Potential for Manure-based Anaerobic Digestion – Motivations, Barriers and Approaches in Six Countries

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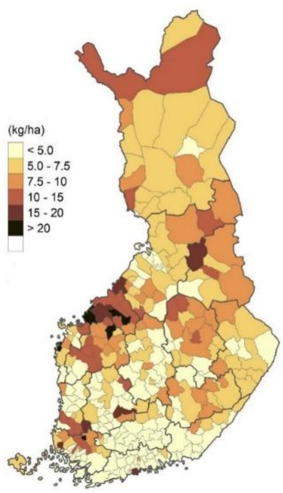

Potential for Manure-based Anaerobic Digestion – Motivations, Barriers and Approaches in Six Countries

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Cover picture: Manure phosphorus per field area in Finland in 2020; originally published in Lemola et al., 2023

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Table of Contents

1 INTRODUCTION

1.1 THE LARGEST UNDERUTILISED RESOURCE FOR BIOGAS PRODUCTION

Manure management, in particular open storage, contributes significantly to greenhouse gas and air emissions from agriculture, mostly in the form of methane and ammonia emissions. Anaerobic digestion of manures and slurries captures and reduce these emissions to atmosphere, producing biogas to replace fossil fuels as well as digestate which can be used as an organic fertilizer to replace fossil fertilizers (Liebetrau et al., 2017). Optimisation of nutrient cycles and good soil health are essential for sustainable agriculture, with organic fertilizers essential for organic farming, making anaerobic digestion (AD) processes are ideally suited to sustainable agriculture (McCabe et al., 2020).

1.2 MANURE BIOGAS AS A SUSTAINABLE ENERGY SOURCE

Among primary feedstocks, organic wastes such as animal manure, are potentially valuable for renewable energy and biofertilizers. Manure produced in Confined Animal Feeding Operations is highly concentrated in some regions, exceeding the needs and limits of cropland. In these circumstances, excessive accumulation of organic waste, especially animal manure, produces soil, water, and air pollution. Manure is a source of methane (CH_4) and nitrous oxide emissions (N_2O) on dairy farms, both of which are GHGs with high global warming potential values. In the U.S., manure management emissions account for nearly 10 % of all anthropogenic methane emissions (Niles et al., 2022). The contribution that manure management makes to total national agricultural emissions of N_2O and CH_4 varies but can exceed 50 % in countries reporting to the United Nations Framework Convention on Climate Change (UNFCCC) in 2009 (Chadwick et al., 2011). Therefore, using manure as feedstock for biogas contributes to meeting sustainable development goals.

International Renewable Energy Agency (IRENA) reported that the overall potential for the biogas industry in 2018 provided 88 Terawatt hours of biogas. Installed electricity generated from biogas reached 18.1 GW in 2018, compared with 8.2 GW in 2009 (IRENA, 2019). Over 20% of electricity produced in the entire biomass-based energy production is generated from biogas, with a share of 4% of heat generation worldwide.

Among different countries, Europe plays a pivotal role in biogas electricity generation. In 2017, Europe contributed to over 70% of the world biogas generation representing 64 TWh, followed by North America accounting for 15 TWh (where the U.S. production represented over 85% of North America's production). Asia produced 4 TWh followed by Eurasia with 1.7 TWh, South America with 953 GWh, and Africa biogas production accounted for 89 GWh (Scarlat et al., 2018; IRENA, 2019).

1.3 ENVIRONMENTAL IMPORTANCE OF BIOGAS SYSTEMS

Manure biogas systems have at least five key roles in contributing to environmental protection and resilience: (1) manure management to avoid soil, water, and air pollution; (2) renewable energy production; (3) supply of organic nutrients; (4) soil amendment function; (5) GHG emission reduction and mitigation. For example, in China, these roles can be described as follows (Dong, 2024):

- **Manure management**

Manure biogas systems help manage all types of animal manure efficiently, preventing manure from being washed into the environment where it may emit odor and GHGs, cause eutrophication and water quality issues, and pollute soil.

Additionally, efficient waste management through biogas systems minimizes land degradation and habitat destruction associated with traditional waste disposal methods.

- **Renewable energy production and fossil fuel substitution**

Biogas derived from manure is a renewable energy that can be produced continuously as long as there is livestock production to generate manure. This provides a steady supply of energy without depleting natural resources. Localized biogas production can enhance energy security by reducing dependence on imported fossil fuels. According to the China Biogas Industry Development Report of 2021, the biogas potential from livestock and poultry manure in China by 2030 and 2060 is approximately 169 billion cubic meters (bcm) and 371 bcm, respectively. The corresponding potential GHG emission reduction resulting from the substitution of fossil fuels is estimated to be 300 million tons (in 2030) and 660 million tons CO_2e in 2060.

Distributed biogas is also a key energy source to compensate for the fluctuating production of other renewable energies. In China every 1GW PV or wind power capacity needs 15-20% stable electricity backup, providing a huge opportunity for at least 30 large scale (5 MW each) biogas plants.

- **Organic nutrients and soil amendments**

Animal manure biogas systems simultaneously produce digestates which are rich in nutrients and can be used as organic fertilizers. This enhances crop productivity, reduces the need for mineral fertilizers, and adds degassed, stable organic matter into soil to improve soil carbon and soil health.

- **Greenhouse gas emissions reduction and mitigation**

Manure produces methane as it decomposes anaerobically. Biogas systems capture this methane thereby avoiding methane emissions to the atmosphere; further reduce GHG emissions as biogas used as energy substitute fossil fuels and digestates used as fertilizer avoid energy-related emissions of mineral fertilizer production and transport. In addition, degassed organic carbon is returned into agricultural soils to become soil carbon, generating net negative emission (removal) of carbon from the atmosphere. To ensure that environmental benefits are realised, attention must be paid to the design and operation of the facilities.

1.4 REALISING THE POTENTIAL BENEFITS OF MANURE BIOGAS

Production of biogas from manure produced at a farm is the very epitome of a sustainable bioenergy system and a circular economy. The system incorporates decentralised production of organic bio-fertilizer and biogas for use in heat, power or transport fuel, whilst simultaneously reducing fugitive methane emissions from open slurry holding tanks, reducing smells and minimising pollution effects on rivers and wells. Therefore, why is the practice of producing biogas from manure not more widespread?

The major factors which define the suitability of manure for an economic AD process include: the biogas potential of the manure; the water content of the manure; unwanted and inhibitory materials in manure; the herd size and/or bird population, and the amount of manure available for the biogas facility.

Manure is an unavoidable by-product of livestock production, consisting primarily of animal faeces and urine but also includes bedding, additional water, and unused feed. Cattle, pig, poultry, horse, goat, sheep, elephant droppings and fishery residues are all sources of animal manure. Some animal farm wastes are not ideal substrates because of their low energy content, making co-digestion with two or more energy-rich substrates more beneficial and profitable. Also, consistent feedstock supply can pose a serious challenge in some areas. Therefore, it is encouraged that organic residues be mixed in to have sufficient feedstock loading and biogas yield during AD (Janni and Cortus 2020; Sommer and Christensen 2013).

The six countries described in this report each have specific regions where the production of specific animal groups is concentrated and the potential for a viable biogas industry is high. The financial viability of AD of manure is contingent upon the provision of incentives. To ensure the effectiveness of any incentivization measure or strategy, it is imperative to take into account the existing farm structures and the characteristics of the manure produced, in order to achieve a significant and efficient impact. Facilities that utilize manure as the primary substrate for anaerobic digestion often operate at a smaller scale, which results in higher specific costs. The types of animals and the forms of husbandry practiced have a pronounced effect on the technically available manure resource, the biogas yield and the costs of biogas produced from manure. Therefore, to be truly effective, support schemes must be designed to accommodate these variables.

To exemplify this, IEA Bioenergy Task 37 published this report which examines the potential of manure for utilization in biogas facilities across six countries: Canada, China, Finland, France, Norway and the United Kingdom (UK). These countries have differing sizes of biogas industry, very different farming practices and a range of climates. It is hoped that the country selection allows the different lessons learned from these six countries to be applied to many countries across the planet.

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2 CANADA

2.1 INTRODUCTION

This update to the 2021 Task 37 report (Liebetrau, 2021) describes the changes that have taken place with respect to anaerobic treatment of manure in different parts of Canada. Over the last four years, there has been significant, renewed interest in the development of new AD projects in Canada. There has been a resurgence in project planning, in seeking permits, approvals, and financing, and in biomethane contract negotiations. However, only a few new AD facilities have been constructed and commissioned in the agricultural sector, indicating that barriers continue to exist vis-à-vis the adoption of AD.

This Canadian update (2024) was derived mostly from interviews with farmers, project developers, and government and industry experts. Organizations that participated include Catalyst Agri-Innovations, Dicklands Biogas, GET Corp., Alberta Ministry of Agriculture and Irrigation, Maple Leaf Foods, Ontario Ministry of Agriculture, Food and Rural Affairs, and Coop Carbone. In North America, the term renewable natural gas (RNG) is generally used for the methane fraction of biogas obtained from an upgrader. For consistency with the other country descriptions, the term biomethane has been substituted for RNG in this section.

2.2 MANURE PRODUCTION, AVAILABILITY AND USE IN AD

Animal production was fairly steady in Canada between 2018 and 2021, making total manure production relatively constant at approximately 21 million DM tons/a (20 million tons of volatile solids). Most manure (over 98%) continues to be directly applied to agricultural soils with no pretreatment. Collected livestock manure is stored in appropriate facilities and applied as fertilizer at specific times of the year, as dictated by provincial regulations or guidelines and farm nutrient management plans (McCabe, 2020). A small amount of beef manure is composted before being land applied as soil conditioner and fertilizer, and approximately 1% of total manure is treated via anaerobic digestion. The rise and volatility of fertilizer costs, experienced over the last years, has increased the demand for manure, almost eliminating manure stockpiles in some parts of the country (Bush, 2023).

Four housed animal groups, namely dairy cattle, beef cattle in feedlots, swine and poultry are considered to produce the most accessible manure for AD. The 2021 tonnages of manure generated by these animal groups are presented in Table 1. The populations of these groups have changed very little since 2018, namely a 1.4% decline in poultry numbers and less than 1% change for the three other groups (Flemming, 2023). Consequently, the total manure that could potentially be available for AD remains relatively unchanged from 2018 at 6.8 million DM tons/a.

Table 1: Animal and Manure Production in 2021 (Flemming, 2023)

Animal Group	Population in 2021	Tons DM, 2021	Tons VS, 2021
Dairy cattle, cows and heifers	1,398,150	3,117,504	2,868,104
Beef cattle at feedlots, heifers for slaughter and steers	2,199,900	1,154,035	1,061,712
Swine (all ages)	14,137,200	1,298,208	1,229,638
Poultry (all ages)	150,531,322	1,270,326	1,192,193
TOTAL, amenable for AD	—	6,840,073	6,351,647

In a country the size of Canada, the total amount of manure available on a national level provides limited insight on the realizable energy potential of manure-based AD. For this, information is needed on farm locations and farm size distribution (by animal group) and the availability of co-substrates as almost all manure is co-digested in Canada. Farm size distribution varies by animal group and by province, with the majority of livestock farmers in Canada having small operations. In a study by Vander Zaag (2023), 89% of 89,262 farms that housed the four animal groups listed in Table 1 were considered to be small farms. For example, in the case of dairy farms, the size class with the most farms (27% of total farms) consists of 20 and 49 dairy cows, and the largest number of cows (21% of total cows) are in the 50 to 74 cow size class. Similarly, in the case of grower hogs, 64% are housed on small farms with less than 1,000 hogs per farm. However, the beef sector is characterized by the two extremes with 1.16 million steers and beef heifers kept on 38,232 small farms, with an average of 30 head per farm; and 1.31 million head kept on 334 farms with 1,000 -10,000 head per farm, and 18 farms with over 10,000 head. However, the beef sector is characterized by the two extremes with 1.16 million steers and beef heifers kept on 38,232 small farms, with an average of 30 head per farm; and 1.31 million head kept on 334 farms with 1,000 -10,000 head per farm, and 18 farms with over 10,000 head.

Manure-based AD Plants

As of December 2023, there were 50 operational manure-based AD plants in Canada. These facilities process approximately 1 million tons of fresh manure (FM) annually.
Liquid dairy manure continues to be the most targeted type of manure for AD due to its high VS content and easier transport and pumpability. Most installations co-digest manure from 300-350 cows (200-250 milking cows plus heifers, dry cows, and calves) in a 51/49 ratio with off-farm food waste.
The first new AD project to treat solid beef cattle manure is awaiting final approvals. To date, there are no stand-alone swine or poultry AD systems operating in Canada. Some on-farm dairy AD facilities include poultry and/or swine manure from nearby farms to increase the total manure input to the digester. As one example, Dicklands Biogas co-digests poultry manure with its dairy manure, and its system can accept the intake of pathogenic material as the system design includes post pasteurization.

However, some AD facilities deliberately avoid adding swine and poultry manure because of biosecurity concerns, i.e. to prevent the risk of disease transfer from infected populations.

Since the 2021 Report, several existing manure-based AD facilities have increased their digester capacity and added biogas upgraders. Two new AD systems have been constructed and commissioned on dairy farms in two different Provinces; two systems, also on dairy farms, are in the start-up phase; one beef feedlot operation is awaiting final approval, and numerous feasibility studies are underway. All of these on-farm AD plants are or will be upgrading their biogas to produce biomethane for injection into the gas network.

2.3 MOTIVATION FOR THE ADOPTION OF MANURE-BASED AD IN CANADA

The reasons for adopting anaerobic treatment for manure and organic residues in Canada have changed over time. There hasn't been a specific policy or initiative at the national level to develop the manure-based AD industry. In fact, the adoption of AD has varied significantly from province to province as well as by sector, i.e. municipal versus agricultural Farmers typically apply manure to local farms, recovering 65-70% of dietary N and P (Feng, 2023) and some carbon to support crop production near livestock farms.

Follow guidelines and nutrient management plans to prevent phosphorus accumulation and negative impacts on water quality. However, 10% of agricultural regions have significantly high P accumulation (Feng, 2023), necessitating the reduction of methane, nitrous oxide, and ammonia emissions from manure storage and application. Research has shown that measures like solid-liquid separation and nutrient recovery can moderately reduce these emissions (Feng, 2023) and generate manure solids for application to distant fields, thereby dispersing the P more widely AD with appropriate manure and digestate storage can reduce these emissions to a greater extent and capture biogas for energy use, but at a much higher cost. To justify an investment in manure-based AD, there needs to be a renewable energy purchaser and a viable business case for a farmer.

Twenty or so years ago, some provinces viewed on-farm AD as a way to boost the supply of renewable electricity and, to a lesser extent, improve the management of livestock manure and organic waste in rural areas. Three provinces established feed-in-tariff (FIT) programs that paid a premium for electricity produced from biogas for a 20-year period, and the Province of Ontario, which offered the highest premiums, saw the greatest development of on-farm AD plants.

To achieve economies of scale and make connecting to the electricity grid easier, most on-farm AD systems aim to reach the 500 kW "sweet spot" (Gorrie, 2010). A large dairy farm with 300-350 cows could observe such a system, which co-digested its manure with local food waste.

In order to fall under agricultural rules, most FIT programs specified that on-farm AD systems could accept up to 49% of off-farm material. This enabled the construction of larger AD systems, which could benefit from economies of scale, achieve higher methane yields compared to processing manure alone, and recover more nutrients. The FIT premiums and the tipping fees provided new “non-farming” revenue streams for these farms, and the long-term contracts to sell most or all of the generated electricity were essential for financial viability. The farms benefitted from the better manure management, recovery of more nutrients in more bioavailable form and undigested carbon for use in crop production, and less manure odour. Some farms captured the heat for their operations from the CHP systems and reused the digestate solids for animal bedding.

Over the last two decades, the electricity grids in all provinces have added more renewable capacity, and the prices of wind and solar power have dropped significantly.

Ambitious climate change goals, policies, and programs have been adopted to reduce GHG emissions in all sectors of the economy. As in other countries, large emission reductions are being sought at the lowest societal cost. Biogas -to- renewable electricity systems became less appealing because of their higher cost, greater complexity, and small potential impact on a national scale.

The provincial FIT programs have come to a close, and only a few years remain for the AD plants that have FIT contracts to receive a premium for their electricity production. Focus has shifted to greening the natural gas system, and two provinces in Canada, Québec and British Columbia, have established mandates to increase the renewable content of their natural gas systems to 10% and 15%, respectively, by 2030. These provinces have set up programs that offer significant premiums for biomethane from biogas and woody biomass via a long-term contract with a gas utility. In British Columbia, up to C$31/GJ can be paid for biomethane, and in Québec, the premium can be up to C$45/GJ. The contracts can be virtual, meaning that biomethane can be purchased from AD projects located in any Province. It is also possible for large emitters of GHG emissions to purchase biomethane and carbon credits/offsets to reduce their environmental impact. Irving Oil (based in the Province of New Brunswick) has entered into a 10-year contract to purchase up to 60,000 GJ of biomethane from the on-farm AD facility in Alberta (GrowTEC). Also, there exists the opportunity to sell carbon offset credits from AD plants to carbon markets in the U.S. and in several Canadian provinces (e.g., Alberta, British Columbia, and Québec).

However, biogas -to-biomethane systems require greater biogas production volumes to be eligible for long-term contracts, and they need to be located close to an accessible natural gas pipeline. That is, the minimum biomethane volume threshold required by natural gas companies (the biomethane purchasers) means that on-farm AD-biomethane plants need to be larger than the on-farm AD-CHP plants. Consequently, in the absence of new policies and programs, farms with AD-CHP systems need to decide what to do next, i.e., to close down their CHP units, access more feedstock, and invest in more digester capacity and a biogas upgrader; find other revenue streams, etc. If the farm has a sufficiently large supply of manure and/or long-term access to off-farm feedstock, the primary motivation for investment in a new AD installation or expansion of an existing operation is the revenue generated from the sale of biomethane. With a 15-to-20-year biomethane contract, a farmer can seek financing, diversify the sources of farm income and operate a financially profitable AD system. The sale of carbon offset credits (Gouvernement du Quebec, 2024a) could generate additional revenue to further incentivize investment. However, this revenue stream is fraught with significant uncertainty, as it relies on the offset protocols for various on-farm AD projects and the evaluation of baseline conditions, among other factors.

Meeting industry sustainability goals and delivering on sustainability action plans are important for Canada's agriculture and agri-food sector. From a climate change perspective, the Canadian dairy industry has made the commitment to be "net zero by 2050". AD is considered to be a good technology that supports healthy carbon, nutrient and water cycles (Dick, 2024), however, as discussed above, conventional AD systems are not financially viable solutions for most farms with the current policy that focuses on biomethane production for injection into the gas network. Also, globally competitive agri-food businesses are working to lower the GHG footprint of their supply chains. Large meat processors, such as Maple Leaf Foods, are exploring AD projects in the Province of Manitoba to reduce the GHG emissions from their hog farms and the farms they source from.

2.4 MAIN BARRIERS TO INCREASING ANAEROBIC TREATMENT OF MANURE

Feedstock Supply and Proximity to Natural Gas Pipelines

Large AD projects that are close to natural gas pipelines are more likely to produce biomethane and get premiums. This implies that the feedstock supply and location serve as the primary barriers to the growth of manure-based AD. New pipeline construction is very costly and not even permitted in all parts of Canada, so new projects need to fit into the infrastructure that already exists in a region or be located close enough to a pipeline injection site for the biomethane to be trucked at a reasonable cost.

Given the relatively small size of most livestock farms in Canada (Vander Zaag, 2023) and their dispersed location in rural areas without gas grid connection (Liebetrau, 2021), there appear to be new opportunities for manure-based AD. These opportunities include: 1) large farms in the dairy, beef, swine, and poultry industries; 2) farm clusters where multiple farms in close proximity can collect manure (CBA, 2021); and 3) farms with consistent access to agri-food waste or the organic fraction of municipal waste. To date, co-digestion with off-farm waste has been key to manure-based AD, providing tipping fees and higher biogas yields, however this feedstock strategy is vulnerable to inconsistent supply due to increased competition, decline in tipping fees and quality issues. Researchers are also questioning the impact of entrained plastics and traces of PFAS in off-farm feedstocks several studies are underway to determine concentration levels in digestate and soils which have received digestate from different types of AD plants. Depending on the findings, alternate feedstock strategies may be required.

