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Economic and climate effects of farm-level biogas adoption: A stochastic partial budget analysis and life cycle assessment for Swedish dairy farming

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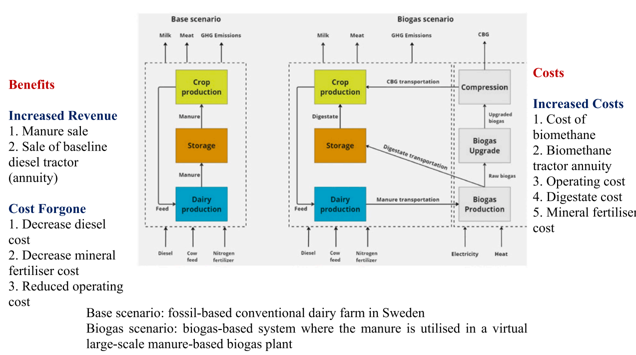
HIGHLIGHTS

- This study evaluate farm-level economic and climate effect of transition to a biogas system.
- We build larger scale central biogas plant with several categories of end-users.
- The transition yields a deterministic annual benefit of 1035 SEK, a simulated net benefit of −5398 SEK, plus 185,000 SEK in unpaid carbon credit, with a 27 % reduction in GHG emissions.
- Policies targeting investment in anaerobic digestion, trading synergy, information sharing and better pricing are needed.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: There is a growing interest in investments in technology that can help farms to become fossil-free, without compromising their economic incentives, and while significantly reducing greenhouse gas (GHG) emissions. Biogas is an interesting technology in this respect, however, the possible farm-level economic impacts from investing in a biogas-based system are not well understood, yet they are decisive to understand farmers' incentives for adoption.
OBJECTIVE: The objectives are to i) develop a scenario which allows the farms to become fossil-free in their input use, ii) assess the farm-level economic consequences of adoption and iii) quantify change in global warming potential in a 100-year period (GWP_{100}) from the biogas-scenario.
METHODS: We use a stochastic partial budgeting approach to simulate farm-level economic benefits and costs associated with changes and uncertainty related to economic effects. We also use life cycle assessment for the quantification of the climate effects, which enable us to examine the potential climate impact in reduction of fossil-based inputs in baseline scenario by transitioning to the biogas scenario. The study is based on simulation for a hypothetical dairy farm with 300 milking cow and a corresponding 325 ha of arable land that produces 75 % mixed grass and 25 % clover.

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RESULTS AND CONCLUSIONS: The result shows that transitioning to a biogas-based system will yield an estimated deterministic net annual benefit of 1035 SEK for the hypothetical farm. However, when considering simulated scenario, the net annual benefit could be negative, amounting −5398 SEK. Besides, there could be a gain of 185,000 SEK from yet unpaid carbon credits, which could be shared between the farm and the biogas plant. In addition, the biogas-system also results in a 218.4 t reduction of CO_2 eq. emission. Therefore, if all milk-recorded cows in Sweden were considered to be part of the biogas system, it theoretically will imply a 27 % reduction in GHG emissions from the use of agricultural machinery. Results thus established that adopting the biogas-based system will not only result in cost-neutral to farmers, but also a considerable reduction in methane emissions.

SIGNIFICANCE: The paper provides a joint farm-level economic and climate assessment of transition from conventional dairy farm to a biogas system, highlighting potential trade-offs and synergies between the two outcomes. Our result offers valuable understanding about how market internalisation of fossil-free transition in dairy farming can happen through the creation of economic and business incentives that encourage trading between farmers and biogas plants.

1. Introduction

Food systems are accountable for about one third of global anthropogenic emissions of greenhouse gas (GHG) emissions (Crippa et al., 2021). Current food production and consumption are unsustainable in a global (Willett et al., 2019) as well as in a local perspective in Sweden (Wood et al., 2019), the empirical basis for this study. Emissions from fossil-based production inputs are mainly attributable to the use of diesel powered-machineries, ammonium nitrate fertilisers from natural gas steam methane reforming and polymer materials for storing and conserving feeds (Lauera et al., 2018; Ahlgren et al., 2008a, 2008b). In 2022, the use of agricultural machinery, and heating agricultural premises in Sweden caused approximately 516,500 t of fossil carbon dioxide emissions (Swedish Environmental Protection Agency, 2023a, 2023b). Transitioning agriculture to fossil-free production practices – shifting to fossil free energy sources and fertilisers – is therefore one important step in reducing agriculture's negative impacts on climate. Farmers' uptake of fossil free production practices is likely by large a decision driven by their economic considerations; if farmers consider uptake unprofitable, they are likely discouraged to transition. However, previous research has also demonstrated that farmers are generally motivated by more than just the economic consequences of their decisions (Leduc et al., 2023; Howley, 2015).

