with formula 6:

6. $h_{\text{sheath incl. hem}} = h_{\text{sheath}} + 0.3$

The radius of the membrane including the hen ($r_{\text{sheath incl. hem}}$, m) was calculated with formula 7:

7. $r_{\text{sheath incl. hem}} = h_{\text{sheath incl. hem}} / \tan 30°$

Finally, the area of the entire membrane ($A_{\text{sheath incl. hem}}$, m^2) was calucalted with formula 8:

8. $A_{sheath\ incl.\ hem} = \pi \times r_{sheath\ incl.hem} \times \sqrt{(h_{sheath\ inlc.\ hem}{}^2 + r_{sheath\ incl.\ hem}{}^2)}$

The price of the membrane alone is 39 euro/m^2. The price of the central pole that holds up the tent-like roof is 580 euro/m. In addition, the installation cost depends on the size of the membrane is 10 000–15 000 euros (Saalasti 2023). The price of the installation of the storage tank for liquid fraction in the farm-scale plant using advanced practices (approx. 8 610 m^3, 12-month storage) was assumed to be 15 000 euros. The price of installing the covers for the ammonium sulfate tank (approx. 185 m^3, 7 days buffer storage) and the concentrate tank (approx. 990 m^3, 7 days buffer storage) of the centralized plant using advanced practices was assumed to be 10 000 euro/pc.

Investment costs, working lives and maintenance costs of dry digestion plants

The formulas for calculating the investment costs of various parts and equipment of dry digestion plant, as well as their lifetimes and basis for calculating their maintenance costs are presented in Table 44. The density of the feeds was assumed to be 400 kg/m^3 when calculating the reactor volume.

Table 44. Formulas for calculating investment costs of dry digestion plant, estimated lifetimes (LT) and the basis for calculating the maintenance costs (MC). V_R = reactor process volume (m^3). V_S = storage tank volume (m^3).

Part/device	Cost formula (€)	Ref.	LT (years)	MC
Reactor silos (2 pcs), percolation liquid tank, gas storage and earthmoving	=0.65*(167.03*V+487 327)	1	20	1 % inv./y
Process technology (incl. pipelines, electricity, and automation)	=0.15*(167.03*V+487 327)	1	10	5 % inv./y

Part/device	Cost formula (€)	Ref.	LT (years)	MC
Installation of the above-mentioned technology	=0.1*(167.03*V+487 327)	1	20	-
Design and permits (incl. biogas plant and gas utilization)	=0.1*(167.03*V+487 327)	1	20	-
CHP-unit + gas blower, activated carbon & removal of condensed water	=2 388.225*e$^{(-0.003*P)}$*P +45 950, where P is electric power (kW$_{el}$)	2	10	1.8 €-cnt/ kWh$_{el}$
Gas boiler	=20 000 (in reserve)	2	20	2 % inv./y
Flare	=10 000	Estimate	20	-
Electrical connection to grid	=10 000	Estimate	20	-
Digestate storage (concrete slab)	=40 €/m^2	Estimate	20	1 % inv./y

References: 1) Luostarinen 2022, 2) Saalasti 2022.

Profitability calculation

The annuity for the investment (A) was calculated with formula 9:

$$9. \quad A = I \times \frac{p(1+p)^n}{(1+p)^n - 1}$$

where *A* is annuity, *I* is investment cost, *p* is interest rate (value 0.05 = 5 % interest) and *n* is lifetime (years). The lifetimes of the various parts of the biogas plants are indicated in Tables 6.1 and 6.2. The payback period (years) was calculated by dividing the subsidized investment cost by the annual revenue. The investment support level was assumed to be 30 % for the centralized plant and 50 % for other plants.

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ISBN PDF 978-952-383-075-2
ISSN PDF 2342-6799