Sequential crops, straw, and agricultural residues supplement manure for biogas production in countries like Italy, France, Denmark, and India, thereby increasing the opportunities for on-farm AD. Canada practices the use of straw in AD to a very small extent, considering it a valuable agricultural product with multiple markets and a relatively expensive feedstock for biogas production. For the past few years, agricultural policy has strongly encouraged the retention of crop residue and cover crops to reduce soil erosion and increase soil carbon sequestration, but has shown ambivalence towards harvesting these materials as feedstock for AD. Therefore, scientific research is necessary to verify the potential use of these agricultural materials for AD without compromising sustainability, as well as to ascertain the logistics and costs associated with these new supply chains.

Under the current policy framework, if there is sufficient feedstock for a 20 to 25-year timeframe and access to the natural gas pipeline network, then a farm site can be considered for AD development. Interviews with farmers and industry experts identified the major barriers to be high investment costs, uncertain revenue streams, complex project development with limited expertise, and challenges in obtaining necessary approvals.

Investment Costs and Revenue Streams

The investment costs for the new manure-based AD plants constructed since 2020 range from C$18 to 70 million (dollar value in 2023), and costs are continuing to rise. Size expansion and switching from CHP to biogas upgrading have increased project costs, and equipment, transport, and construction costs have grown significantly since 2019. Supply chain and labor shortage issues continue to linger in this post pandemic period. Several cases resulted in the abandonment of advanced-stage projects due to inflation, which escalated the costs to a point where construction was no longer viable. Clearly, it is a difficult environment for most farmers to raise this large amount of capital. At the national level, there is no government program dedicated to support the build out of the AD industry in terms of grants or loans to offset the high capital costs, or operating incentives, such as payment for use of manure. In the Province of Québec, the PSPGNR program has supported feasibility studies for several on-farm AD projects, but it is not yet known which ones will be able to attract the necessary financing and move to the construction stage (Gouvernement du Québec, 2024b). Some AD projects have been successful in receiving a grant or loan through a competitive climate change funding program, but others have not. Finally, biogas-to-biomethane projects in Canada currently lack the investment tax credits that have proven to be highly beneficial for the adoption of other renewable technologies (Helmore, 2023).

When it comes to revenue streams, other than biomethane sales, there is significant uncertainty. Competition for off-farm feedstock is high, and tipping fees are declining, with some people predicting that a farm might one day have to pay for these feedstocks. Nutrient recovery from waste streams and digestate products, more broadly, are recognized to be beneficial for the environment and reduce synthetic fertilizer purchases, but farmers are rarely compensated for digestate sales generally, another farm may pay for the transport of digestate to a farm, but this isn't always the case. Finally, the determination of a farm's financial benefit from carbon credits/offsets remains undetermined. To date most on-farm AD projects have transferred future credit ownership to the buyer in their biomethane or electricity contracts. Project eligibility to earn credits is not a certainty, and depends on the baseline conditions, feedstock mix, protocols and specific emission factors.

- **Project Design, Equipment and Expertise**

When compared with a decade ago, there is a lot of activity in the AD industry today; however, it is still a relatively small industry in Canada. Project design and equipment are not yet standardized, with every manure-AD project being unique and most equipment being imported from EU countries. Interviews noted that logistics, in particular, can complicate project development significantly. Developers continue to break new ground, often remarking that they need to educate many people along the way (Feinberg, 2023). At the global level, the development of AD has grown dramatically over the last 4 years, and consequently, there is a shortage of experienced people who are able to design and build AD systems (Dick, 2024). While AD companies have added staff, they would naturally prefer to grow their presence and technical capacity in countries with more favourable conditions for investment (i.e. higher growth potential). Finally, in Canada, more design resources are being allocated to municipal AD projects that are larger than manure-based AD, have public sector financing, and additional waste management drivers.

- **Regulatory Frameworks and Approvals**

Regulatory frameworks and approval times differ significantly from province to province (CBA, 2022). In the Province of Alberta, projects that involve off-farm waste are classified as waste management projects that require many more steps to obtain approval, while in the province of Ontario, approval for on-farm AD projects is considered quite straightforward and was not identified as a barrier. The new on-farm AD system built in the Province of British Columbia had to meet very high standards for clean soil, water, and air, which in turn translated into an expensive design that requires three operators. In the province of Québec, the environment ministry's proposed new digestate regulations could restrict the types and amount of off-farm material that could be taken in by on-farm AD plants, making it difficult for these plants to collect sufficient feedstock and enough revenue.

Similarly, community acceptance can be a barrier in some regions of the country but not in others. New projects in the Provinces of British Columbia and Alberta had to address community opposition associated with odour pollution. These projects had to install more covers, buildings and equipment to capture and destroy odorous emissions, thereby increasing project capital and operating costs. In the province of Québec, some project developers have noted community resistance to project size, i.e., some communities favor small AD plants and oppose larger ones that would benefit from economies of scale.

2.5 INTERESTING FEATURES OF NEW DEVELOPMENT

Recently constructed or under development on-farm AD projects in Canada are upgrading their biogas to produce biomethane for pipeline injection. In order to be financially viable and meet the minimum biomethane volumes for grid injection, new projects are larger and have more digester capacity than the on-farm AD CHP systems of the past. New on-farm AD systems are either designed as centralized systems that take in feedstock from several farms or they include food waste depackaging equipment and storage capacity.

Historically, farms owned and operated the majority of farm AD systems. Changes to ownership structure have emerged over the last few years, with more third-party private sector investment. Private sector investors purchased both the existing agriculture-based digester systems (GrowTEC and Lethbridge Biogas) in Alberta. EverGen Infrastructure Corp now has 67% ownership in GrowTEC (EverGen, 2023), and Skyline Clean Energy Fund has complete ownership of Lethbridge Biogas. The new centralized digester built in Warwick, Québec is owned by a thirteen-member agricultural cooperative, and is operated by a separate cooperative, Coop Carbone. The new pilot project in Brinston, Ontario is owned by an industry partnership of GET Corp. and GFL, and will be operated by GET Corp. Two Hills RNG is the first commercial biomethane production investment of the Alberta energy company, ATCO.

To meet the Canadian dairy industry's "net zero" goal, a third-party entity (GET Corp) was created with the aim of treating 80% of the country's dairy manure and developing viable AD projects for dairy farms across Canada. With the assistance of Danish expertise and equipment, GET Corp is piloting its concept to treat manure and on-farm residues from nearby farms, without additional off-farm waste, and to truck the biomethane to a pipeline injection port.

Some of the unique features of new on-farm AD systems are summarized below.

Coop Agri-Energie Warwick (Province of Québec) - first centralized (community) on-farm digester in Canada began operations in 2021, Feedstock: 50,000 t/a = dairy manure from 5-6 farms (50%) + sludge of municipal WWTP (10-15%) + agrifood waste (35-45%); built on agricultural land next to gas pipeline; owned by an agricultural cooperative; capital cost $12 million (including injection port) – received federal and provincial government support; The German equipment includes a hydrolyser, a mesophilic CSTR, a post-digestion system with a total recovery time of less than 30 days, a membrane biogas upgrader, and a 20-year contract with Energir for 85,000 GJ. There is no income from the sale of carbon credits, and the cooperative distributes 46,000 t/a of digestate to its members based on their specific nutrient needs. The project contributes to the reduction of greenhouse gas emissions in the dairy industry, the province's biomethane target, and the goals of the circular economy.

Figure 1: Coop Agri-Energie Warwick AD facility (Coop Agri-Energie Warwick, 2024)

The AD system at Dicklands Biogas, a dairy farm in British Columbia with 400 milking cows, began operations in 2023 ; Feedstock: 82,000 t/a = co-digestion of 51% dairy and poultry manure with 49% off farm food waste; owned and operated by farm; cost rose dramatically to $45 million with almost no government support; design includes storage and repackaging equipment for food waste all under negative pressure to reduce odours; mesophilic CSTR with RT of 35+ days; odour-controlled digestate treatment system that produces 4,000 t/a organic fertilizer pellets for sale, 53,000 t/a of clean water and 9,000 t/a of water with residual ammonia and COD that is used for irrigation; AD facility is located next to the cow barn and the compressor noise is attenuated to avoid negatively impacting milk production; the project includes a membrane biogas upgrader, a 20-year contract with Fortis for 180,000 GJ, and supports the Province's renewable gas target, community goals, and the dairy industry's net zero goal.

GET Corp. (Province of Ontario) – first pilot of Sustainable Agriculture Program for Canada's dairy industry; centralized digester model that started up in 2024; Feedstock: dairy manure from 5-6 nearby farms (90%) with bedding pack and straw (10%), no food waste; owned by GET Corp. and GFL; Green Island and SEGES Innovation provided Danish design, equipment, and digester operation; thermophilic silo digester; biomethane to be trucked to injection port; expect biomethane and carbon credits to be sold to U.S. market; digestate to be returned to participating farms for soil fertilization; the project aligns with the dairy industry's goal of achieving net zero by 2050 (https://www.get-corp.ca).

Figure 2: GET Corp. Pilot AD Project in Brinston, Ontario (GET Corp., 2024)

The project at Rimrock Renewables, located in the Province of Alberta, began in 2021 and is currently awaiting approvals. It will be the largest on-farm AD system, producing 450,000 GJ biomethane, and the first to co-digest solid beef manure with food waste. The project is expected to cost $70 million, with some support from the provincial government. It is owned and operated by a joint venture between Tidewater and Rimrock Cattle, and it has installed concrete slabs in the feedlot to reduce sand and stone contamination of the beef manure. Planned equipment: storage and depackaging equipment for food waste and covered digestate storage; mesophilic CSTR; odour control of feedstock handling and digestate to address community concerns (https://rimrock-renewables.com/).

2.6 CONCLUSION

There remains substantial untapped potential to recover energy from Canada's dairy, beef, swine, and poultry farms. However, most of this animal production takes place on small and mid-size farms, and the current policy drivers and incentive structure target only large farms or farm clusters that are located near a natural gas pipeline. The use of straw, cover crops, and other agricultural residues could be further explored as a feedstock supply for AD, especially as sourcing of off-farm waste is becoming more competitive and questions are arising about feedstock quality and the impact on digestate application.

The manure-based AD industry is in a state of transition in Canada. With the ending of the FIT renewable electricity programs, the future of existing on-farm AD – CHP plants is uncertain. Renewable gas mandates and the associated high prices offered for biomethane are driving new AD development on large farms and in farm clusters over the last 4 years, despite the development of numerous projects, only a handful of new manure-based AD plants have come into operation. More centralized (hub and spoke) AD systems are being built. All new on-farm AD facilities have larger digesters and biogas production capacities than the existing AD-CHP plant, and are focused on maximizing biomethane production for pipeline injection. As the costs of manure-based AD systems have risen substantially, a shift from the farmer owner-operator model is being replaced by third-party ownership.

The commitment to sustainable value chains is important for Canada's agriculture and agri-food sector, and the dairy industry wants to achieve "net zero" GHG emissions by 2050. The dairy industry continues to lead the livestock industry with highest adoption of AD, and a pilot centralized digester model, based on Danish design and technology, is being tested. If it proves to be financially successful, plans are to replicate the model across the country. New AD projects are also under development in the meat processing industry to reduce GHG emissions from swine production.

Opportunities for manure-based AD are regional. They depend strongly on the commitments to clean energy, waste management, climate change action, and a circular economy of individual provinces and the specific needs and opportunities of a region. The minimum biomethane production threshold, the absence of investment tax credits and the lack of special measures to support the use of manure in AD contribute to slower adoption in Canada than the growth that is observed in the U.S., Europe, South America, and Asia.

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3 CHINA

3.1 OVERALL POTENTIAL

With the improvement of people's living standards, the consumption of meat, eggs, and milk in mainland China[1] has also been increasing year by year (Figure 3 and Table 2), with a vigorous development of large-scale farming. The proportion of large-scale dairy farms (dairy cow inventory exceeding 100 head) increased from less than 12% in 2002 to 51% in 2017 (Zhu et al, 2020). The proportion of fattening pigs in large-scale pig farms (the annual output over 500 head) increased from 2.5% in 1998 to 37.52% in 2020 (Zhao, 2023). While for large-scale broiler farms (the annual output over 10,000 head), the proportion increased from 75.2% in 2005 to 85.7% in 2021 (Ding et al, 2023). Large-scale poultry and livestock farming has advantages like higher production efficiency, lower management costs, better disease control, etc., but it also leads to intensive manure generation.

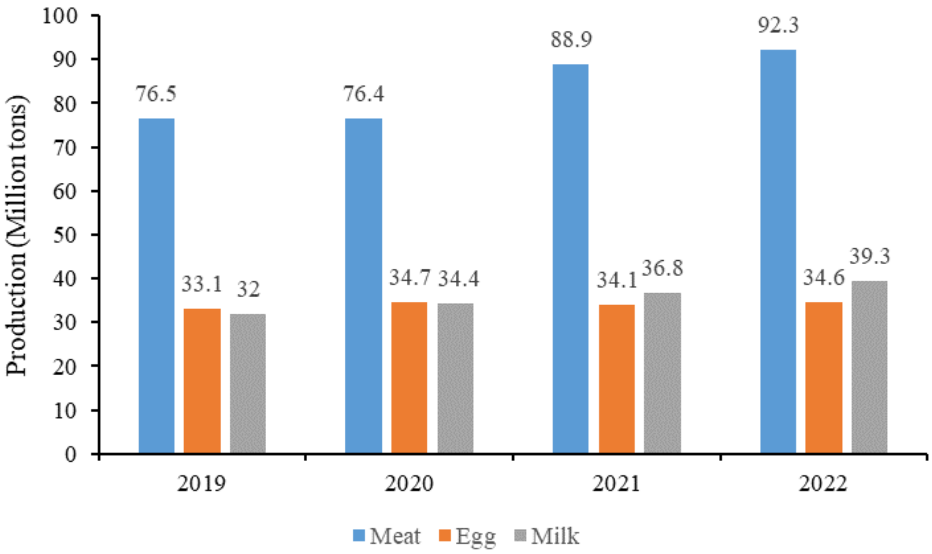


Figure 3: Meat, egg and milk production in China (National Bureau of Statistics of China, 2019, 2020, 2021, 2022)

At the beginning of the "13th Five-Year Plan"(2016), the annual generation of livestock and poultry manure was about 3800 million tons, including 1800 million tons of pig manure, 1400 million tons of cow manure (1000 million tons of fattening bulls and400 million tons of dairy cows), and 600 million tons of poultry manure. At that time, the comprehensive utilization percentage was less than 60% (National Agricultural Modernization Planning 2016-2020). Since 2016, China has increased its focus on agricultural pollution risks, leading to a reduction in animal production and a 19.7% drop in manure generation to 3.05 billion tons in 2021 compared to 2015. However, livestock and poultry manure are still the main sources of agricultural pollution (Lv et al., 2022).

[1] The statistical data in this article only encompasses mainland China, excluding the regions of Hong Kong, Macau, and Taiwan.

Table 2: Fattening pig, fattening bull, broiler, processed feeds and grain yield in China (National Bureau of Statistics of China, 2018, 2019, 2020, 2021, 2022)

Species	2018	2019	2020	2021	2022
Fattening pig (million head)	693.8	544.2	527.0	671.3	700.0
Fattening bull (million head)	4398	4534	4600	4708	4840
Poultry (billion head)	13.09	14.64	15.57	15.74	16.14
Processed feed (million tons)	237.63	228.85	252.76	293.44	302.23
Grain yield (million tons)	657.89	663.84	669.49	682.85	686.53

The livestock and poultry manure were mainly used as fertilizer, with less than 1% being converted to biogas in 2015 (Xuan et al., 2018). In 2016, China released a plan to promote agricultural waste utilization, especially for manure full valorisation: to treat the manure via biogas and biomethane technologies, and to use it as a source of rural energy and organic fertilizer locally. China has announced a series of policies and instructions to ensure the ultimate recycling of manure-based nutrients in agricultural systems.

Table 3: Recent policies for encouragement for livestock and poultry manure biogas

Policy	Relative Content
Instructions for Livestock and Poultry Manure Use (State Council Document No. 48, 2017)	Focus on large-scale farms, treat the manure via biogas and biomethane technologies, and use it as source of rural energy and organic fertilizer locally.
Animal Husbandry Law of the People's Republic of China, 2022	Encourage the utilization of livestock and poultry manure as source of rural energy and organic fertilizer in agricultural fields, and clarify the standards.
Instructions on Promoting the Standards for Livestock and Poultry Manure Utilization, 2023	Encourage the utilization of livestock and poultry manure as source of rural energy and organic fertilizer, improve the standard system, with a focus on synergetic reduction of pollution and carbon emissions as well as safety.
Action Plan for Methane Emission Reduction and Control, 2023	Promote livestock and poultry manure utilization technologies, such as closed treatment of manure, gas collection and utilization. Develop rural biogas and encourage large-scale biogas/biomethane projects.

The "Action Plan for Methane Emission Reduction and Control" (Chinese Ministry of Ecology and Environment, 2023) encourages good manure treatment practices to reduce methane emissions from the livestock and poultry industry.

Biogas technology has at least the following five key roles in manure treatment and valorization: (1) manure treatment to avoid soil, water, and gas pollutants; (2) renewable energy production; (3) organic nutrients; (4) soil amendments; (5) greenhouse gases emission reduction and mitigation (presentation at BBEST conference). Biogas potential from livestock and poultry manure in China by 2030 and 2060 is about 169 billion cubic meters (bcm) and 371 bcm, respectively. The greenhouse gas emission reduction potential by means of substitution of fossil fuels is estimated to be 300 million tons and 660 million tons of carbon dioxide equivalent (China Biogas Industry Development Report, 2021).

3.2 STRUCTURE OF AGRICULTURE AND SPATIAL DISTRIBUTION OF MANURE

	Region	Province
I	**North China** (Huang-Huai-Hai Plain)	Inner Mongoria, Beijing, Tianjing, Hebei, Shanxi
II	**Northeast China** (Northeast China Plain)	Liaoning, Jilin, Heilongjiang
III	**East China** (Middle-lower Yangtze Plain)	Shandong, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Taiwan
IV	**Central China** (Loess Plateau)	Henan, Hubei, Hunan
V	**South China**	Guangdong, Guangxi, Hainan
VI	**Southwest China** (Yunnan-Guizhou Plateau, Qinghai Tibet Plateau)	Chongqing, Sichuan, Guizhou, Yunnan, Tibet
VII	**Northwest China** (Northern arid and semiarid region)	Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang

Figure 4: Seven regions in China for livestock and poultry production (Data from Zou et al., 1985)

Note: Northeast China has a low average annual temperature, flat terrain, fertile land, and large, concentrated planting areas. North China has relatively low temperatures, flat terrain and a high level of facility-based agriculture. It is the main production base for cotton, peanuts, sesame, tobacco and vegetables in the country. Northeast and North China have larger farms, well-developed cattle breeding, and a higher proportion of biogas from animal manure. Central and southern China have relatively high temperatures; dense river networks and water systems; subtropical and tropical climates; major rice cultivation (2-3 seasons), abundant rainfall; and relatively high poultry production. East China has a relatively small environmental capacity, small land area per capita and high GDP per capita. Compared to other regions, East China's livestock and poultry farming, primarily concentrated in large-scale farms, faces higher pollution control requirements. Northwest China is a vast and sparsely populated region with a dry climate and low rainfall. This region is home to relatively few large-scale livestock farms. The southwest region's topography is primarily hilly and mountainous, with a relatively small amount of arable land per capita. Small and medium-sized animal farms predominate in the region.

Livestock and poultry manure production in the seven regions are shown in Table 4 and the moisture content of livestock and poultry faeces and urine are given as Table 5. The spatial distribution of livestock and poultry structure and the breeding scale in China in 2017 are shown in Table 6.