Biogas is the result of anaerobic digestion of organic substrates like manure, wastewater or sewage sludge, energy crops and on- or off farm waste materials (Petersson and Wellinger, 2009). A biogas co-digester plant can be fed with food processing waste, biosolids, fats and oil grease and other agricultural residues. The raw biogas is then processed and used to produce biomethane which can be used as vehicle fuel or for injection into the gas grid. The biomethane can also be burned for production of heat and electricity. The remaining digestates are used to produce bio-fertiliser and can also be used for animal bedding, soil amendments, gardening, or landscaping. According to Energigas Sweden (2022), Sweden currently has 284 biogas production plants of which half are dedicated to co-digestion facilities for production. In 2022, biogas production amounted to 2.3 TWh, of which 1.3 million tonnes of livestock manure was used as substrate in 79 of the plants representing roughly 11 % of the total biogas produced (Energigas Sweden, 2022). Besides, 2.8 million tonnes of digestates were used as fertiliser, whereas two-thirds of the raw gas was upgraded to biomethane while the remainder was used for heat production and industrial use (Swedish Energy Agency, 2023; Energigas Sweden, 2022).

Several studies have established positive environmental effects of biogas production of farm waste production in general (Villarroel-Schneider et al., 2023; Villarroel-Schneider et al., 2022; Cucchiella et al., 2019; Sefeedpari et al., 2019; Lauera et al., 2018; Yazan et al., 2018). For example, Lauera et al. (2018) argued that feeding manure as a substrate in anaerobic digestion (AD) plant is useful for solving several environmental issues including pollution, odour, pathogen and nitrogen and for securing the livestock waste management problem. Sefeedpari et al. (2019) highlighted AD as a promising approach with significant potential for reducing GHG emissions, enhancing nutrient recovery, and improving nitrogen availability in fertilisers for plants. Cucchiella et al. (2019) presented an economic analysis of biogas and biomethane plants that utilize various types of animal residues. They mainly focused on electricity generation from biogas and how upgrading contributes to emission reductions and improved environmental performance. Villarroel-Schneider et al. (2023) used techno-economic optimisation to develop a polygeneration plant for a group of 30 small dairy farms, providing electricity, refrigeration, biogas for cooking, and fertilisers. This pathway was an extension of integrated solution for dairy farms, offering power generation, combined heat and power plants, and digestates (Villarroel-Schneider et al., 2022). However, Yazan et al. (2018) conducted an in-depth investigation on the impact of manure quantity, transportation distance, dry matter content, pricing, and discharge costs on the financial feasibility of manure-based biogas supply chains. They developed a business-focused approach that utilised animal manure to produce biogas and digestates, establishing a regional framework between manure suppliers and biogas producers. So far, other evidence has displayed the strategies to increase biogas production from farm residue through logistical methods and system optimisation (Amon et al., 2007; Stürmer et al., 2011; Helliwell, 2018; Shortall et al., 2019; Stolarski et al., 2020). Notwithstanding the contribution of previous literature, it can be noted that previous research has so far mainly concentrated on calculating environmental consequences and on techno-economic analyses. The farm-level economic and climate impacts of biogas-based systems, including costs, benefits, risks, and uncertainties, are not yet well understood. It also remains unclear how GHG-emission reductions translate into economic consequences for farmers. This is crucial for understanding farmers' incentives to transition, as well as if and to what extent policy support might be needed to encourage a transition.

The aim of this paper is to evaluate the farm-level economic and climate effects of transitioning from a conventional system to a biogas-based system. We focus on dairy production in Sweden and develop a scenario that enables dairy farms to become fossil-free in their input use by switching to a biogas system for fuel and fertiliser use, and by assessing and comparing the economic and climate consequences of this transition relative to a baseline scenario. We build the biogas scenario assuming the existence of a larger scale central/municipal biogas production plant with several categories of end-users, which would be less sensitive to seasonal variations from one type of end-users, allowing us to avoid large storage costs. We propose a working system where farmers sell slurry manure to a central biogas plant, switch to biomethane tractors, utilised digestates from the plant, and purchase biomethane at a contract price. This developed framework enables farmers to evaluate benefits and costs of supplying slurry manure to a central biogas facility and adopting biomethane tractors, while considering risks and uncertainties in biogas scenario that may affect their economic situation. Similarly, the framework offers an opportunity to reduce the potential climate impact of the diesel baseline scenario by transitioning to the biogas scenario. The change in global warming potential in a 100-year period (GWP_{100}) among the two scenarios was calculated based on IPCC sixth assessment values (IPCC, 2021).