Table 4: Livestock and poultry manure generation in China in 2020 and 2021

Year	Area	Category of livestock and poultry				
		Fatteniing pig	Dairy cow	Fattening bull	Laying hen	Broiler
2020 (million tons)	North China	35	48	33	/	/
	Northeast China	46	27	34	/	/
	East China	74	23	29	/	/
	Central China	112	9	54	/	/
	South China	42	2	18	/	/
	Southwest China	87	24	128	/	/
	Northwest China	17	31	67	/	/
	Total	413	164	364	56	112
2021 (million tons)	North China	35	51	59	/	/
	Northeast China	46	27	63	/	/
	East China	77	23	22	/	/
	Central China	116	9	48	/	/
	South China	39	2	17	/	/
	Southwest China	97	25	113	/	/
	Northwest China	17	28	65	/	/
	Total	428	165	386	56	112

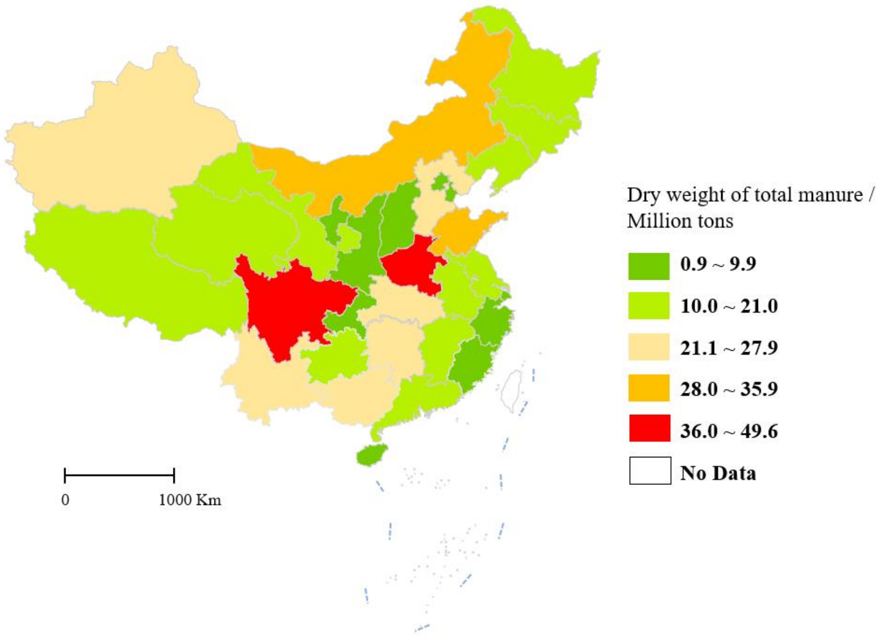
Note: Manure (t) =SL * RP * ER/1000 + RS * [365/ (RP+CP)-ROUNDDOWN (365/(RP+CP),0)] * RP * ER/1000. Where, SL: annual livestock number for slaughter (head); RP: days of raising period (d); ER: livestock manure excretion rate (kg/d/head); RS: livestock number raising at end of the year (head); CP: cleaning period (d) after the raised livestock is sold (Data from Institute of Agricultural Environment and Sustainable Development, 2009 and National Bureau of Statistics of China, 2020, 2021).

Table 5: Moisture content of livestock and poultry faeces and urine (National Agricultural Technology Extension Service Center, China Agricultural Press, 1999)

Manure category	Pig		Cattle		Poultry
	Faeces	Urine	Faeces	Urine	Faeces
Water content (%)	67.25-70.23	93.98-98.04	74.00-76.08	94.05-94.68	49.90-54.72

Table 6: Spatial distribution of livestock and poultry structure in China in 2017 (China Animal Husbandry and Veterinary Yearbook 2017-2018)

Region	Large-scale intensive farming, million head					Household low-intensive farming, million head				
	Fattening bull	Dairy cow	Pigs	Sheep	Poultry	Fattening bull	Dairy cow	Pigs	Sheep	Poultry
North China	1.98	1.56	37.6	29.71	555.72	14.27	1.46	56.07	145.28	951.7
Northeast China	2.27	0.53	34.67	4.09	697.39	13.36	1.13	65.96	34.26	1486.74
East China	1.56	0.94	141.29	9.43	2993.8	10.87	0.43	119.79	69.88	4021.64
Central China	1.35	0.12	115.21	4.03	765	13	0.31	162	61.35	2405.84
South China	0.1	0.08	47.77	0.24	287.89	6.49	0.03	76.65	7.65	2579.88
Southwest China	0.93	0.15	22.07	1.4	135.3	35.71	1.26	219.98	84.52	1798.18
Northwest China	1.54	0.43	13.91	13.91	34.47	19.57	2.37	30.65	144.57	361.44



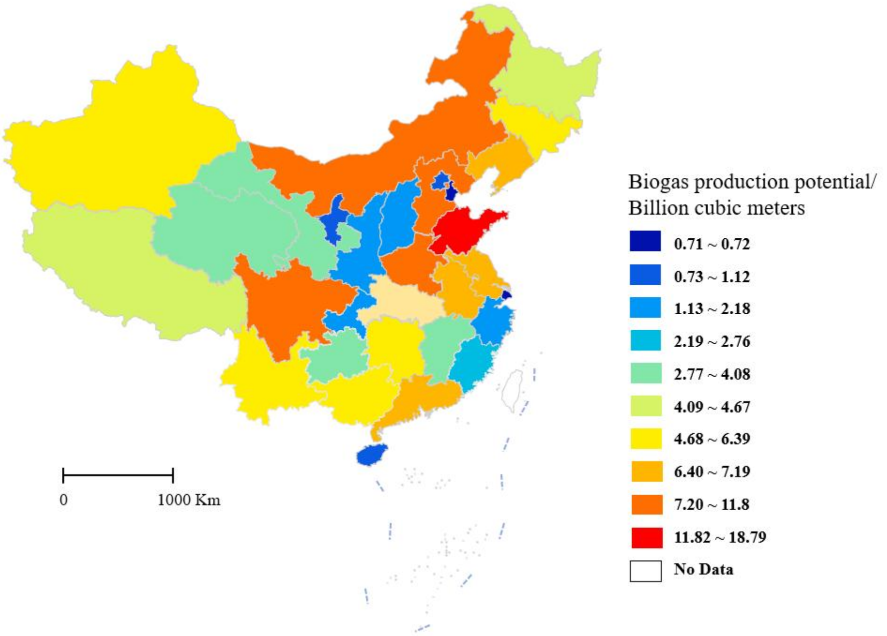


Figure 5: Manure (dry matter) generation and its biogas production potential in different provinces of China (Data from Li et al., 2022 and Wei et al., 2018)

Henan and Sichuan have the highest manure generation, with the highest large-scale pig production. Shandong Province is also a large animal production province, and so is the livestock and poultry manure generation. In 2018, the amount of livestock output of fattening pigs, fattening bulls, sheep, and poultry in Shandong Province was 50.82 million head, 3.63 million head, 26.82 million head, and 238 million head, respectively. The production reached approximately 268.6 million tons (Yu et al., 2021). About 76% of the manure was returned to the agricultural field, 14% to generate biogas, about 5% for organic fertilizer production, and still about 5% un-treated (Yu et al., 2021).

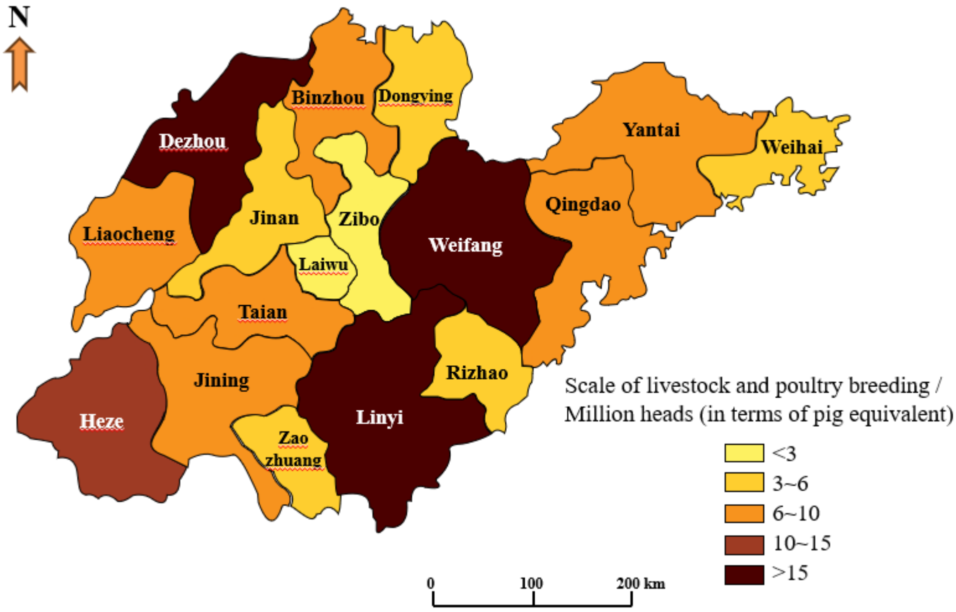


Figure 6: Scale of livestock and poultry production in Shandong Province in 2018 (Data from Yu et al., 2021)

Yantai is one of the cities in Shandong province with the fine utilization of livestock and poultry manure. The average amount of livestock and poultry manure production was around 7.8 million tons during 2010-2019 (Zhou et al., 2021). Fattening pigs and cows generated 4.58 million tons and 1.4 million tons manure, respectively. Fattening pigs' manure was the main feedstock for biogas production. The 2019 Yantai Solid Waste Pollution Prevention and Control Information showed that in 2019, the manure utilization was 9.6 million tons, accounting 96.95% of the total manure (Yantai Ecological Environment Bureau, 2020).

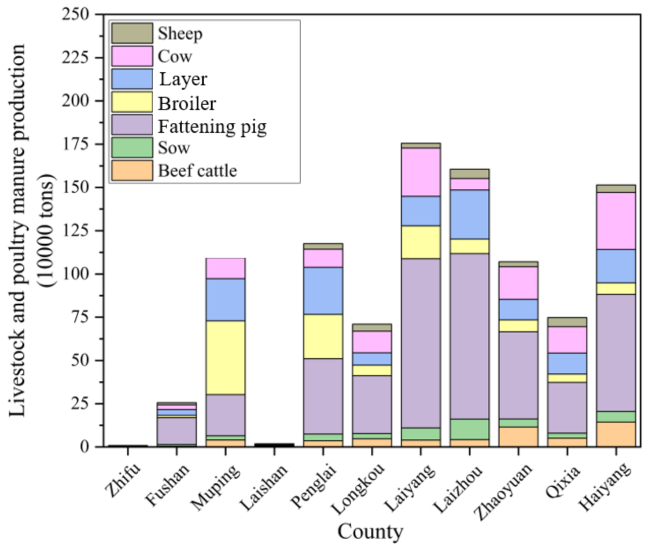


Figure 7: Livestock and poultry manure production in Yantai City in 2019 (Data from Zhou et al., 2021)

3.3 STATE OF THE ART OF MANURE UTILIZATION

There are three main types of manure management respective treatment in China, quite similar to the whole world: storage, composting and biogas oriented anaerobic digestion (AD) (Figure 8). Among these, manure storage and composting are the treatment before manure application on agricultural fields as fertilizer.

Xuan et al. (2018) identified a total of 61,054 large-scale livestock and poultry manure treatment projects during the 12th Five-Year Plan period. The large-scale livestock and poultry manure were mainly used for only fertilizer, about 1% for biogas generation first (and then the digestates return to the agricultural system as fertilizer), which means almost all the energy contained in animal manure was wasted. Over 75% of pig, cow, and beef cattle manure was in storage for agricultural use, because of high water content and further treatment difficulties and costs. A little less proportion, around 65%, of laying hens and broilers manure was in storage, and more than 30% was put into composting, because lower moisture content of the manure makes it easier to produce commercial organic fertilizers.

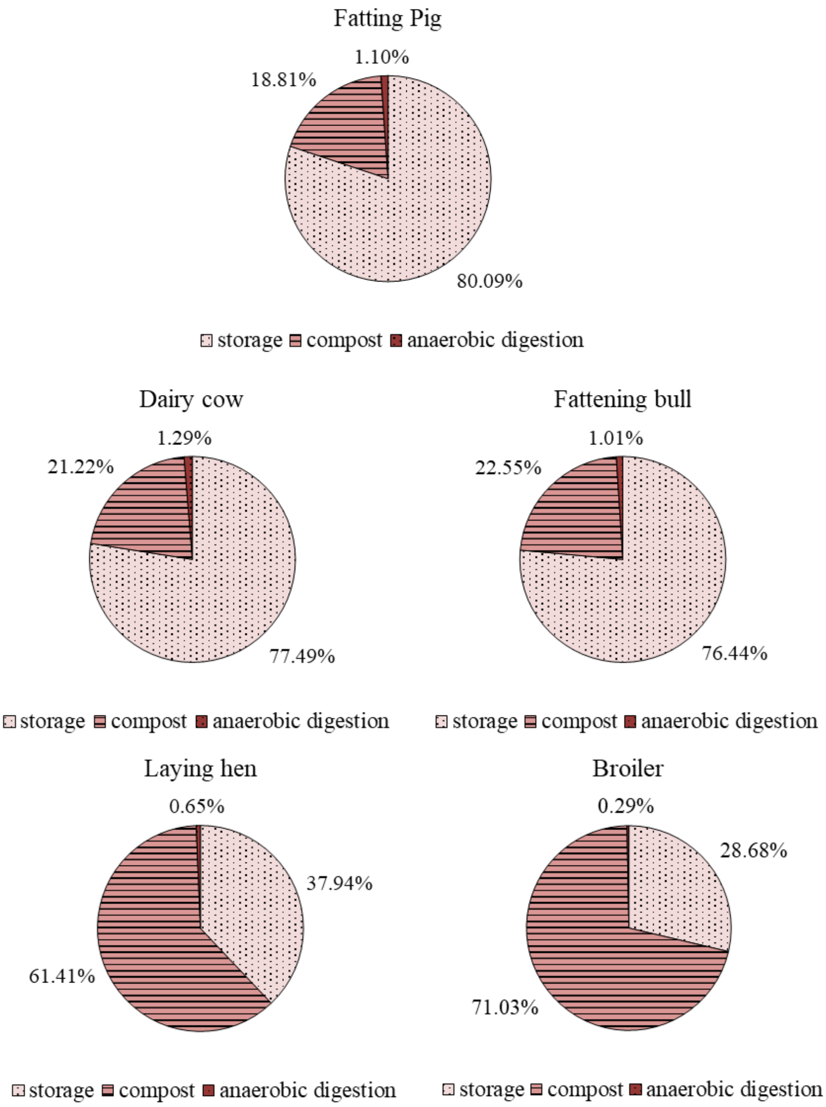


Figure 8: The proportion of different manure treatment in large-scale livestock and poultry farms (Xuan et al., 2018)

However, the wastewater (if any separated from the manure) from livestock and poultry farms was stored (about 35%) or mainly anaerobically digested (about 55%) and then returned to the fields for agricultural utilization. Only about 7% of the wastewater took anaerobic followed by aerobic treatment for a standard discharge or circular water utilization; About 2% wastewater was directly treated with the biological fermentation bed (animals live on a very thick biomass bedding and the faeces and urine drop on and mixed with the bed material, which is subsequently degraded by microbials in the bed material) which is integrated into animal houses (Xuan et al., 2018).

The 13th Five Year Plan for National Rural Biogas Development estimated that anaerobic digestion could easily harvest about half of the manure's energy potential as biogas, about 55 bcm, while the remaining hard-to-degrade component could become soil amendments. With anaerobic fermentation and biogas production, almost all nutrients could be kept in the digestates and almost all methane emission could be cut off. Other ecological and hygienic parameters are quite similar as composting. For some cases (e.g. manure from different farms) further treatment or a thermophilic AD is needed to make the digestates more hygienic.

China offers all common anaerobic fermentation processes for manure treatment and biogas production (Figure 9).The completely stirred tank reactor (CSTR) has been proved to be more suitable for large-scale manure treatment because it has perfect in-tank mixing of the fermentation materials, stable fermentation and biogas production, and relatively low investment and running cost. The Up-flow Anaerobic Sludge Blanket (UASB), with its relatively stable process, can be applied to wastewater following the solid-liquid separation of manure. Underground biogas reactors typically operate on a plug flow process, either with or without a horizontal plug-flow stirrer. They are typically sealed with a black UV-resistant film known as geomembrane, and are often compared to covered lagoons. It requires significantly less investment and is easier to operate, boasting good thermal insulation and low energy consumption. However, its biogas production rate is lower and its fermentation cycle is longer. China also uses other anaerobic fermentation processes, such as the up-flow sludge blanket (USB). The USB offers several benefits in treating medium-low solids content liquid manure (TS).

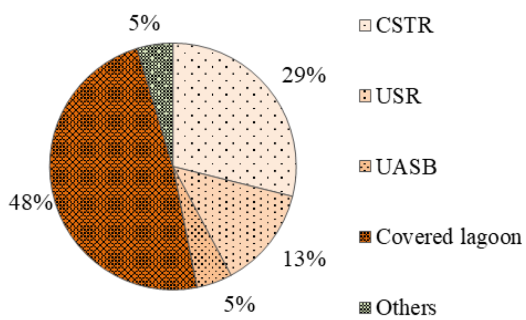


Figure 9: Different anaerobic fermentation technologies for manure treatment in China (Zhou et al., 2022)

In recent years, with the encouragement of governmental policies, the biogas industry has developed rapidly in China. Most biogas plants consume livestock and poultry manure as feedstocks. Household biogas plants, and medium- and large-scale biogas plants can be constructed to treat household animal manure and manure from medium and large-scale animal farms. Large-scale biogas plants can also be used to treat the collected manure from regional animal farms.

By the end of 2015, there were 103,898 small and medium-sized biogas projects, 6,737 large biogas projects, 34 super large biogas projects, 458 biogas projects using straw as the main raw material, and 110,517 biogas projects using livestock and poultry manure as the main raw material (Figure 10). China has abundant biogas raw materials, mainly consisting of livestock and poultry manure and crop straw, with production amounts of 700 million tons and 3 billion tons respectively. On the other hand, the use of livestock and poultry manure as fermentation raw materials is more prevalent.

Biogas utilization is shifting from rural household cooking to domestic gas supply, combined heat and power generation, and now to biogas upgrading to biomethane. It is also interesting to see some biogas-to-bio-methanol or even bio-hydrogen trials.

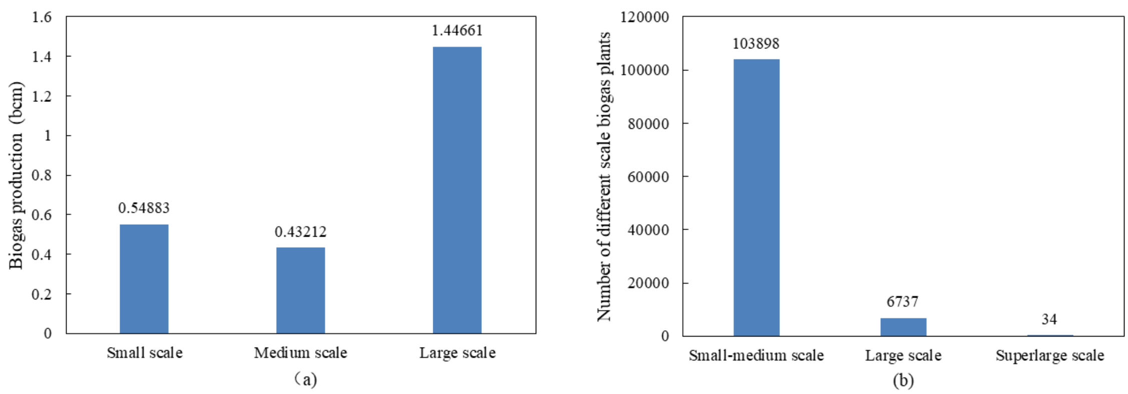


Figure 10: Different scale biogas plants in China: (a) biogas production; (b) numbers of biogas plants (National Development and Reform Commission, 2017)

By the end of 2016, the number of household biogas plants reached 43.8 million, and the medium and large-scale biogas plants number had further growth, up to 113,400, including 51 super-large biogas plants with a daily gas output of more than 5,000 m3, 7,200 large-scale biogas plants with daily biogas production between 500 m3 and 5,000m3, 10,700 medium-sized biogas plants (daily biogas production 150m3-500m3) and 95,200 small biogas plants (daily biogas production lower than 150m3)(China Rural Statistical Yearbook-2016).

Biogas fermentation generates phytohormones (Table 7) and essential aminol acids (Table 8).

Table 7: Phytohormones generation in anaerobic digestion (mg/L) (Li, 2016)

Phyto-hormones	Chicken manure		Cow dung		Pig manure	
	Raw manure	Biogas slurry	Raw manure	Biogas slurry	Raw manure	Biogas slurry
Gibberellin acid (GA_3)	1.45± 0.65	44.83± 1.68	3.06± 0.67	38.53± 1.40	4.25± 0.26	16.37± 2.16
Indoleacetic Acid (IAA)	4.44± 0.03	36.84± 4.32	7.05± 0.92	17.38± 2.31	4.37± 0.02	21.17± 2.02
Abscisic acid (ABA)	6.45± 0.15	13.23± 2.82	7.24± 0.28	23.53± 2.27	8.79± 0.37	35.59± 3.42

Table 8: The content of essential amino acid in biogas digestates (Li, 2016)

Essential amino acid	Content (mg/L)
Asparagine	12.3
Threonine	5.42
Glutamic acid	14.01
Glycine	8.07
Alanine	6.56
Cysteine	26.49
Valine	12.7
Leucine	1.24
Phenylalanine	12.03
Lysine	7.65
Tryptophan	7.1
Asparagine + Glutamine	356.03
Isoleucine	7.16

3.4 ENGINEERING CASE

3.4.1 Jiangsu Xinyi Animal Manure Treatment and Valorisation Project

In order to solve the problem of animal manure treatment and crop fertilizer reduction in a region (usually a county region), China has carried out pilot projects to promote the animal-crop integration in the whole county region in recent years. Jiangsu Xinyi Animal Manure Treatment and Valorisation Project (the "Project") is located in Huaying Agricultural Ecological Industrial Park of Jiangsu Xinyi County (the "Park"). The project, with total investment of 65 million Yuan, is designed to treat whole livestock manure and some crop residues in the park.

Figure 11: Overview of Jiangsu Xinyi Animal Manure Treatment and Valorisation Project

Table 9: Process parameters of Jiangsu Xinyi animal manure treatment and reuse project

Parameter	Indicators
Fermentation Process	Continuous Stirred Tank Reactor (CSTR)
Temperature	Mesophilic temperature 36 ~38°C
Stirring	Continuous stirring
HRT	25 d
Fermentation volume	Four 5,000m^3 vertical-stirring mesophilic CSTR anaerobic fermenters with special sand and scum discharge design
Feedstocks	Chicken manure, duck manure, pig manure, crop residues
NH_4 concentration in the fermentation tank	About 6,500 mg/L
Raw material collection and pretreatment methods	Animal manure and other organic waste within 30 km of the Park are collected and transported to the biogas plant site. Mixed stirring precipitation and hydrolysis as pretreatment.
Daily processing capacity	463 t agriculture waste (333 t duck manure, 120 t pig manure, 10 t crop residues), TS-6~10% of feed

Biogas production	24,500 m^3/d
Methane content	55~60%
Biogas upgrading	Two biological desulphurization units (4 m diameter with 12 m height) plus one chemical desulphurization unit, with 70%-120% processing flexibility and daily processing capacity of 22,000 m^3
H_2S content	20 ppm after desulfurization
Biogas storage	Double-membrane gas tank
Biogas utilization	Heating in the Park or to upgraded biomethane for export to natural gas network through membrane purification system to produce CNG (Compressed natural gas)
Daily slurry production	246.5 t/d
Slurry digestate treatment	Project recycling (reuse) and crop field application in the Park after certain period of storage
Fibre digestate treatment	The daily 63t fibre digestate, mixed with 40t of crop residues (peanut shell, rice husk, straw, etc.) is treated in a flipping composting /deodorizing composting system
Organic fertilizer	24,000 t/a

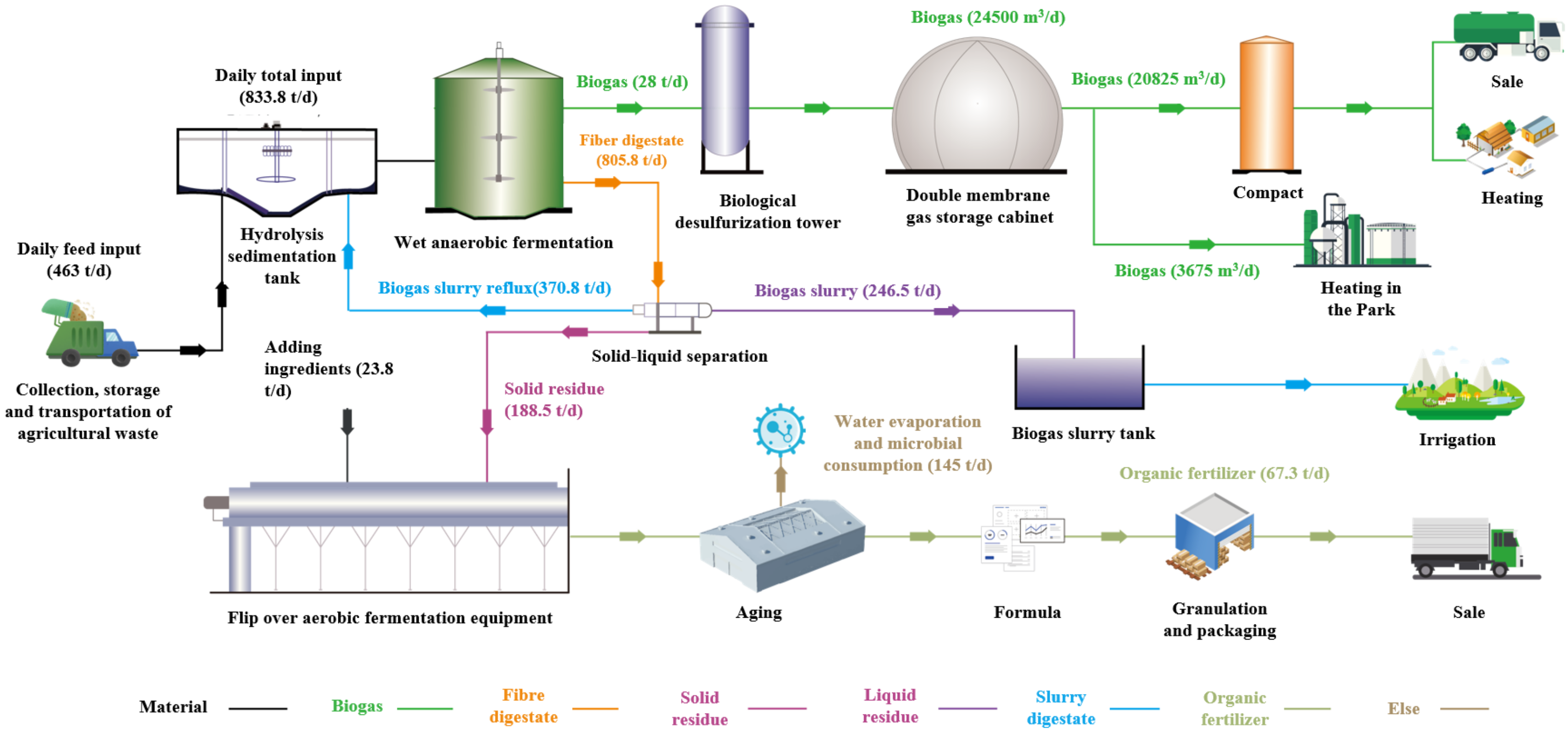


Figure 12: Process flow of Jiangsu Xinyi animal manure treatment and valorisation project

This project is a demonstration project approved by the Ministry of Agriculture and Rural Affairs of the People's Republic of China to promote the resource utilization of livestock and poultry manure throughout the county.

By selling biogas, organic fertilizers, and providing waste treatment services to generate revenue, the project's annual operating income has reached over 3.7 million Euros per year.

Since September 2020, the project has been operating efficiently and stably 24 hours a day, 365 days a year, for 3.5 consecutive years.

The project has been proved to be a successful model for regional promotion of the green agricultural development, continuously improves the performance of centralized treatment of regional organic waste, integrates and transforms forward-looking technologies such as carbon emission reduction and comprehensive utilization of biogas slurry.

3.4.2 China Modern Dairy Holdings Ltd.

China Modern Dairy Holdings Ltd. (Modern Dairy) was established in 2005 and listed on the Hong Kong Stock Exchange in 2010. Modern Dairy pioneered the 10,000 head large-scale dairy farming in China, and has now operated more than 60 large-scale farms in 14 provinces across the country, with more than 500,000 dairy cows and nearly 10,000 tons of fresh milk production per day. The company released the FRESH sustainable development strategy, focusing on five pillars of "future, responsibility, environment, society and health". It has released ESG reports for ten consecutive years, taking the lead in setting the industry-leading “carbon peaking and carbon neutrality” target, and vigorously promoting the green transformation of the industrial chain. Modern Farming has joined the United Nations Global Compact Organization (UNGC). (https://www.xiandaimuye.com/)

All Modern Farming dairy farms have realized the harmless utilization of manure as resources and adopted the energy ecological biogas engineering process, building manure collection and pretreatment, anaerobic fermentation, biogas purification and utilization, and biogas residue treatment and utilization systems. 100% of the existing pastures are equipped with a complete automatic manure collection and treatment system, and the biogas generated by anaerobic fermentation is used for power generation and heat production. Reduce greenhouse gases from energy outsourcing and manure management. Biogas from cow dung replaces 30% of conventional energy every year. The average carbon footprint in 2023 is 0.89 kg CO_2e/kg FPCM (fat and protein corrected milk). Modern Farming is the only Chinese livestock company selected in the COP28 "2023 Corporate Climate Action Case Collection". (https://www.xiandaimuye.com/)

Table 10: Energy Use in Modern Farming

Indicator	Unit	2023	2022	2021
Manure biogas	Mm^3/a	189	168	165
Biogas electricity	MWh	115,130	107,550	68,180
Biogas steam	Thousand tons	490	460	390

Table 11: Greenhouse Gas Emissions in Modern Farming

Indicator	Unit	2023	2022	2021
Total GHGs	tCO_2e	2,309,312	2,064,838	1,325,668
Scope 1 GHGs	tCO_2e	1,946,733	1,654,589	1,116,992
Scope 2 GHGs	tCO_2e	362,578	410,249	208,676
GHGs intensity	tCO_2e/M Yuan	171.59	167.94	201.24
GHGs intensity	tCO_2e/FPCM	0.89	0.90	0.91

Note: GHGs inventory includes carbon dioxide, methane, and nitrous oxide. GHGs accounting is calculated based on the "2021 Baseline Emission Factors for Chinese Regional Power Grids" published by the Ministry of Ecology and Environment of the People's Republic of China, as well as the "IPCC 2006 National Greenhouse Gas Inventory Guidelines 2019 Revised Edition" published by the Intergovernmental Panel on Climate Change (IPCC).

3.5 LESSONS LEARNT AND PERSPECTIVES OF MANURE UTILIZATION

Biogas has at least five roles for the green development, nutrients, energy, water, carbon, and organic matter (NEWCOM, Figure 13). Evidently to collect almost all livestock and poultry manure into biogas plants for biogas production will degas the manure, resulting in at least 90% manure management methane emission reduction (Ju, et al, 2022)(Table 12), which accounts for the same rate of methane emission reduction for non-ruminants and accounts for about 30% of the ruminants whole production chain methane emission reduction.

Biogas can also contribute a lot to paddy rice methane emission reduction, by taking the rice straw away from the land and degas it in biogas plants. The degassed organic matter should be returned to the field to keep soil organic matter stable or increase. The methane emission reduction in double-cropping rice field in temporal and sub-tropics zone is about 213 kg CH_4/(a·ha), while in single season rice field in cold zone is about 81 kg CH_4/(a·ha) (Yan, et al, 2022).

The world climate change mitigation strategy presents an unprecedented opportunity for biogas industry to flourish. However, despite its potential and well-developed technologies, the industry continues to face challenges. To fully realize its potential, government support is essential, including subsidies for manure treatment, incentives for biogas power generation and biogas upgrading to transportation fuels, and the establishment of robust greenhouse gas emission reduction accounting and trading systems. Furthermore, effective biogas plant management, continuous technological innovation, and the adoption of best practices for digestate field application are crucial for the industry's growth and sustainable manure treatment. Here are major obstacles currently impeding the development of biogas industry:

- Inadequate awareness of biogas importance in the new situation of coping with climate change;
- Insufficient support by a clear and traceable, stable and sustainable, and friendly and reliable policy scheme;
- Short of financial tools to realize the economic value of biogas ecological benefits;
- Lack of driving forces to develop standards, to innovate technologies, and to account the ecological contributions of manure biogas plants.

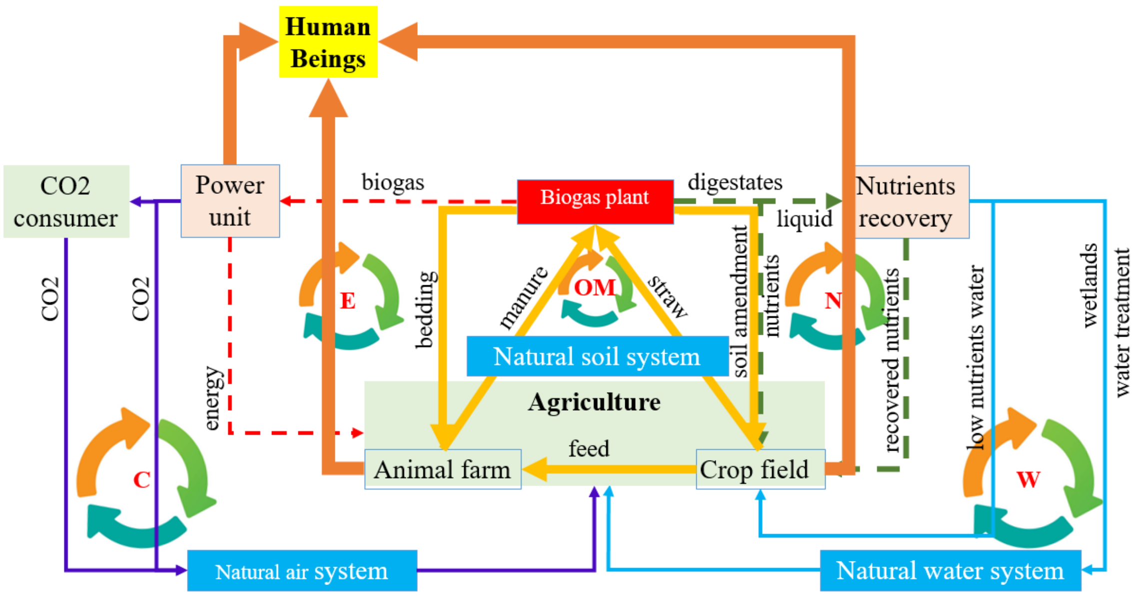


Figure 13: Overview of agricultural biogas roles in nutrients, energy, water, carbon and organic matter recycling, for coping with climate change

Table 12: Annual GHGs emission from one adult milking cow (iBEST calculation)

GHGs source	GHGs emission				Total emission of enteric and manure management kg CO_2e	GHGs emission reduction compare to 100% lagoon	
	CH_4 kg	N_2O kg	CO_2 kg	Sub $kgCO_2e$		Non-CO_2	Total
Enteric methane	96	0	0	2,688			
100% manure in biogas plant	14.1	0.25	0	461	3,149	93	67
100% manure in stack retting	12.9	2.08	0	912	3,600	86	62

100% manure for open lagoon	234.8	0.55	0	6,720	9,408		
100% manure for compost	3.21	1.68	36.6	572	3,260	92	65
85% manure for compost# +15% manure for biogas*	555 $kgCO_2e$				3,243	92	66
85% manure for compost+15% manure for open lagoon	1,494 $kgCO_2e$				4,182	78	56

Note: (1) iBEST is **National Center for International Research of BioEnergy Science and Technology authorized by Ministry of Science and Technology and affiliated in China Agricultural University.** (2) No electricity needed for stacking and open lagoon, electricity for biogas plant is from biogas so no additional CO_2 generated; only electricity for composting. 100% in stack, or compost, or lagoon is in practice impossible because there is liquid and solids. 85% of the manure could be in solid phase. However, 100% manure could be treated in a biogas plant. (3) Emission factors are from IPCC, 2019.

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4 FINLAND

4.1 INTRODUCTION

In Finland, livestock production is segregated from crop production with dense animal farming on certain areas of the country. This results in regional surpluses and deficits of manure nutrients from the nutrient recycling point of view, while it may also create opportunities for larger scale manure processing. Most of the manure produced is used in fertilization as such and manure processing into renewable energy and/or recycled fertilizer products is still scarce. However, there is an increasing interest in the implementation of especially anaerobic digestion due to its potential to produce energy as biogas, to recycle nutrients from different suitable biomasses, and to reduce environmental effects with respect to gaseous emissions and nutrient loading into waters.

4.2 MANURE PRODUCTION AND AVAILABILITY IN FINLAND

Livestock production in Finland is dominated by cattle production, both for dairy and beef (Table 13). The number of cattle has been slowly decreasing over time especially due to a drop in the number of dairy cows and was in total 834 000 heads in 2022. Also, pork production has been declining since 2008 with 1,061,000 pigs in 2022. Poultry production has, in turn, increased due to increasing consumption of poultry meat, with the number of poultry being 14,356,000 in 2022. There are also smaller numbers of sheep and goats on Finnish farms. Additionally, horses, ponies and fur animals are of relevance to manure management.

Table 13: Number of livestock in Finland in 2022 (Luke, 2023a)

Animal category	Number of animals
Cattle	834,000
Pigs	1,061,000
Poultry	14,356,000
Sheep	132,000
Goats	6,300

The amount of manure produced in Finland is about 13 million tons per year (calculated ex housing, i.e. as manure collected from animal housing prior to further handling; Table 14). As evident also from the number of livestock, most of the manure is from cattle comprising 75% of all manure produced.

Table 14: The amount of manure produced in Finland and its nutrient and organic matter (as volatile solids, VS) content (Luke, 2023b, Luostarinen et al., 2023a)

	Amount (t/a)	Organic matter (t/a)	Nitrogen (t/a)	Phosphorus (t/a)
Livestock manure in total	12,959,083	1,815,877	73,011	15,189
Horse manure	643,840	192,235	2 ,718	484
Sheep and goat manure	109,734	22,334	781	156
Poultry manure	241,860	108,699	5,748	2,319
Cattle manure	9,752,247	1,318,024	50,565	8,629
Pig manure	2,099,851	146,370	9,898	2,108
Fur animal manure	111,551	28,215	3,301	1,493

Table 15: Energy potential of manure as biogas in Finland (Miettinen et al., 2022)

Manure	Energy potential (TWh/a)
Cattle manure	2.501
Pig manure	0.495
Poultry manure	0.250
Sheep and goat manure	0.011
Horse manure	0.325
Fur animal manure	0.063
Total	3.645

*Methane production potential (m^3CH_4/t-VS): cattle slurry 200; cattle solid manure 200; pig slurry 320; pig solid manure 230; poultry manure 210; horse manure 160; sheep and goats 100; fur animals 235. 1 m^3CH_4 = 1 kWh.

The shares of different manure types (slurry, different solid manures and urine) are also calculated and considered in the manure data (Grönroos et al. 2017). This offers the possibility to estimate biogas production potential of manure in greater detail. For 2020, the energy production potential of manure as biogas was estimated at 3.65 TWh (Table 15).

In practice, most of the manure produced in Finland (92.8%) was applied on fields without any processing (Luke, 2023b). The processing technologies used include anaerobic digestion (~2.5% of total manure amount), composting (~4.0%), mechanical separation (~0.57%) and thermal drying (~0.13%). Most of the existing biogas plants digesting manure are farm-scale installations with cattle slurry dominating the manure types being digested. There are new biogas plants digesting manure being built and under planning at the time of writing. The plants include both smaller farm-scale plants (<10,000 t/a), middle-sized farm co-operative plants (10,000-50,000 t/a), and large-scale centralized plants (up to 500,000 t/a). The share of manure directed to anaerobic digestion is therefore expected to increase significantly in the coming years.