We use a stochastic partial budgeting approach to simulate the economic benefits and costs associated with these changes and uncertainties related to the farm-level economic effect. In our setting, we consider the stochastic partial budgeting approach more helpful, compared to e.g. the net present value approach, as it allows for detailed and highly policy relevant analysis about which factors in the model are particularly influential for the outcome. The stochastic partial budgeting approach has previously been successfully used to estimate economic effects in relation to adopting alternative agricultural practices (e.g. Manevska-Tasevska et al., 2024; Owusu-Sekyere et al., 2023; Jerlström et al., 2022; Haseeb et al., 2020; Ahmed et al., 2021; Alvåsen et al., 2017), but has so far not been extended to develop the farm-level economic consequences of adopting a biogas solution to become fossil-free in inputs use. We use the stochastic partial budgeting approach to assess the change from a baseline to a biogas scenario, including an investment in a biomethane tractor by considering its annuity, to reflect the time value of money. Similarly, we account for the annuity of selling the diesel tractor and compare these to annual income and cost changes to determine the yearly net benefit change. Our approach explicitly incorporates the stochastic nature of income and cost fluctuations, allowing us to account for risk and estimate a confidence interval for the net benefit change. The quantification of the climate effects is based on life cycle assessment (LCA) methodology (JRC-IEA, 2010). This study provides a novel contribution of joint farm-level economic and societal climate assessment of transitioning a conventional dairy farm to a biogas system, which allows in-depth discussion about potential trade-offs and synergies between the two outcomes. Particularly, this paper provides the first attempt to help understand market internalisation of fossil-free transition in dairy farming through the creation of economic and business incentives, while, at the same time providing practical insights into the climate consequences.

2. Materials and methods

2.1. System description

A fossil-based hypothetical conventional dairy farm in Sweden, referred to as base scenario, is compared to an alternative biogas-based system where the manure is used in a virtual large-scale manure-based biogas plant, i.e. biogas scenario (Fig. 1). In the base scenario, the tractors for field operations are fuelled with conventional diesel and the manure from the dairy production is applied on the crop fields as organic fertiliser. In the biogas scenario, the manure is transported to the biogas plant where it is anaerobically digested. The gas is upgraded and compressed to obtain compressed biogas (CBG). The tractor is assumed to be CBG powered and the CBG required for the field operations is transported to the farm, while the surplus CBG generated from the manure is assumed to be sold on the market. Furthermore, the digestate from the biogas plant is assumed to be transported and used as an organic fertiliser on the dairy farm.

We designed a virtual dairy farm to represent a typical conventional large dairy farm in Sweden, located in Uppsala County. It was assumed that it was feasible for the farm to have 300 milking cows with 38 % yearly replacement (Swedish Environmental Protection Agency, 2023a, 2023b), and 325 ha of crop land, with a crop rotation including a grass and clover mix for 4 years, followed by 1 year of barley. Each dairy cow was assumed to produce 1 calf/year, and 114 milk cows, 36 heifers and 150 calves were assumed to be sent to slaughter every year. The milk production rate assumed to be 10,000 kg Energy Corrected Milk (ECM) per milking cow per year. The cows' feed rations were assumed to consist of a combination of farm-produced forage and purchased concentrates, with a concentrate fraction of 55 % in the total feed. The forage primarily included a grass and clover mix, which contributed to the silage with a metabolisable energy (ME) content of 10.1 megajoules