While the Finnish livestock production is regionally concentrated to certain areas, also the highest biogas production potential from manure is on these same areas (Figure 14). Most of the cattle production is found in western and central Finland, while pig and poultry production are concentrated to southwestern and western Finland. Also, fur production is mainly on the western coastline of Finland, with the other animals more widely spread around the country. To highlight the spatial distribution of manure in Finland and to tie it with field area available, a map comparing the availability of manure phosphorus and field area is presented in Figure 14 (Lemola et al., 2023). The segregation between livestock and crop production can be seen in the central, western and southern Finland with little manure phosphorus available per field area in the regions of light yellow and a lot of manure phosphorus available per field area in the regions of dense livestock production. In northern Finland agricultural area is scarce explaining the seemingly higher manure phosphorus availability per field area.

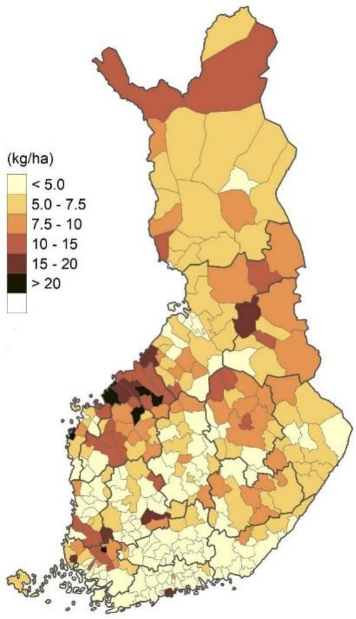

Figure 14: Manure phosphorus per field area in Finland in 2020 (on average for all country 6.7 kg/ha). The borders of municipalities are marked with grey line and those of regional Centers for Economic Development, Transport and the Environment with black line (Originally published in Lemola et al., 2023)

4.3 MOTIVATION FOR THE ADOPTION OF MANURE-BASED AD IN FINLAND

The techno-economically feasible energy production potential as biogas from anaerobic digestion has often been estimated to be about 10 TWh/a in Finland. Of this, approximately 1 TWh is currently being produced (Figure 15). While the number of large-scale plants co-digesting different wastes and side streams from municipalities and industries has increased in recent years, the utilization of manure and other agricultural side streams is still low. All-in-all, most of the unused biogas production potential is in the agricultural side streams.

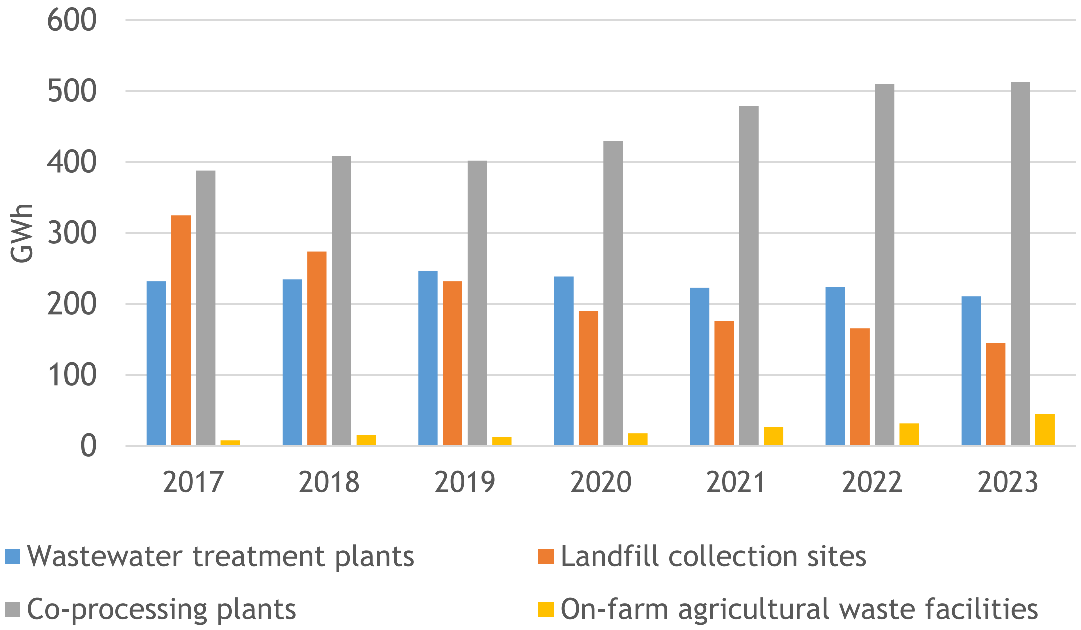

Figure 15: Development of biogas production per plant type in Finland (GWh, Official Statistics of Finland, 2024)

The Finnish biogas sector aims at increasing the biogas production to 4 TWh by 2030 (Finnish Biocycle and Biogas Association). Of this target, 2 TWh would be produced from livestock manure and side streams of food production, the share of manure in the aimed 7 million tons of feed capacity per year being 4.7 million tons (approximately 30% of all manure produced and 67% of the planned feed capacity).

The Finnish Biogas Program was prepared under Ministry of Economic Affairs and Employment in 2019 (Ministry of Economic Affairs and Employment, 2020). While the Program aimed at supporting overall increase in biogas production for energy and as one of the measures to decrease Finnish greenhouse gas (GHG) emissions, also the issues of nutrient recycling and support for implementation of new manure processing technologies were acknowledged. Thus, the Finnish targets to increase biogas production from manure are based on several expected benefits.

Finland has an ambitious target of becoming carbon neutral by 2035 and all measures towards this are needed. Biomethane is seen as an important option especially for heavy duty transport to reduce fossil fuel consumption and related climate impacts in transport sector. This is a significant driver for large, centralized biogas plants digesting manure. Also, increased self-sufficiency in energy has gained value and is an important reason for investing in biogas production for overall Finnish energy sector, but also for individual farms considering farm-scale biogas plants. This is also an economic issue for the farms: own energy production saves energy costs of purchased energy.

Finland has also aimed at being a model country for nutrient recycling since 2010. Livestock manure is estimated (at the time of writing) to cover 65% of phosphorus fertilization needed in Finland if the manure phosphorus could be evenly distributed to the fields (Lemola et al., 2023). Overall, the issues of self-sufficiency and security of supply also regarding fertilizers has become more significant due to high dependence on imported nutrients from politically volatile regions. Environmentally the regions of surplus manure nutrients hold the increased risk of nutrient loading to waters. Thus, biogas production is seen as part of the solution to increase nutrient use efficiency, reallocate manure nutrients (both locally from livestock farms to crop farms and regionally from surplus regions to regions in deficit), replace mineral fertilizers, and to reduce overall nutrient use and related environmental impacts.

While digestate or its mechanically separated fractions offer new possibilities to reuse the manure nutrients already in farm-scale via improved use of nitrogen and partial separation of nitrogen and phosphorus into solid and liquid fractions, these end-products may also be more interesting for neighboring crop farms to receive. This would already improve manure nutrient use. Larger-scale farm-cooperative biogas plants may offer reallocation options for manure nutrients between participating farms, while centralized biogas plants may be able to further process digestate into such concentrated recycled fertilizer products that can be transported longer distances and truly solve the regional nutrient surpluses. At the same time, well-designed, -built and -operated biogas plants can reduce the GHG-emissions from manure management (Luostarinen et al., 2023b; Lehtoranta et al., 2024) and replace mineral fertilizers with recycled options to reduce the climate impact of all fertilization.

4.4 MAIN PROBLEMS/BARRIERS OF INCREASING MANURE FOR BIOGAS PRODUCTION

The main obstacles for increasing biogas production from manure are economic. While the biogas plants digesting different wastes and side streams from municipalities and industry have been able to build profitable business based on especially gate fees and energy sale, manure biogas does not follow the same principles.

At a farm level, the investment and running costs are entirely the responsibility of the farmer, and in order to decide to invest in their own biogas plant, the farmer needs a sufficient return, usually in the form of a combination of benefits. The average size of Finnish livestock farms has been rather low, thus affecting the economy of potential biogas production on farms (the larger the farm, the better the profitability of biogas plants). While the size of farms has been growing, this has meant large investments already to the livestock production, leaving less possibilities to invest simultaneously also in manure processing. In addition, the price of energy has been rather low, reducing the economic benefit of producing biogas for own energy consumption. Furthermore, the main livestock production in Finland, cattle production, require less energy, especially less heat than other livestock, further affecting the profitability of farm-scale biogas plants. The other benefits of biogas plants may be more difficult to value economically, thus e.g. the benefit of more soluble nitrogen in digestate in comparison to unprocessed manure has not been sufficient to further boost the profitability of farm-scale biogas plants.

In farm-cooperative biogas plants, the benefits of recycling the manure and potential other agricultural residues via the plant need to give the participating farms sufficient benefits for them to invest in the joint plant. A few good examples of such cooperatives are available in Finland in which the participating farms and potential other companies receive synergies for the cooperation and are also able to share the investment costs. The cooperative provides a valuable service to its member farms by facilitating the redistribution of manure nutrients. This system allows each participating farm to receive an adjusted amount of nutrients, either less or more, depending on their initial contribution of feed materials.

Centralized biogas plants basing a significant share of their feed input on manure most likely need to build their economy on a wider combination of returns as the farmers rarely are willing to pay gate fees for manure. Their main income is from energy, but some of it also comes from additional feed materials with a gate fee. The centralized plants also need to find income from the digestate as it a major product from the plant and in this, solutions benefiting both the plant (receiving manure to biogas) and the farmers (getting rid of potential surplus manure and/or receiving suitable recycled fertilizer products) are required. As there are in practice only one larger biogas plant in Finland digesting manure, the issue is still new to the Finnish livestock farms. There are concerns over whether the cooperation with centralized biogas plants as totally separate business from the farms is beneficial to the farms with respect to ‘what do we get from this’. The building of trust, working practical management of the manure and good agreements benefiting both the farmers with the manure and the biogas plants wanting to digest the manure are in a key position when planning new centralized biogas plants basing much of their feed input on manure.

Several different incentives are available for different scales of biogas plants digesting manure to help solve the challenges with profitability. Farm-scale and farm co-operative biogas plants have long been supported by investment support with separate support rates for farms utilizing the energy themselves (40%) and for those selling (most of) the energy (30%). However, in 2021, the investment support was (temporarily, still valid at the time of writing) increased to 50% of acceptable costs for both biogas plant operations to promote biogas production on farms. Since then, the number of agricultural, farm-scale and farm cooperative biogas plants (capacity roughly 5,000 – 40,000 t/a) has increased. In addition to these, large-scale biogas plants digesting different feed materials, including manure, can apply for investment support from the Ministry of Economic Affairs and Employment (energy and investment aid for projects with a budget of 5 million euros or above). The support for biogas plants has usually been maximum 30% of acceptable costs.

Also, the demand and price of biogas or biomethane is an uncertainty which is slowing investments down. The distribution obligation increasing gradually to 34% after 2029 with the goal of increasing the availability and use of biofuels (and sub-goal for second-generation biofuels increasing from 2% in 2021 to 10% in 2030) and the emission reduction scheme for transport affect the plans for biomethane production. Biomethane was added to the distribution obligation at the beginning of 2022, but the planned changes to level and ambition of distribution obligation make long-term planning difficult. Also, the demand for investment support has been increasing and its adequacy for all planned installations is a concern.

Other financial support is not available for farm-scale biogas plants digesting manure and using the digestate themselves. However, incentives to deliver or sell digestate or further processed fractions from it are available in the attempt to boost the market for recycled fertilizer products and thus promote reallocation of manure nutrients especially in regions of surplus. In the Finnish Common Agricultural Policy, measures related to the use of manure and recycled fertilizer products are directed to crop farms receiving or buying them (including digestate or further processed fractions from it in support of circular economy, more precisely nutrient recycling. The support does not distinguish between unprocessed manure or manure processed with any technology and in any scale. Also, a totally new incentive mechanism called “nutrient recycling support” was implemented in the beginning of 2024 (81/2024; Ministry of Agriculture and Forestry, 2024). It offers operational grants to biogas plants producing biogas and recycled fertilizer products for the market from manure or waste from the management of aquatic vegetation (i.e. not applicable when the farm uses the digestate itself). The grants are awarded via a competitive tendering process through which the applicants compete for support for the costs of processing phosphorus into recycled fertilizer products.

At the time of writing the first tendering process was just decided on, awarding the support to five different biogas operators. There are no decisions on continuing the support further after the first round, but experiences are collected of the mechanism’s impact to evaluate the potential continuation later.

4.5 INTERESTING FEATURES OF NEW DEVELOPMENT

The use of manure as a feed in biogas plants is increasing at the time of writing. According to data collected by Finnish Biocycle and Biogas Association for 2024-2027, eight large, centralized biogas plants digesting mostly manure are being planned with over 0.9 TWh of capacity as energy in total and 200,000 – 500,000 t of feed per year each. In addition, 11 farm-scale plants (5,000 – 20,000 t/a each) and 10 farm cooperative/’middle-scale’ biogas plants digesting agricultural feed materials (20,000 – 50,000 t/a each) are being planned.

Most of the biogas plants built and being planned are based on conventional CSTR-type digesters, though some biogas plants also use dry fermentation technologies of continuous plug-flow or batch-operated leach bed types. Most of the biogas plants digesting manure also co-digest other feed materials: in farm-scale plant biomasses, often different grasses otherwise produced on the farm and in farm cooperatives plant biomasses (grasses, straw) and other suitable materials from the local businesses (e.g. potato side streams). In centralized biogas plants, manure is only used to a limited extent, mainly as a minor component of the feedstock, which consists of municipal and industrial waste and by-products. Manure is usually not directed to those biogas plants which digest sewage sludge as the digestate or its further processed derivatives containing sewage sludge are more restricted in use as fertilizer products both with restrictions in regulation and due to major crop buyers forbidding the purchase of crops fertilized with sewage sludge containing fertilizer products.

Most of the smaller farm-scale biogas plants make use of the biogas energy via CHP units, using the produced electricity and heat themselves. However, few farm-scale biogas plants also upgrade and sell compressed biomethane. As a novel possibility, there are plans to build farm-scale biogas plants as a satellite to a centralized biogas plant (also basing the feed mixture mostly on manure) with the aim of transporting compressed biomethane from the farm-scale plant to the centralized plant for the production of liquified biomethane for heavy transport. The farm-cooperative plants digesting manure are divided between CHP-production and that of compressed biomethane depending on their location (if suitable for a biomethane filling station) and potential energy user as one of the partners in the cooperation (e.g. a greenhouse using all produced energy).

There is currently only one larger biogas plant digesting mostly manure (Jepuan Biokaasu Ltd) and they produce and sell compressed biomethane as transportation fuel and to industries to replace natural gas. The centralized biogas plants in the planning stage at the time of writing and basing most of their feed on manure are planning to upgrade biogas into biomethane, but in a liquefied form. The conversion of the biogas carbon dioxide into methane (e-methane) is also being planned in some of these future centralized plants.

The digestate from farm-scale plants is usually used totally on the same farms. Some of the newer plants on cattle farms separate the digestate with a screw press and use the solid fraction as bedding material in cattle housing. The digestate from farm cooperative biogas plants is usually applied on the fields of the participating farms, but on some plants part of the digestate is also transferred or sold to other farms than the ones participating in the cooperative. This is more common when the biogas plant is digesting mainly pig slurry due to the participating pig farms having less use for the manure phosphorus ending up in the digestate and thus a larger share of it is available for use on other farms.

The centralized biogas plants basing most of their feed input on manure are currently considering what to do with the digestate they produce. As their capacity is very high in the Finnish context (200,000 – 500,000 t/a) and they are planned on locations of dense livestock production, the need to invest in digestate processing is significant. However, at the time of writing, it appears that not many of these plants are ready to invest in much other than mechanical separation of the digestate due to wanting to focus on biomethane production, the high cost of more advanced digestate processing and underdeveloped market for recycled fertilizer products with concerns over the price achievable. It also depends on the region and the farms surrounding the plant whether there is a demand for the large volumes of digestate as such or as separated fractions within a small enough radius from the plant to enable its logistics. In some of the planned regions the phosphorus status of the field soils close by is rather high, decreasing the demand for the phosphorus in the digestate and increasing the need to transport it further away. This may drive towards more advanced processing of the digestate solid fraction. Also, the high volume of liquid fraction (or digestate as such) may be very difficult logistically to distribute with e.g. available storage capacity and the intense transportation needed limiting the solution. This, in turn, drives towards concentrating the liquid fraction into smaller volumes. It is also not known at the time of writing what kind of demands the environmental permitting places on the centralized biogas plants. Especially in regions with high P-status in field soils, manure phosphorus surplus and poorer state of the surface waters, demands for digestate processing are to be expected.

4.6 CONCLUSION

Manure biogas is a great opportunity in Finland to enhance the use of manure both as energy and as a source of recycled nutrients and organic matter.

Implementation of biogas production from manure requires still public financial support as its efficient use requires a large change in the manure use on farms with farm cooperatives and larger processing plants taking part of the manure processing and distribution as opposed to each livestock farm only managing the manure themselves. Public support should be available in the longer term to ensure stability during the market development phase for biomethane and recycled fertilizer products. Also, the regulation regarding manure management and fertilizer use should drive towards more precise fertilization and equal fertilization limits to all fertilizer products to push manure into biogas plants.

To ensure the sustainability of the manure biogas (and biogas from all other feed materials), the design and operation of the biogas plants should include proper consideration of emission reduction within the plant and when consuming the end products. Inadequate execution and management of the plant and use of the end products may result in deterioration of the benefits of biogas plants and failure to reduce the emissions into the environment. Such bad investments should be avoided by setting clear and strict requirements on how the biogas plants should be built and maintained and how the emissions from biogas energy use and digestate reuse are minimized. This can be achieved within environmental permitting and the sustainability requirements related to Renewable Energy Directive of the EU. The resulting costs should be supported with suitable incentives which should only be granted when the sustainability of the entire biogas production chain is properly addressed.

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5 FRANCE

5.1 OVERALL POTENTIAL

According to Agreste, the French Statistics and Forecasting Department of the Ministry of Agriculture, the average farm size is growing quickly in France (Agreste, 2022). The average area has increased from 20 hectares (ha) in 1970 to 55 ha in 2010 and 69 ha in 2020, whilst the number of farms decreased from 1.6 million in 1970 to 0.4 million in 2020.

The current animal population in France may be summarized as follows:

• 16.4 million cattle (IDELE, 2023a);

• 12.2 million pigs (Chambre d'Agriculture, 2023);

• 7.8 million sheep and goats (IDELE, 2023b; IDELE, 2023c);

• 14,000 poultry livestock units (ANVOL, 2020) raising 274 million birds comprised of 65.1 million laying hens, 22.3 million pullets, 143.6 million broilers and 43 million other poultry (Agreste, 2023).

However, these population numbers cannot provide an exact estimate of the amount of manure that is available for biogas production as there are many factors influencing the accessibility of manure.

The Transition(s) 2050 report (ADEME, 2021) estimated the total slurry and manure fresh matter (FM) availability to be 120 million tons FM/a (or 24.2 million tons DM with 19.4% organic matter). The Biomass Resources National Observatory (ONRB) undertook an independent assessment (FAM, 2022, 2023) which found a similar estimate of 131.6 million tons FM/a. Assuming that 5% of the manure resources are unavailable because of disease risks (e.g. paratuberculosis, brucellosis), it is estimated that 25 million tons FM is treated in AD plants.

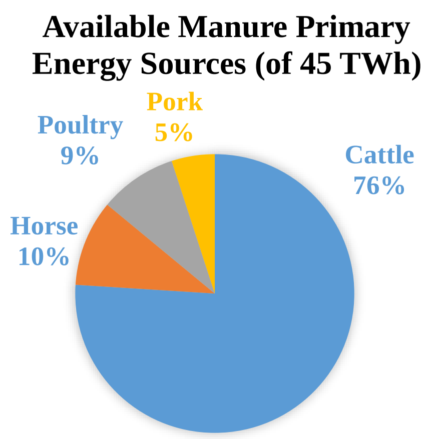

Figure 16: Energy from Available Manure from Cattle, Swine, Poultry and Horses (ADEME, 2021)

ADEME 2013 biomass report estimated the primary energetic potential of slurry and manure to be 60 TWh in 2030 (ADEME, 2013). Of this overall potential, 40 TWh could be available and 22 TWh could be effectively used as a source of primary energy via French AD plants. It is forecast that 50% of the liquid manure and 60% of the solid manure will be utilized, representing 95.5 million tons FM/a (France Stratégie, 2021).

In all of its scenarios, the Transition(s) 2050 report (ADEME, 2021) considers greater use of manure to be counterbalanced by a reduction in livestock population, thereby stabilizing primary energy from manure over the long term.

Table 16: Production and utilization of manure in France

Manure Description	Million tons (Mt) FM/a - ONRB 2021 dataset	Effective Calorific Value (TWh) ADEME estimates (2013, 2021)
Liquid (L) Manure PRODUCED	197 (42 available, rest is deposited in pasture)	
Solid (S) Manure PRODUCED	85.5	
L+S manure PRODUCED	282.4	60
L+S manure AVAILABLE	131.6 (120 Mt FM - ADEME estimate)	5.2 (ONRB dataset) – available L manure 35 – available S manure 45 (or 40 in ONRB dataset) - available L+S manure
L+S manure USED	25	22
Available % of L+S PRODUCED	45%	
Used % of L+S PRODUCED	9%	
Used % of L+S AVAILABLE	19%	
Used % of AVAILABLE in 2050	10-35% (ADEME estimate)	
Manure used in 2050		24.3

5.2 STRUCTURE OF AGRICULTURE AND SPATIAL DISTRIBUTION OF MANURE

Manure resources are mostly concentrated in Western France (Britanny with 18% of national production, Pays de la Loire with 14% and Normandy) and South-West France (Pyrenees). Despite the high availability of manure in these regions, it is still underutilized for energy.

Today, most manure is applied directly to the fields, in part due to the cost of materials but also because the animal husbandries are scattered over very large territories.

5.3 STATE OF THE ART OF MANURE UTILIZATION

Manure represents 54.8% of the total feedstock entering AD plants in 2021 (FAM, 2022). Thanks to its good accessibility, buffer power and purchase price premium, one fifth (19%) of the total available manure is converted into energy in France, significantly higher than former estimates (ADEME, 2016). However, manure's low biological methane potential (circa 30 Nm^3 CH_4/t FM) implies that it must be digested with other more energetic inputs, such as crop residues, organic biowaste or intermediate crops. The increasing prevalence of anaerobic digestion (AD) in France does not inherently suggest that it poses a competitive threat to local resource utilization, provided that interregional exchanges remain economically viable and ecologically sustainable. Assuming that the fertilizing efficacy of digestate from AD is comparable to that of untreated manure, the deployment of manure in AD facilities primarily presents supply challenges that are contingent upon its availability within a given region, rather than directly competing with the use of untreated manure.

Table 17: Supports and constraints to the use of manure for energy in France

Supports	Constraints
Huge and steady volumes of manure over the short term	Too many animals bred in sensitive eutrophic areas can raise or worsen issues related to water quality. The opposite issue in regions where livestock are very scattered and the manure resources are widely distributed.
French feed-in-tariff premium and income diversification for livestock and poultry farmers	Unwanted or inhibiting material inputs (e.g. plastics, traces of antibiotics) are more abundant than in countries that use more energy crops (and less manure) as feedstock for AD plants.
Setting up mitigation or substitution financial mechanisms as the "Low Carbon Label" that reward avoided GHG emissions associated with manure (if there was no AD plant)	Social and ecological acceptance (by population) is very limited for large AD plants, in turn limiting the opportunity to optimise plant costs.
Improving manure management to reduce methane potential loss (current slurry methane potential loss is 25-68%) with slurry pit covers marketed and installed by a specialized company	Historically limited growth of the dry AD process, i.e. technical issues associated with dry digestion quickly jeopardized profitability.
	Evolution of the livestock industry could decrease manure availability as, for example, animals spend more time in pasture or animal populations become smaller to limit the manure-related GHG impacts

5.4 COST STRUCTURE

The cost of manure application (€ 1.5-3/m^3) is significantly less expensive than digestate application (€ 4/m^3). The price discrepancy can be explained by the different sprayer equipment (e.g. drop pipe, burier) which is more expensive for digestate application.

In addition, not all farms have the minimum quantity of manure available to build and operate an affordable AD plant. Aggregation with surrounding farms can be an option but this can also encounter local opposition if the project is deemed too big.

5.5 LESSONS LEARNT AND PERSPECTIVES ON MANURE USE

- **Using livestock manure for anaerobic digestion**

France's desire and choice is clear: first mobilize waste resources before considering biomass from crops for AD. Livestock manure therefore remains a priority input/feedstock. Also, French research continually supports innovation in order to remove or reduce the obstacles to the use of manure for AD, e.g. complex treatment for strawy manure, digester incorporation issues, etc. In the future, the quantity of manure could change depending on the change (possibly reduction) in cattle production between now and 2050 and trends in livestock practices (particularly increased time in pasture). Therefore, the ADEME Transition(s) scenarios for 2050 provide utilization rates ranging from 10 to 35% of the available livestock manure.

- **Reasons to use manure in anaerobic digestion**

Even if manure has a low methane potential, it is usually available in very large volumes and constitutes an excellent base for the biology of anaerobic digestion. Anaerobic digestion not only lowers the unpleasant smell of slurry, but it also significantly reduces agricultural GHG emissions.

- **Incentives and support mechanisms**

Most support mechanisms in France provide a clear signal that promotes the use of livestock manure. For example, feed-in-tariff (FIT) rates increase with the rate of manure use, and eligibility or selection criteria favour manure for investments, subsidies, and calls for projects.

The biomethane FIT is not always sufficient to compensate for the lower methane potential (methane yield) of manure. This can be difficult to explain to policymakers who want to see reductions in the cost of biomethane.

- **AD plant technologies**

One the first lessons for on-farm AD operators was to adopt technologies to improve the management of inert materials, such as the removal of string, rocks, blocks, metal, etc. All of these materials can cause equipment breakdown and necessitate a lot of system maintenance. Today, all AD system manufacturers provide a stone trap system and farmers are more vigilant about the quality of manure, including manure from collective providers such as stud farms or stables.

Solid AD systems appeared quickly in France in response to the desired objective to treat manure first, and, more specifically, dry biomass. Many builders focused on continuous or discontinuous dry process solutions, both in the form of new and adapted processes. Compared to liquid AD and its technical and energy solutions, solid AD systems have not met expected levels of performance.

Feedback indicates that the choice of technology should not only be based on the methane potential or the dry matter content of the inputs but, firstly, on the operators' expectations regarding the robustness of the technology to feed complex and viscous inputs and to manage the concentration of short-chain fatty acids to avoid a blockage of the physical and/or biological process.

Finally, it should also be mentioned that a psychrophilic (low temperature) digestion process can be a complementary AD solution in France. That is, existing slurry pits can be covered to capture the biogas when operators do not want to make a large investment in biogas upgrading. Seventy such units are in operation in France, and the slurry pit covers have demonstrated good performance with the captured biogas used for water heating on farms.

- **Cases of two AD plants treating manure: Méthabate and Terragr'Eau**

The Méthabate AD unit involves two farms located in Le Mesnil en Vallée (Loire Valley). Despite the high dry matter content of farm residues (cattle manure), continuous stirred tank reactor (CSTR) with a rather liquid digestate was selected as technology of choice. This requires the addition of more liquid inputs and recirculation of the liquid part of the digestate. The biogas is sent to a cogeneration (250 kW_e) unit, with the electricity being sold and the recovered heat provided to a neighbouring agricultural greenhouse. The site treats feedstock 13,825 t/a, mainly livestock manure. The primary digester residence time is 29 days with an average organic loading of 5 kg OM/m^3/day. After primary digestion, the material is fed to a continuously mixed post-digester. The total residence time, in the primary and post-digesters, is 108 days with a yield of 113% of the methane potential. Taking into account the uncertainties around the determination of methane potential of some of the digester inputs, this high yield indicates that the unit captures the biogas production potential of the inputs. The unit's electrical consumption amounts to 22% of the electricity sold, which is quite high but within the range of what is observed at similar installations. The investment cost was €2.2 million, with annual revenues around €365,000 and operating expenses around €200,000. The installation thus achieves satisfactory economic profitability.

Terragr'Eau is an AD plant located in Vinzier (Alps) which treats manure produced at 41 different farms in the region. It is an innovative operating model as the local public authorities are now in charge of the AD plant that was initially funded by a private consortium. The local public authority collects livestock manure in the territory (region) in order to reduce sanitation risks on the impluvium for the commercial water spring Evian. It can treat organic inputs 33 kt/a, mainly manure, and inject, on average, 57 Nm^3/h of biomethane. About 26 kt of liquid digestate are recirculated, and the hydraulic retention time is around 43 days with an organic loading rate of 2.6 kg $OM/m^3/d$. These indicators are representative of an AD unit with a low organic loading, short hydraulic retention time and long recirculation. The yield is approximately 78% of the methanogenic potential. The main problem that was encountered was equipment blockages that were related to the introduction of feedstock. Electrical consumption of digesters, air treatment and biomethane compression represent 19% of the primary energy production. The investment cost was €9.6 million, with annual revenues around €0.9 million and expenses around €1.3 million. Although the expenses exceed the revenues, the main purpose of this AD plant is to protect the impluvium.

5.6 CONCLUSION

The potential for converting livestock manure into energy continues to be promising in France as more AD plants are reaching completion and these plants are technically able and open to incorporating all types of manure.

While manure can be used on its own as a single feedstock, French AD plants must often supplement the manure with substrates that have a greater methane potential. Some farmers are joining together to build collective units (centralized plants) that accept different types of feedstock.

There are still ways to increase manure use in France thanks to financial incentives that favour manure as inputs to AD, public-private partnerships and ongoing technical improvements.

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6 NORWAY

6.1 INTRODUCTION

This chapter provides an update on the status of Norway in the report "Potential and Utilization of Manure to Generate Biogas in Seven Countries," published by IEA Bioenergy Task 37 in June 2021.

The use of manure for biogas production is among the proposed measures by the Norwegian Environment Agency (2020) to obtain climate targets, although the previous target to utilise 30% of manure for biogas production before 2020 was not reached. An increase in the share of manure used for biogas production to 25% by 2030 has been calculated to represent a reduction of GHG emissions by 253,000 tons CO_2e, accumulated in the period from 2021 to 2030 (Norwegian Environment Agency, 2020).

The use of manure for biogas production has been prioritised by the Norwegian government the recent years, providing incentives to boost its use such as subsidies and investment support. As a result, both the quantity of manure and the total number of biogas plants treating manure have increased. This have not yet had an impact on the overall biogas production, which has remained at 0.7 TWh the previous years (Norwaste, 2024). The theoretical potential for biogas production in Norway is estimated to be up to 6 TWh with the current feedstock base and current technology, of which manure constitute 1.6 TWh (Lyng and Berntsen, 2023). The potential sources are mainly cattle, followed by sheep, pigs and small quantities from poultry.

6.2 MANURE PRODUCTION AND AVAILABILITY IN NORWAY

The realistic potential of using manure for biogas is determined by the number of animals as well as the size and location of each farm. According to the National Statistics of Norway (Statistics Norway, 2023a), there has been a decreasing trend in the number of farms (holdings) keeping domestic animals the last years: -0.4% between 2022 and 2023 and -12.5% since 2012. The total number of farms with animal husbandry was ca 25,500 in March 2023, dominated by breeding of cattle (48,5%) and/or sheep (51,7%), while pigs, hens and dairy goats come at much lower percentages (6%, 5%, 1%). Despite the decreasing number of farms, the number of animals per farm is increasing for cattle, sheep (>1 year old) and hens (Statistics Norway, 2023b). This indicates that the amount of manure remains relatively constant, and that it becomes more centralized in terms of geographical location.

As the use of manure for biogas production currently is low, the current practice is to use untreated manure as fertilizer. To minimize nutrient runoff, the number of animals (and thus the size of the farm) is limited by the available national regulation on animal manure. Fertilization is restricted to defined periods of the year, and the farms are required to have sufficient storage capacity, corresponding to a minimum of eight months of manure production.

Figure 17 presents the increasing trend of use of manure for biogas production in the period 2013-2022 (graph adjusted to English from Norwegian Environment Agency, 2022), expressed by the total quantities of manure delivered to biogas plants.

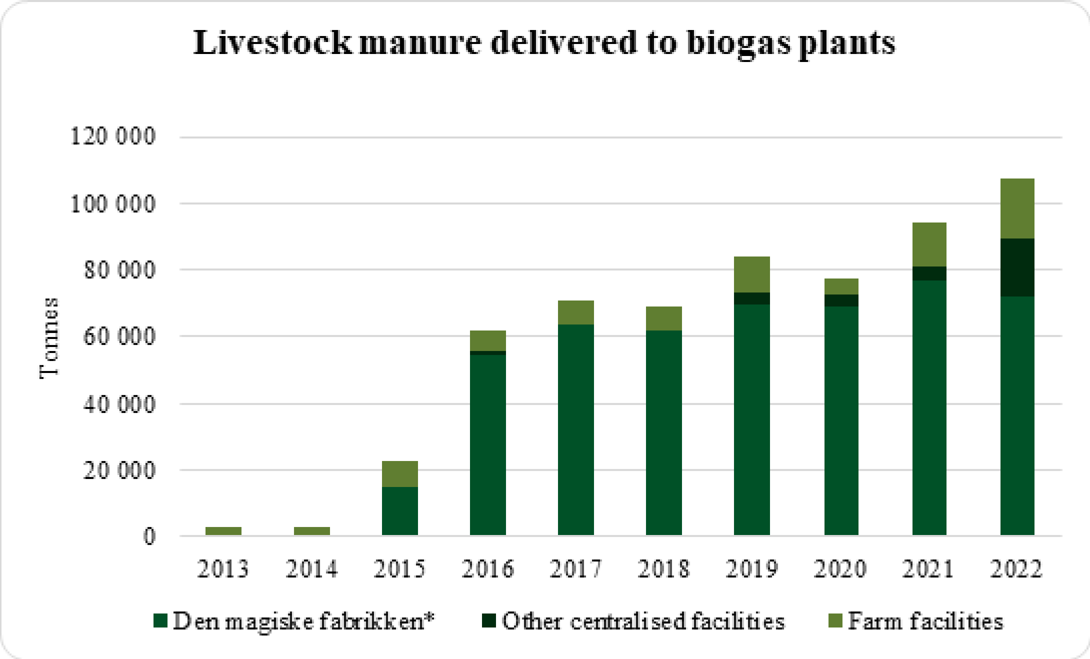

Figure 17: Quantities of livestock manure delivered to biogas facilities in the period from 2013 to 2022 (adjusted from Norwegian Agriculture Agency, 2023)

The graph shows that the majority of the manure which is used to produce biogas is treated in a centralised plant named The Magic Factory (Den Magiske Fabrikken), where it is co-digested with food waste from households and industry. In most plants the manure is co-treated with other feedstocks such as food waste, fish sludge or fish silage. Small scale plants mostly treat their own manure, but also collaborate with neighbouring farms or local communities to treat their organic waste.

As of 2020 only 1% of the total livestock manure produced had been used for biogas production. In 2022, 107 000 tons manure were processed for biogas production – a 14% increase, however only the 1,3% of the totally produced manure (Norwegian Agriculture Agency, 2023).

The infrastructure and technologies used in Norway vary and depend on factors like the quantity and quality of manure, local conditions, the use of the AD products/by products, etc. The suppliers/constructors of the plants are either Norwegian or from neighbouring countries (e.g. Sweden or Denmark); the plants are designed to fit the specific requirements of each location. In Norway, the infrastructure usually includes CSTR (continuous stirred-tank reactors) with retention time of approximately 30 days. There are also exceptions with deployment of batch reactors and pilot plants testing technologies with shorter retention time (8 days). Examples are the Antec technology (patented biofilm plugflow technology) and the Telemark reactor (patented farm scale plant applying upflow anaerobic sludge blanket (UASB) technology).

The number of biogas plants treating livestock manure has been increasing, reaching 14 plants in 2023, as shown in Figure 18. Currently 9 new facilities that will process manure are under planning or construction (Norwaste, 2024).

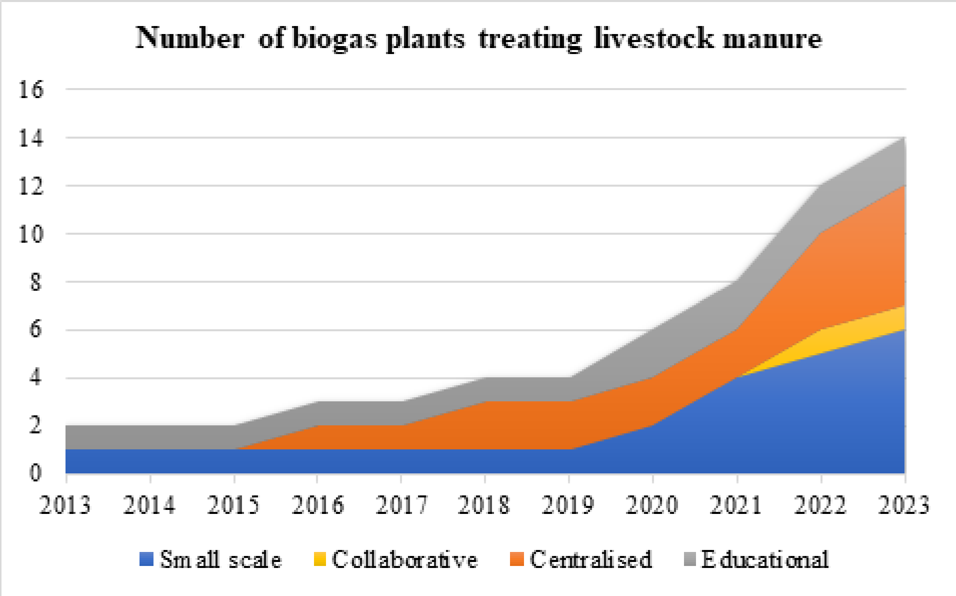

Figure 18: Number of biogas facilities treating livestock manure ("own estimations" based on information from the Norwegian Agriculture Agency)

The Norwegian biogas plants treating manure can be divided into three main categories: small scale, collaborative, centralised and educational. Each of the four categories are described in the following sections.

Small scale, on-farm biogas plants: The local, on-farm facilities include the ordinary parts of a biogas plant such as storage/mixing container, AD reactor with insulation, control room, heat and electricity generators, heat exchanger, pumps, and distribution channels between the various elements. There is quite often a mix of manual, automated and remotely controlled operations, e.g. measuring the filling levels of a container or the gas pressure. External energy supply is normally available for either starting up the operation of the plants or acting as back-up energy supply. The sizes of reactors vary (from 600 to 1200m^3), and the biogas is normally used to generate heat and electricity to be used on the farm. In some cases, the electricity may be sold to the grid.

Collaborative, agriculture-based plants: A new type of centralised plants with agricultural input has emerged in Norway, in response to long transport distances to centralised facilities and to the high costs of capital and time investment for constructing and maintaining an on-farm biogas plant. Svanem Biogas is the first collaborative biogas plant in Norway which started up its activity in December 2022, with support from Innovation Norway and involvement of various regional actors. The facility is processing ca 15 000 m^3 of livestock manure, fish silage and sludge from twelve farms and three fish hatcheries around lake Helndsjøen in Heim municipality in Trøndelag. The plant is operating with three biofilm reactors of 105 m^3 produced by the technology provider Antec. A sanitation facility is treating the digestate to be used as fertilizer by the local farmers. The facility is expected to produce approximately 2.7 GWh annually.

Educational Farm based plants: Biogas from manure is also produced in small-scale facilities installed in special upper secondary schools, where students are trained in small farms on topics like animal breeding and care, agriculture, etc. Students are trained in manure processing with AD, producing biogas and the other beneficial by-products in locally developed facilities (e.g. the patented Telemark reactor, a small (10 m^3) reactor developed at the University of Southeast Norway).

Centralised plants: Large-scale plants, co-treating the manure with other substrates: e.g. food waste, fish sludge and other. The Magic Factory (Den Magiske Fabrikken) is one of the largest centralised plants, operating since 2015. Manure from surrounding farms and food waste from households is treated in the facility, which produces biogas upgraded to fuel quality and used for transport, biofertilizer is returned to livestock and cereal farms. A share of CO_2 from upgrading is used for production of tomatoes in a closely located greenhouse. A unique characteristic of this plant is that it also includes a knowledge and experience center open for educational purposes to groups from schools, universities, and other actors interested in circular food systems.