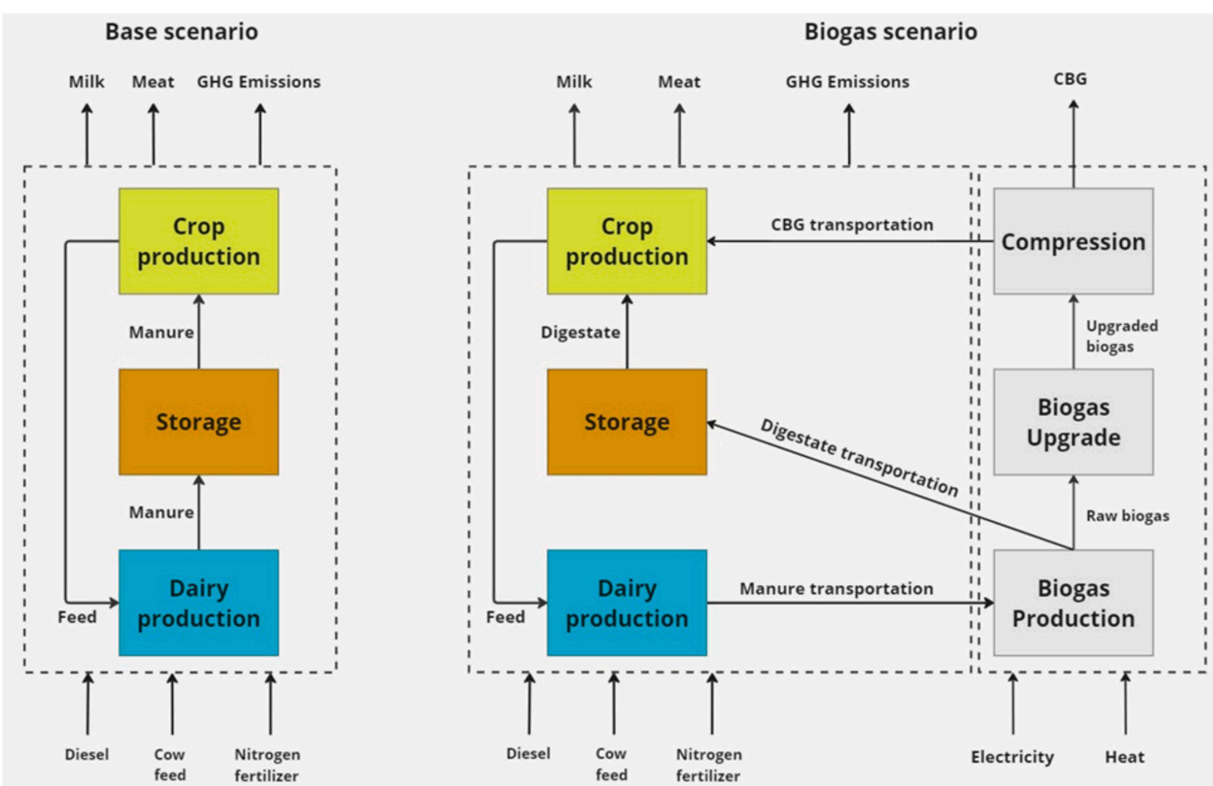

Fig. 1. Schematic representation of the base scenario and the biogas scenario.

per kilogram of dry matter (MJ ME/kg DM). Table 1 and Table 2 summarize the assumptions regarding animals and crops, respectively.

The grass/clover mix yield at the farm is calculated 2080 tons of DM per year, while the barley yields 279.5 tons of DM. This covers the silage, and pasture needs of the dairy farm plus a portion of the grain. The rest of the feed (grain and concentrate) is assumed to be purchased. Furthermore, it is calculated that 7704 tons of slurry manure is produced annually, which is stored on the farm in long-term storage and used as an organic fertiliser together with mineral fertilisers on the fields in the base scenario.

Transportation logistics play a crucial role in the economic feasibility of biogas systems, particularly concerning the cost-effective movement of slurry manure and the strategic placement of the plants. Hence, effective coordination between the central plants and farms are essential to minimise transportation costs. For instance, transportation costs and the physical location of the plant are instrumental in determining the plant's economic viability (Hansson et al., 2007; Hiloidhari et al., 2017; Tagliabue et al., 2021; Feiz et al., 2022). Gunnarsson et al. (2008) analysed transport system design, storage distance, farm size, and forage area, finding that when the average transport distance decreased from 17 km to 8.5 km, costs diminished by 30 %. Hansson et al. (2007) evaluated how an organic farm could achieve self-sufficiency in renewable motor fuels by transporting biofuel from an industrial facility and then returning it to the farm for consumption. Adopting this framework, in this study we assume that the municipal plant manages the collection of slurry manure from farms to the municipal facilities and subsequently returns biomethane to the farms for consumption. This approach leverages the plant's logistical capabilities, providing an incentive to alleviate transportation costs for farmers.