6.3 MOTIVATION FOR THE ADOPTION OF MANURE-BASED AD IN NORWAY

Based on a review of relevant political initiatives and newspaper articles including interviews of farmers which uses manure for biogas production, five main motivations for adaptation of manure-based AD were identified (Figure 19).

Environment and Climate: In 2016 the Farmers Union entered a climate agreement with the Norwegian government, with the target to reduce emissions of greenhouse gases from agriculture by 5 million tons CO_2 equivalents in the years between 2021 and 2030. Consequently, the Norwegian agriculture developed a climate action plan, which includes the use of manure for biogas production as one of the proposed measures. Reduction of the storage time for manure reduces direct greenhouse gas emissions in agriculture GHG emissions. In addition, the replacement of fossil fuels by biogas can reduce impacts in other sectors.

Financial incentives: To make livestock manure a more attractive feedstock for biogas production, the Norwegian government offers subsidy schemes (Landbruksdirektoratet, 2020) to agricultural enterprises that meet specific requirements. The support is offered as:

Investment support, co-financing of the design and installation of small-scale and large-scale biogas facilities provided by Innovation Norway/Bionova and Enova.

Economic support per ton of manure used for biogas product, both farm scale and centralized. The support is currently at 833 NOK per ton of dry matter (Forskrift, 2020-12-14, 2754).

Circularity: The farmers become more and more aware of the need for circularity in food production and embrace the principles of Circular Economy (CE). Modern agri-entrepreneurs are interested in adopting the trend of CE in their activities, to gain from the recovery and redistribution of nutrients based on their needs.

Energy independence: Until now prices for heat and electricity have been relatively low in Norway, and the incentives for the use of biogas for these purposes have been limited. Recently, however, electricity prices are higher and more unstable. This can increase motivation among farmers to investing in biogas facilities with the vision of becoming self-sufficient with regards to their electricity and heating needs.

Value creation: The production of biogas and other useful byproducts can potentially lead to economic savings in terms of reduced costs for energy use or sales of biogas as a fuel.

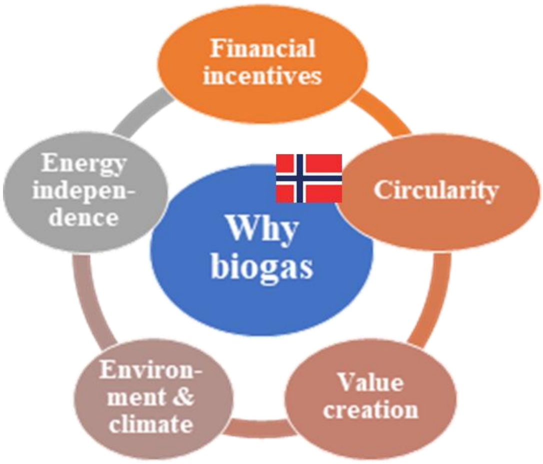

Figure 19: The main drivers for use of manure for biogas production in Norway

6.4 MAIN BARRIERS OF INCREASING ANAEROBIC TREATMENT OF MANURE

Despite the increased number of biogas facilities, the new financial incentives (2021-2030) and the recognition of biogas value from farmers, there are still considerable obstacles related to the use of livestock manure for biogas production in Norway. The main barriers are related to the economic viability of the biogas plants and the technical challenges with the infrastructure. In some cases, we see a combination of the two factors: biogas production never reached the minimum expected plant efficiency which led to higher expenses than profit and leading in some cases to shutting down the facility (e.g. Liholmen biogass at Båtsfjord, North Norway).

Farmers are reluctant due to the total costs of investment (despite the financial support of up to 45% of the total investment) and the pay-off period, given that most of the Norwegian farms are relatively small and the individual profitability is lower. In addition to this, not all applicants receive financial support. The farmers/agri-entrepreneurs are also concerned about the "post-subsidy" period; there is no official announcement yet about the plan after 2030, when the program will be concluded.

Closing, it is worth noting two more points which may be barriers for the use of manure for biogas:

The spatial distribution of farms in Norway is such that the distance to central biogas plants is rather long, which leads to high transport costs and high costs for storing facilities in farms (pre-storage tanks).

The cold climate may require considerations related to insulation and increased energy use to keep a stable production during winter.

The lack of competitiveness of manure as raw material for biogas production, since biogas facilities in Norway treat mainly food waste and sewage sludge. For these plants, the waste treatment cost represents an important share of the income. Manure has a lower energy content and higher logistical costs and is therefore not considered a relevant feedstock for many existing plants.

6.5 INTERESTING FEATURES OF NEW DEVELOPMENTS

The main trends in the development of manure for biogas production in Norway is described below.

Co-digestion of manure with fish sludge and/or fish silage: While manure so far mainly have been co treated with food waste in Norway, many of the newly established plants and the plants under development will co digest the manure with marine residual resources such as fish sludge and fish silage. As the fish farming industry is quite large in Norway, the potential of using marine residual resources for biogas production is large. So far the fish sludge for biogas production mainly comes from on-shore fish farming, but the collection of fish sludge from sea-based farming is also being explored as stricter regulations may be introduced in the future. A feedstock mix of marine waste and manure is seen as beneficial as the marine waste has high energy potential, while the manure has a stabilizing effect on the digestion process. There is, however, lack of knowledge about how the use of marine resources will affect the quality of the digestate. This knowledge gap will be addressed by the research project "Circulizer".

Collaborative plants driven by the green sector: Traditionally biogas production in Norway has mainly been a waste treatment technology and the construction of new biogas plants have been initiated by the waste sector. Several of the new plants treating manure are, however, initiated and owned by farmers.

6.6 CONCLUSION

The use of manure for biogas production in Norway has experienced significant growth in recent years; however, it remains at a relatively low scale compared to other countries. Based on the number of new plants in the planning stages and the existing support systems, this upward trend is expected to continue. Nevertheless, it remains to be seen whether a more substantial share of the considerable potential will be realized.

Compared with other IEA Task 37 member countries in this report, it seems that the use of manure for biogas in Norway is more strongly motivated by its contribution to reduce greenhouse gases to obtain climate target than some of the other countries. The focus on biogas as an energy carrier has been lower in Norway than in some other countries. This can be explained by the large share of renewable energy and relatively low energy prices due to a large hydropower industry. In addition, most regions do not have gas grids, and thus the biogas must be used to produce heat and electricity on small scale and upgraded and compressed or liquefied at large scale plants, to be transported to biogas filling stations. The recent increase in energy prices and a larger focus on self-sufficiency and energy security may result increased similarities with countries in terms of framework conditions for the use of biogas in the future.

The recent rise in energy prices, coupled with an increased focus on self-sufficiency and energy security, may lead to greater similarities in framework conditions for biogas utilization in Norway and other countries in the future. Additionally, the growing interest in collaborative, agriculture-based biogas production could enhance opportunities for knowledge exchange with nations where farm-based biogas production is more prevalent. Collaborative farms may also serve as hubs for nutrient distribution among farms, which is particularly relevant in regions with high livestock density, especially given that new fertilizer regulations are stricter regarding the nutrient application limits per hectare.

To foster a more sustainable and circular food system, nutrient recycling is essential. In this context, Norway could draw inspiration and insights from Finland, which aspires to be a model country for nutrient recycling.

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7 UNITED KINGDOM

7.1 INTRODUCTION

In the UK, the majority of manures and slurries are applied to land, with only approximately 3% of the estimated 80-100 million tons of livestock waste being allocated for anaerobic digestion (AD). The production of these materials is not evenly distributed across the country due to varying regional agricultural characteristics.

Over the decade from 2013 to 2023, there has been a general decrease in the total populations of cattle (-2.9%), sheep (-3.2%), and pigs (-4.1%), while the total number of poultry breeding and laying fowl has increased by 14.4%. However, between 2022 and 2023, the total number of cattle and calves remained relatively stable, pig numbers decreased slightly by 2.5%, sheep and lamb populations saw a slight increase of 0.3%, and poultry numbers decreased by 1%.

Horses are not included in agricultural statistics, as they are generally considered part of a separate economic sector, specifically as recreational or sporting animals. Nevertheless, under a Freedom of Information request, the Central Equine Database (CED) reported a figure of 899,583 horses as of January 16, 2023. It is noted that the actual number of horses is likely to be higher, as the CED only records animals with passports. Other sources, such as the British Equestrian Trade Association, estimate the number to be around 850,000.

7.2 MANURE PRODUCTION AND AVAILABILITY IN UK

Whilst it is possible to estimate manure quantities based on total numbers of livestock, the amount which might be available for anaerobic digestion very much depends upon agricultural practices on the farm, as well as within the region. For example, dairy cattle in England may be housed 4-6 months of the year (typically November to April), whereas milder Irish winters mean that they are likely to be housed only 3-4 months of the year (i.e., November to February). Table 18 shows the number of animals as at 1 June 2023 whose manure/slurry production could potentially be used in anaerobic digestion.

Table 18: Number of livestock in UK in 2023 (Defra, 2023)

Animal	Number of animals
Cattle	9,555,426
Pigs	4,683,319
Poultry	178,141,587
Sheep and lambs	31,802,536
Goats	108,126
Horses	899,583

Data from Defra “Livestock Populations in the United Kingdom at 1 June”; Latest goats data is 1 June 2021 and 16 June 2023 for horses; other sources (e.g. BETA) quote around 850,000).

By far the largest volume of manure produced is from beef and dairy cattle, with 59% of cattle manure and 90% of cattle slurry being applied to grassland in 2022 (Defra, 2022). Although these products are generally used on the farm, excess manures/slurries can be exported for use; however, official figures on farm imports/exports of manure were discontinued after the 2013 British Survey of Fertilizer Practice (BSFP) report, as it was thought that the volumes were too small to be of significance and the data were therefore not robust.

The BSFP 2022 report estimates that 85.1 million tons of manures are applied to UK farmland. The report was designed to capture manufactured fertilizer usage from a group of surveyed farms, so may not be as robustly representative of farmers using organic manures; nevertheless, it examines the use of the organic fertilizer, so estimates quantities that are captured. The report gives no definition of 'Other FYM' (Farmyard Manure) or 'Other farm', but their combined volumetric total of the materials spread to land is relatively small at 1.5%

The BSFP report also considers municipal wastewater biosolids applied to land (3.6 million tons/4%) and other non-farm organic materials such as compost, paper wastes and brewery effluents (7.7 million tons/~8%) which are not included in Table 19.

Table 19: British Survey of Fertilizer Production 2022 (BSFP): Estimated manure volumes applied to land (Defra, 2022) (FYM - Farm Yard Manure)

	Volume (Mt; Mm^3)
Cattle FYM	35.3
Cattle slurry	43.3
Pig FYM	2.2
Pig slurry	1.8
Layer manure	0.4
Broiler/ turkey litter	0.8
Other FYM	0.9
Other farm	0.5
TOTAL	85.1

The production of manures and slurries is broadly regionally based. South- and northwest England (particularly Devon, Cornwall, Cheshire and Cumbria) are known for dairy farming, as are parts of Scotland (e.g., Dumfries and Galloway) and Northern Ireland. Sheep farming is common in Wales, particularly in the hilly areas of Powys, Gwynedd and Ceredigion, and parts of Scotland. Beef cattle are particularly important in Scotland and Northern Ireland. Pig slurry is mainly produced in counties with less rainfall, such as East Yorkshire, Humberside and East Anglia. Significant concentrations of pig and poultry farming exist in the East and Northeast of England, with further poultry operations in areas such as north Wales and the Wye Valley. Intensive pig and poultry operations are less likely to have sufficient land base to spread nutrients on, so these operations will tend to sell/utilise these materials locally.

Because cattle manure/slurry forms a large proportion of the overall available materials, a map of the beef and dairy population density in Great Britain (i.e. the UK without Northern Ireland) is shown in Figure 20 (APHA, 2021). Agricultural policy is the responsibility of the devolved administrations (i.e., England, Scotland, Wales and Northern Ireland), so the combination of this and the removal of the requirement to report to the European Union (EU) post-Brexit means that data production, timings and methodologies are not seamlessly aligned. This is likely to continue as post-Brexit agricultural policies evolve differently in the devolved administrations. Nevertheless, these maps provide a visual indication that the west of England and the borders/eastern side of Scotland tend to be where most of these materials arise.

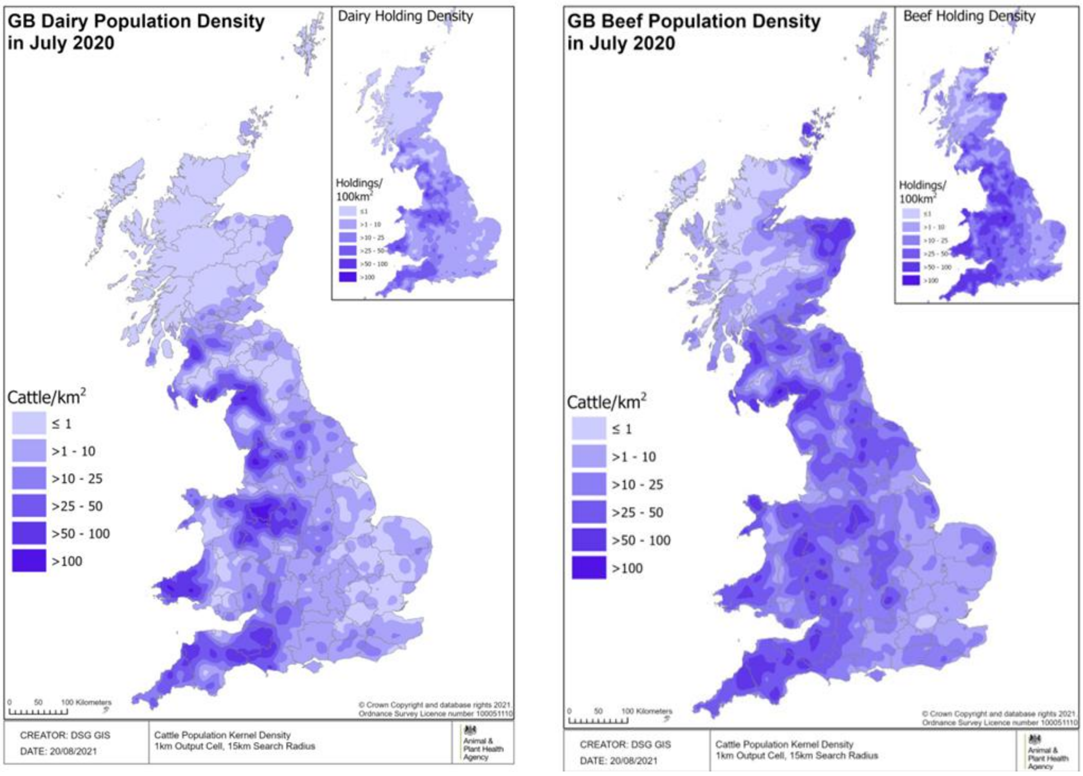

Figure 20: **(left) GB dairy population density (2020) and (right) GB beef population density (2020) from APHA Livestock Demographic Data Group: Cattle population report**

When trying to ascertain the dry matter (DM) content of these materials, it should be noted that dilution with rainwater is likely to be greater in the western side of Great Britain, but will also be affected by wash water addition, run-off from hardstanding or roofs and rainwater ingress into uncovered slurry stores. A number of different sources for slurry/manure nutrient and DM content are available, but if they do not have their own data, farmers typically use the AHDB Nutrient Management Guide (RB209). RB209 is a best practice guide on the application of fertilizers and organic materials to crops and grasslands. It has been developed over the past 50 years and has become increasingly sophisticated, aiding farmers to produce better nutrient management plans.

When installing slurry/manure anaerobic digesters into such farms, technology suppliers normally aim to minimise water ingress into the plant, due to the parasitic energy required to heat the water which is not offset by additional biogas production. In order to estimate the energy potential of these feedstocks, Table 20 utilises the BSFP volumetric data in Table 19 and combines it with dry matter, volatile solids and specific methane production data from the Anaerobic Digestion Assessment Tool (ADAT), developed by the Bioenergy and Organic Resources Research Group (BORRG) at the University of Southampton and IEA Task 37 (ADAT, n/a). Asterisked figures are not available as standard ADAT data, so have been derived from the biogas feedstock calculator from the Bayerische Landesanstalt fuer Landwirtschaft (BLfL) (BLfL, 2024). Whilst RB209 has been updated to include digestates, the dry matter figures do not always align well with either the ADAT or the BLfL figures, so have not been used in the energy calculations. BSFP volumes for ‘Other FYM’ and ‘Other Farm’ are assumed to be for sheep and horse manure, respectively.

Table 20: Calculation of potential energy value of slurries/manures in Great Britain (data marked * from BLfL 2024; remainder from ADAT) (BMP- Biochemical Methane Potential)

Manure	Volume, Mt (FM)	Dry Matter, % of FM	VS, % of FM	BMP Nm^3/t VS	Gross energy Value, GWh/a
Cattle FYM	35.3	25%	80.0%	190	13,335.36
Cattle slurry	43.3	9%	83.0%	185	5,949.53
Pig FYM*	2.2	23%	82.5%	240	956.55
Pig slurry	1.8	5.5%	82.0%	260	205.83
Layer hen manure	0.4	30%	75.0%	325	318.77
Broiler/turkey litter	0.8	60%	75.0%	300	1,083.20
Other FYM (e.g. sheep)*	0.9	30%	80.0%	248	535.73
Other farm (e.g. horse)*	0.5	28%	75.0%	165	171.90
TOTALS	85.1				22,556.86

The nutrient value of these materials is also considerable, with 430,489 tons of nitrogen, 230,933 tons of P_2O_5 and 534,243 tons of K_2O contained within them.

The availability of the nutrients to the crop depends on a number of factors including crop type, application timing, application method, delays between application and incorporation into the soil, soil types and soil nutrient indices. In particular, nitrogen losses need to be minimised, as these feedstocks have high levels of readily-available nitrogen (RAN) compounds that have a propensity to volatilise.

Application of high RAN materials such as manures, slurries and digestates must be done under Nitrate Vulnerable Zone (NVZ) rules (Defra, 2024a) and those from 'The Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018 (known as 'farming rules for water'), and similar relevant legislation in the devolved administrations.

Such rules mean that high RAN materials need to be stored for longer, and therefore increasing numbers of agricultural holdings have introduced slurry storage for longer periods. In 2019, for example, only 23% of holdings had more than 6 months' storage; by 2023, this had increased to 49% (Defra, 2024b).

7.3 USING MANURES IN BIOGAS PLANTS

Although cattle manures and slurries form the largest volume in terms of fresh material, poultry farming poses a particular nutrient overload problem where there are concentrations of such operations, for example, in Ballymena (Northern Ireland), Powys (Wales) and Herefordshire (England). The IEA Task 37 Ballymena Case Study (IEA, 2019) showed how a large biogas plant can strip the nitrogen for export off-site use as a concentrated ammonium fertilizer to replace fossil fertilizer. However, areas such as the catchment of the River Wye, have seen a considerable growth in intensive poultry units with an estimated 32 million poultry in 2024 (up from 23 million in 2017) being farmed in Powys, Herefordshire, Gloucestershire and Monmouthshire (iNews, 2024). The Department for Environment, Food & Rural Affairs (Defra) has created a cross-sectoral River Wye Action Plan (Defra, 2024c) to help address some of the issues affecting the catchment which include excess nutrients, particularly phosphates from agriculture (72%-74%) and wastewater (21%-23%); invasive plant species; high/low river flows due to climate change and sedimentation, all of which are damaging the ecosystem, pushing it into an environmental status of 'Unfavourable – Declining'. The 9-point plan helping farmers to retain nutrients in the field by providing funding for sustainable farming practices; doubling grant approvals for slurry stores; and piloting the use of on-farm micro-AD systems. The Environment Agency, which is the regulatory body responsible for environmental permitting, has also helped poultry farmers and food producers in the region to ensure that poultry manure can be shared with other farms and used for purposes such as AD. Some time will be needed to ascertain whether these cross-sectoral measures improve the environmental status of the area.

Unlike some other European countries, the UK has never had a specific 'manure bonus' or similar incentive to increase the volumes of manures and slurries in AD plants. Until 30 November 1994, the Farm and Conservation Grant Regulations 1989 provided 50% funding for facilities for the handling, storage and treatment of agricultural effluents and wastes. These facilities could include slurry tanks, weeping wall systems or anaerobic digesters. Farmers who installed AD systems under this grant primarily used the biogas for space heating, usually to heat their farm buildings via boilers or heat storage stoves such as Agas and Rayburns. Under this and some subsequent incentives, many of the farmers who installed systems primarily digesting slurries and manures pointed out numerous advantages (Bywater, 2011, Letcher, 2015), as follows.

- **Faster re-grazing, as digestate was incorporated more quickly on grassland than raw slurry.**
- **Slurry handling and spreading can be a major operation on a farm and might include rainwater addition, breaking up crusts and significant pumping/mixing energy - digestate is a much easier product to handle. Less rainwater ingress also meant less energy required to spread it.**
- **Reduced odour, with at least one pig farm installing the system to minimise slurry spreading odours in the local village.**
- **Certain farms noted a reduction in weeds, as AD kills some weed seeds.**
- **Some digester owners pointed out that their animals were healthier since they were no longer housed on top of their slurry (which went into the digester as quickly as possible), that the AD process killed some pathogens and that better grassland incorporation meant that animals were not grazing on ground 'capped' by raw slurry spreading.**
- **A few farmers trialled spreading digestate on pasture in strips versus leaving strips bare, in order to see the difference in growth due to the increased nitrogen availability in digestate. Some farmers noted that digestate supported clover production in a way that fossil fertilizer did not.**
- **Those that used the biogas through a boiler or heat storage cooker extolled the virtues of finally having a warm house, with 'free' heat in farmhouses that were typically thermally inefficient, eliminating the need for expensive, high carbon heating oil.**
- **Where digestate was separated, the ability to target nutrients, typically using the liquid portion on grassland and the fibre portion on crops. Some farmers made extra income selling the digestate fibre to gardeners.**
- **Some farmers noted that they had more worms in the soil, with one farmer mentioning that this was the case only if he didn't use shallow injection.**

A 2015 Business Interaction Voucher funded by UK Research and Innovation (UKRI) via the AD Network was carried out by the Renewable Energy Association and Dr David Styles, Bangor University. This project examined the benefits of small-scale AD using manures and slurries, emphasizing its GHG emission reduction potential and cost-effectiveness compared to other methods. On-farm AD captures methane emissions from manure that would otherwise be released, providing significant GHG savings. It also displaces fossil fuel use for fertilizer and energy production, further reducing net GHG emissions. Although small-scale AD is less cost-effective per kWh compared to larger-scale electricity generation, it is much cheaper when considering carbon savings. The study found that AD can avoid 1,449 kg CO_2e per tonne of cattle slurry dry matter and can generate 443 kWh of electricity, with a GHG abatement cost of £60 per tonne of CO_2e saved at an incentive rate of £0.20 per kWh. This compares favourably to £182 per tonne for other renewable electricity generation. Deploying AD across UK dairy farms could save up to 1.8 million tons of CO_2e annually. The report concluded that small-scale AD is a cost-effective method for GHG abatement and recommended revising the incentive regime to support its wider adoption.

The main relevant incentive regime at the time of the project was the Feed-In Tariff (FiT) which provided an incentive per kilowatt-hour of electricity generation.

7.4 MAIN PROBLEMS/BARRIERS OF INCREASING MANURE FOR BIOGAS PRODUCTION

After the Farm and Conservation Grants closed in 1994, there was essentially an 8-year hiatus in incentives for AD deployment. Subsequent policy incentives encouraged electricity production via the Renewables Obligation (RO) which ran from 2002 to 2017 and the Feed-In Tariff (FIT) 2010 to 2019; and biomethane production via the Renewable Heat Incentive (RHI) 2011 to 2021 and the Green Gas Support Scheme (GGSS) 2021 to 2028.

A further market-based system, the Renewable Transport Fuel Obligation (RTFO) provides certificates for the use of biomethane in vehicles, but no digesters have based their income stream solely on this system, as there is no floor price and, in a relatively small market, the certificate price fluctuations can be dramatic (ADBA, 2024). Under the RHI and the subsequent GGSS, AD operators could also flexibly opt to use gas in the RTFO.

None of these UK policy incentives specifically promoted the inclusion of slurries and manures. If a cubic metre of digester space costs £X and the aim of the incentive is to maximise electricity (or biomethane) production, it is rare that a farmer will forego income and decide to utilise that digester space for slurry, which might produce 20-25 m^3 of biogas per tonne, when maize at 180-220 m^3 of biogas per tonne produces considerably more energy. Poultry manure, with its higher biogas potential, tends to be included more often in AD, not least because intensive poultry units may not have the land base required to spread such a highly nitrogenous feedstock. These high nitrogen levels also mean that many AD operators also limit the proportion of poultry manure into an AD plant in order to limit ammonia concentrations.

A further barrier to the inclusion of manures and slurries in AD is the fact that these feedstocks are classified as wastes and therefore fall under Environmental Permitting regulations (Defra, 2024d). Early versions of the FIT and RHI schemes did not require the inclusion of any wastes in the feedstock, so there was a proliferation of crop-only digesters. If any waste (including manures/slurries) is introduced to the digester, the AD site needs to become a permitted facility for waste processing, with associated regulatory oversight and compliance burdens which can be both complex and expensive.

UK policy mechanisms have generally incentivised energy (i.e. biogas) production. This discourages farmers from building digesters where the main feedstocks are slurries and manures, as much of the energy value has already been extracted by the animal. Such digesters show a lower payback on capital investment when compared to utilising the same capacity to digest energy crops, for example. The policies have not specifically allocated funding for slurry digesters, however, so higher value digester feedstocks such as maize and grains are preferentially utilised. The original Feed-In Tariff scheme had to be paused, reviewed and resumed, due to the runaway success of solar PV which quickly consumed the overall budget available for other technologies in the scheme. Budgetary control was therefore introduced in the form of a degression mechanism, which has continued in some form for the RHI and for the GGSS. The degression mechanism includes a provision that, if applications for a given technology at a given tariff level reach a certain volume (capacity), subsequent applications are moved to the next quarterly budget tranche which is at a lower tariff level. This may continue until the tariff level becomes too low for economic deployment of the technology, particularly for smaller plants. However, the budget was allocated at technology level without specific categories for small, medium and large AD plants. For example, there might be 5 MWe capacity available in a given quarter. If 2 x 2.5 MWe plants apply to the scheme, the capacity level is immediately reached, the tariff is degressed and further applications are offered the lower tariff level. An alternative approach would have ring-fenced categories for small (<250 kWe), medium (250-499 kWe) and large (500-5000 kWe) plants in order to ensure deployment across all size categories.

A number of AD industry members lobbied for a sub-100 kWe tariff which might also have encouraged the deployment of slurry/manure plants (i.e., up to 1000 dairy cow equivalent), but this was not supported by the UK Government (DECC, 2011).

The RHI and GGSS were designed to promote biomethane injection. Since the equipment required to do this is expensive, as is the requirement for propane addition, these incentives typically apply to plants producing more than 1 MWe equivalent, which is far too large for AD plants based primarily on slurry/manure feedstocks. Whilst newer RHI plants and all GGSS plants must utilise 50% wastes or residues (by energy content of the biomethane production), most slurries and manures are excluded in favour of feedstocks with higher biomethane potential, further contributing to the low overall uptake of manures in UK AD.

The high water content and relatively low energy value of many manures and, in particular, slurries, means it is uneconomic to transport them long distances to centralised plants, so local treatment and digestate use makes good sense. However, the Danish cooperative model has not been widely adopted in the UK: in the early 2000s, the Holsworthy AD plant in Devon was designed along these lines to digest slurry from local dairy farms; but several of the farms were no longer able to participate in the initiative for various reasons and the plant owners gradually phased out this feedstock in favour of food waste which attracts gate fees and produces more biogas (Andigestion, n/a).

Digestate fibre can be a useful component in peat-free horticultural mixes, but its production at small scale is too expensive for farms to attain PAS110 'End of Waste' certification (WRAP, 2014), and there is currently no low-risk position or aggregation mechanism to allow these enterprises to sell their digestate as they did 30 years ago.

Nearly 15 years ago, the Royal Agricultural Society of England produced a report on AD (Bywater, 2011) in which the following key barriers were identified: although some of the detail has changed, many of these still apply.

Regulation, permitting and planning. Planning can be expensive and time-consuming and is carried out at Local Authority level, so there can be issues with consistency across the UK. There is no fast-track planning for AD projects which have a clear environmental benefit, such as those digesting slurries and manures. Such systems are often regarded as major farm diversification operations for the purposes of planning and taxes (rates) and not as an environmentally advanced piece of farm equipment. The permitting required to bring even small amounts of local feedstocks on site in order to supplement slurry feedstocks (particularly when cows are out to pasture in summer) can also be expensive and take excessively long to be issued.

Lack of access to capital grants and finance can still be an issue, particularly as fully compliant AD plants can be expensive and farm incomes are low, which can impact on borrowing. For example, in the year up to 2022, only the top 50% of farms in England made a profit from agriculture alone and that profit was around £79,500 (Defra, 2024e). Around 25% of farms made an average loss of £27,800 from agriculture. There is ongoing uncertainty around post-Brexit agricultural support mechanisms which may also affect investment plans for some farm businesses (Horton, 2024).

Type and scale of current incentives. The only incentive currently available to UK AD plants is the GGSS which is not designed for the type of smaller, off-gas grid AD plants which run on these feedstocks. There are no longer any incentives for CHP use and with no guaranteed income stream, funders are unlikely to fund AD plants on the RTFO alone. Government is increasingly in favour of 'subsidy-free renewables'.

Whilst this may be appropriate for offshore wind or solar PV, the downward pressure on food prices over the past century has meant that farmers are often unable to obtain sufficient income to offset/mitigate the environmental costs of livestock production, so some mechanisms do need to be in place to facilitate this.

7.5 BIOGAS POLICY

The recent extension to 2028 of the Green Gas Support Scheme (2028 GGSS) for biomethane injection to grid and the change of UK government in July 2024 may affect the near-term establishment of any policies intended specifically to support the AD of manures and slurries. The UK's Department for Energy Security and Net Zero (DESNZ) launched a call for evidence on the Future Policy Framework for Biomethane Production in February 2024 which closed on 25th April 2024 (DESNZ, 2024). The Framework aims to support the UK's net zero and energy security goals and recognises the strategic role of biomethane, particularly from wastes, to achieve this. The current RHI and GGSS support schemes are expected to deliver around 8 TWh of biomethane injection by 2030 which is short of the UK Government's current Biomass Strategy (DESNZ, 2023) aim to produce 30-40 TWh of biomethane production by 2050. A number of respondents to the call pointed out that manures and slurries were particularly underutilised wastes in AD, but that their diffuse and rural nature meant that gas grid injection was often not possible, and that off-grid biomethane or biogas production for energy use (transport, heating, CHP) might be a way forward.

Nevertheless, the UK still has some interesting British commercial and near-commercial technologies operating in the manure/slurry AD sector, a selection of which are described below.

The first of these might not be considered to be conventional anaerobic digestion, as it involves the capture, upgrading and utilisation of fugitive emissions (primarily biogas) from covered slurry lagoons, and there are at least two companies operating in this sphere. One of these, Bennamann, is based in Cornwall, a rural region known for its agriculture and tourism, where nearly 61% of the properties in the county are off the gas grid. Their pilot project (Bennamann, 2024) on 6 dairy farms owned by Cornwall County Council will provide biomethane from a mobile upgrading unit to power vehicles for Cormac, the company which looks after the Council's fleet of vehicles. It is envisaged that this relatively low-cost approach will allow small-scale farmers to join the biomethane market.

Whilst biogas capture and utilisation is not uncommon in warmer climates, the quantities of gas coming off such lagoons might be surprising in the more temperate UK climate. QUBE Renewables (QUBE, 2024) provide a lagoon and estimate that a typical 5500 m^3 lagoon emptied once a year and kept at ambient Somerset temperatures could provide around 46,480 m^3 of biogas per year.

In England, such slurry storage biogas capture systems have not been funded by the initial Slurry Infrastructure Grants (SIG) (RPA, 2024). Covering such stores reduces rainwater ingress and spreading costs, as well as addressing ammonia and methane emissions. Capture and utilisation of the biogas makes both logical and environmental sense, and the UK Government has indicated a willingness to include this in future SIG grants.

Because UK dairy farms are often located near to each other, a Cheshire-based project (RASE, 2022) has proposed the installation of smaller-scale AD on several farms where the gas could then be piped to an upgrading and injection facility. This would allow each site to split the capital and operating costs of the upgrading equipment and enable sites without gas grid access to inject biomethane.

7.6 CONCLUSION

Because their energy value is relatively low and their water content can be high, it is not cost-effective in the UK to transport slurries and manures long distances to large, centralised AD sites. Additionally, manure production sites are dispersed and are often located in regions far from the gas grid. Nevertheless, manures are an underutilised resource which can be highly polluting. There is, however, no specific policy in the UK that encourages AD plants to utilise slurries and manures, especially at relatively small scale (< 100 kWe-eq, i.e., equivalent to the slurry from 1000 dairy cows).

The biomethane production gap between the UK Biomass Strategy's 2050 aims and existing production means that a consistent long-term policy which includes these resources needs to be implemented well before the end of the 2028 GGSS. This would help to provide rural farming businesses with low-carbon energy security, particularly in the numerous regions which are off the gas-grid, have weak electricity grids, suffer from poor housing stock and utilise high carbon intensity fuels such as diesel and heating oil for their energy needs. The hard-to-monetise positive externalities of AD on animal and soil health are invaluable and this use of the technology could help to support both food and energy security in the UK.

Specific policy incentives and activities might include:

- **The provision of a floor price for the Renewable Transport Fuel Obligation so that on- and off-grid biomethane production could have a minimum predicted income stream and therefore be a 'bankable' project. This might be coupled with a contracts for difference style ceiling price, where producers pay back the difference should certificates go over a certain value.**
- **Tax incentives for businesses wishing to decarbonise their supply chain. For example, milk processors could be offered tax rebates, exemptions or similar to part-fund AD plants on farms in order to reduce their Scope 3 emissions.**
- **A specific incentive to support the inclusion of slurries into AD.**
- **Carbon pricing has been mooted as a potential policy lever to support AD, but although farms have the ability to sequester carbon in soils (a difficult and long-term aim), plants and trees, most agricultural activities cycle carbon, so this is an emerging area which is likely to be fraught with controversy. Nevertheless, CO_2 pricing could be structured in such a way as to help support the AD of manures and slurries.**
- **A review of the planning process to ensure that small, primarily slurry/manure-based AD plants on farms are regarded as environmentally advanced slurry handling systems and fast tracked. This should also recognise that other feedstocks need to be utilised to support digester income and operation if livestock are not housed in the summer months.**
- **Assessment of the engineering, environmental and economic aspects of slurry storage covers with biogas capture and utilisation, with a view to potential wider roll-out and capital support (i.e. data capture and analysis for the SIG).**

Policy should, as far as possible, not dictate the biogas (energy) use. On large CHP AD plants, heat is often wasted, so the overall efficiency falls, but on smaller plants the heat can often be used in buildings, in the dairy, in farm diversification operations (camping showers, etc).

Many farms would benefit by electrifying some of their smaller vehicles, their pumps and even their heating (i.e., utilisation of heat pumps). On other sites upgrading to biomethane may be a better option.

With the removal of peat from horticultural products, there exists a potential circular economy opportunity to utilise digestate fibre as part of a peat-free mix, if a low-risk position or end-of-waste policy for aggregated materials was available.

After more than 50 years of policy-driven ‘boom and bust’ for small-scale on-farm slurry/manure AD in the UK, a number of innovative British companies are emerging in this sphere and a long-term policy vision which promotes the myriad benefits of slurry/manure AD would not only support decarbonisation of the agricultural sector but create skilled jobs in rural areas.

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8 CONCLUSION

Manure is a sustainable substrate for energy provision. The report updates the status of anaerobic digestion of manure in six IEA Bioenergy Task 37 Member countries, Canada, China, Finland, France, Norway, and the UK, emphasizing the importance of using manure as a source for renewable energy production.

The analysis of anaerobic digestion of livestock manure across the six countries reveals both challenges and opportunities.

1. Current manure generation and utilization

Significant and pretty stable or a little declined amounts of livestock manure is produced in the six countries, primarily from cattle, swine, and poultry, with production patterns varying based on regional agricultural practices. Farm sizes increase, number decrease.

Only about 1%~3% of livestock manure is used for anaerobic fermentation to produce biogas, indicating a significant underutilization of this resource for renewable and clean energy production.

Most manure, including the manure after biogas extraction, is used for field application to add nutrients and fibres to the soil.

The potential for biogas production from manure is vast but varies by region with significant opportunities identified, particularly if combined with other organic waste streams, but many facilities struggle with operational efficiency.

2. Motivations for adopting anaerobic digestion

The driving factors for manure anaerobic digestion are environmental concerns (e.g., reducing water and soil pollution and reducing greenhouse gas emissions), chemical fertilizer replacement, financial incentives (subsidies for renewable energy) and then the foreseen profit, and the desire for energy independence and sustainability in agricultural practices.

The global methane pledge and national strategies for climate change mitigation has posed new driving forces for manure biogas production by 2030.

3. Challenges and opportunities to manure biogas expansion

Under the new situation of coping with climate changes, the first common obstacle to expanding manure biogas is the awareness of biogas importance and contribution to global methane pledge. With a full aware of this by policy makers and financial investors, new political, infrastructural and financial tools will be created to promote and guarantee the manure biogas flourishment.

Economic viability is the second challenge. High capital costs for infrastructure, low-energy-value feedstocks, limited financial incentives specifically for manure biogas, and insufficient value realization for biogas ecological contributions, make manure biogas difficult to be attractive.

Regulatory constraints are a common challenges in all countries. Complex permitting processes, over-claim on safety and construction, differences in regional regulations, and the classification of manure as waste, which necessitates additional compliance measures but does not have waste-treatment subsidies like city waste.

Geographical distance from existing gas and electricity grids impacts the feasibility of manure biogas and poses logistical challenges. The super large scale biogas plants on the super large livestock and poultry farms needs to transport the digestates for a long distance. Considering the low nutrients in the digestates, it causes economic deficit to the biogas plants.

4. Sustainability and circular economy

Anaerobic digestion can help mitigate agricultural pollution, convert waste to renewable energy, and recycle nutrients. All the six countries are recognizing the importance of implementing anaerobic digestion of livestock and poultry manure as a strategy to contribute to a circular economy. For instance, Finland aims to enhance nutrient cycling and energy independence, aligning manure biogas with broader agricultural and environmental goals.

The biogas facility should be seen as an essential constituent in the circular economy agricultural system. Its output must not be focused on energy yield alone but also, as a source of valuable bio-fertilizer to be recycled back onto agricultural land which is the starting point for feed for animals which produce the manure. Beside the provision of energy and the reduced greenhouse gas emissions.

5. Comparative learnings between the six countries

Solutions and experiences from various countries demonstrate different approaches to managing manure for energy production, highlighting unique regional challenges and successful case studies. Norway could adopt collaborative approaches seen in Finland; the UK could benefit from Finland's focus on nutrient recycling and the establishment of supportive regulations. Countries like China demonstrate the potential for significant biogas production through large-scale investments and supportive public policies. Further, biogas plants play the compensation role in the energy network.

6. Future directions for livestock and poultry manure biogas production

There is a necessity for clear, long-term policies that specifically target manure utilization in anaerobic digestion to overcome existing barriers and encourage investment. Improvement in community awareness, education regarding benefits, and financial mechanisms could enhance the acceptance and expansion of biogas technology.

The collective potential of enhancing anaerobic digestion practices has significant implications for climate change mitigation, energy production, and sustainable agricultural systems. For substantial progress to be made, there must be a coordinated effort among stakeholders, including government bodies, the agriculture sector, and technology providers, to create supportive frameworks and incentives.

To fully exploit the potential of manure biogas, the report suggests enhancing policy frameworks, increasing public and private investments, and fostering educational initiatives to support farmers in implementing sustainable practices.

In summary, achieving the vast potential of manure biogas requires addressing the barriers and challenges outlined in the report. Each country's unique context shapes its approach, but shared learning and effective policy-making can lead to meaningful advancements in manure biogas conversion.

Further Information

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