In the biogas scenario, the same annual amount of slurry manure is assumed to be transported (four times a week) by a truck with trailer (40-ton payload, as described in Mårtensson, 2018) to the biogas plant, assumed to be located 25 km from the dairy farm. On the same trip, digestate is assumed to be transported to the farm and stored in long-term storage. Table 3 summarizes the assumptions relating to biogas production. The slurry manure generates 121,800 normal cubic meter (Nm^3) upgraded biogas, of which 20,900 Nm^3 is consumed in the virtual farm' crop production using the CBG fuelled tractor. The remaining upgraded biogas is assumed to be sold to the market by the biogas plant and used in trucks or buses elsewhere. The CBG is assumed to be transported to the dairy farm three times per year using CBG composite mobile gas storages with 5.25 tons of deliverable capacity as described in Dahlgren et al. (2011).

The diesel consumption for barley and grass/clover cultivation in the base scenario was calculated based on work by Flysjö et al. (2008) and by Baky et al. (2010). In the biogas scenario, diesel consumption for the transportation of manure and digestate to and from the plant, was calculated based on using truck with trailer, long-haul traffic following Mårtensson (2018). Overall, 17,726 l of diesel were consumed for crop production in the base scenario, and 4690 l of diesel was consumed for transportation of manure, digestate and CBG in the biogas scenario.

The composition of the digestate depends on the used substrates for digestion in the biogas plant. In this study, where cattle slurry manure is mono-digested, the digestate is assumed to have the same total amount of plant nutrients per ton as the manure (Andersson et al., 2022). However, the ammonium nitrogen is assumed to be 30 % higher due to net mineralization of organic N in the anaerobic digestion process. The assumed plant nutrient content of manure and digestate are displayed in Table 4.

Based on the assumptions, using the digestate as fertiliser in the biogas scenario resulted in a reduction of 4970 kg of nitrogen mineral fertiliser use compared to spreading manure in the base scenario.

Table 1
The assumptions related to animals for the designed virtual dairy farm.

Animal type	Population	Manure production (kg VS DM/day/head)	Grazing period (months)	Manure collection during grazing (%)
Milking cows	300	5.39	4.9	38
Heifers 12–24 months	150	2.26	6.3	0
Heifers 10–12 months	150	1.57	4.3	0

Note: VS = *volatile solids, DM = dry matter.*
Source: Swedish Environmental Protection Agency (2023a, 2023b).

Table 2
The assumptions related to crops for the designed virtual dairy farm. Long-term nitrogen effect of manure is assumed for the farm having one animal unit per hectare, with at least 30 years of animal husbandry.

Crop	Yield (DM ton/ha/year)	Nitrogen fertiliser requirement (kg N/ha/year)	Diesel (litre/ha/year)	Long-term nitrogen effect of manure (kg/ha/year) *
Mix Grass 75 % clover 25 %	8	128*	48.3**	20
Barley	4.3	90*	79.5***	20

Note: DM = dry matter.
Source: * Andersson, et al., (2022); ** Flysjö et al. (2008); *** Baky et al. (2010).

Table 3
Key parameters assumed for the biogas production.

Parameter	Unit	Amount
Manure slurry - TS content	%	9*
Manure slurry - VS of TS content	%	80*
Manure slurry density	kg / m^3	1000
Distance to the biogas plant	km	25
Specific methane (CH_4) production	Nm^3 CH_4/ kg VS	0.213*
Methan content in raw gas output	%	65*
Compressed natural gas (CNG) engine/diesel engine efficiency	%	86**

Source: * Carlsson and Uldal (2009); ** Achilles et al. (2011).

2.2. Simulation approaches

2.2.1. Stochastic partial budget and data inventory

To evaluate the farm level economic consequences of implementing the biogas scenario, we constructed a model to outline estimates of total economic benefit change and total cost change in a partial budget manner using economic data. Table 5 provides a summary of variables used to construct the costs and benefits associated with the change from the conventional to the biogas scenario, with their respective distributions. Data used for the selected scenarios, were obtained from Statistics Sweden, Sweden's central bank and Swedish Energy Agency. Data that could not be obtained from these sources were derived from expert elicitation and desk research (Table 5). In addition, we used the result from the moment conditions to predict which input variables

Table 4
Assumed plant nutrient content of manure and digestate.

	Tot-N (kg/ton)	Organic N	Ammonium N (kg/ton)	P (kg/ton)	K (kg/ton)
Manure slurry	4.3	2.15	2.15	0.6	3.8
Digestate	4.3	1.505	2.795	0.6	3.8

Source: Andersson, et al., (2022).

Table 5
Summary of variables used in the partial budget.

Variables	Units	Data	Reference	Distribution
Annual manure collected	m^3	7704.40	System description	Deterministic
Price of slurry manure	SEK/m^3	15	Expert elicitation	Weibull
Diesel tractor	SEK	2,276,827[1]	Statistic Sweden, 2020, Swedish manufactures association, John Deree	Deterministic
Effective interest rate[2]	%	4	Swedish Central Bank (2023)	Weibull
Diesel consumption on crop field	litre/ year	17,726	System Description	Deterministic
Annual price of diesel	SEK/l	14.80	Swedish energy agency (2023)	Weibull
Nitrogen mineral fertiliser	Kg N/ year	16,131	System description	Deterministic
Nitrogen mineral fertiliser (biogas scenario)	Kg N/ year	11,161	System description	Deterministic
Price of synthetic fertiliser	*kg N/SEK*	6.83	Market estimation (2023)	Weibull
lubrication cost	*% of diesel*	9	Edwards (2017), machinery calculator [3]	Deterministic
Biogas consumption on crop farm	*Nm^3/ year*	20,900	System description	Deterministic
Annual price of biomethane	SEK/m^3	11.96	Swedish energy agency (2023)	Weibull
Biomethane tractor price	SEK	2,290,603	New Holland (2023)	Weibull
Accumulated repair cost	% of purchase	17.55	Edwards (2017), machinery calculator	Deterministic
Lubrication cost	*% of biogas*	15	Edwards (2017), machinery calculator	Deterministic
Digestates	m^3	7704	System description	Deterministic
Price of digestates	SEK/m^3	17.55	Expert elicitation	Weibull

Note: *1.* The investment cost of the tractor is given 2,276,827 SEK.
2. *Although* John Deere set the interest rate period (APR) at 4.33 %. Annuity of 4 % discounted and 15 years maintenance was employed.
3. The calculator infused with current figures.

significantly affected the outcome variable. We generated an in-sample data of possible farm-level economic outcomes to increase the accuracy and precision of the point estimate result. This enabled us to determine the expectations and variations of the proposed change in net benefit and to generate series of probability distributions whose forecast we adopted to assess the sensitivity of the input variables. To this end, we built a stochastic partial budget based on Monte Carlo simulation using the excel add-on @Risk (Palisade, Ithaca, NY) (Palisade, 2024), to characterise the farm-level economic consequences of the virtual dairy farm from switching from the conventional to the biogas scenario. We assumed stochastic variables that are likely to fluctuate within the lifetime of the biogas scenario; mainly, the price of diesel, price of slurry manure, price of biomethane, price of fertiliser, price of digestate, and biomethane tractor price. Weibull distribution was used to generate the probability density function (PDF) (Kızılersu et al., 2016) (see appendix A).

Costs: Several costs were assumed to change in response to the transition from the baseline scenario to the biogas scenario (Table 5). Above all, we assumed the purchase of a biomethane tractor (modelled as an annuity to take into consideration the annual depreciation and cost of capital invested in the tractor), purchase of upgraded biogas from the municipality biogas plant, and added operating costs (repair and maintenance). In reality, several tractors operate on a farm but for simplicity, we assume that given the size of our virtual farm, the chosen biomethane tractor is sufficient to carry out the daily activities.

Benefits: In terms of benefits, there were assumed added income and reduced costs (Table 5). The assumed added incomes were the sale of slurry manure to the central biogas plant and diesel tractor in the baseline. The assumed reduced costs were a reduction in diesel consumption, synthetic fertiliser consumption cost and reduced maintenance and repair costs. The detailed of total cost saved from diesel is presented in Appendix B.

Table 5 provide the variables used in the partial budget. The investment cost for diesel engine tractor and biogas tractor are quite similar but with different annuities. This is because the tractors are assumed to have different lifetime (n) (see box B1). In addition, partial budget allows us to compare the cost recovered from old tractor (diesel engine) and new tractor costs (biomethane tractor) to estimate the difference in the new budget. Therefore, the diesel tractor is assumed to have operated for at most ten years before switching to biogas tractor, to replicate a realistic farm scenario. The investment cost was estimated at 2,276,827 SEK (Statistic Sweden, 2020; John Deere, 2023) while the depreciation was set at 4 % for 10 years (Edwards, 2017). Since there is no market readily available for slurry manure supplied to the central plant, farmers are instead assumed to be reimbursed an amount equivalent to fertiliser value of their manure at current fertiliser prices. Similarly, the price of digestate is constructed based on the nutrient content of the digestate estimated at 17.55 SEK/m3. This is because digestate has higher concentration of plant available ammonia-Nitrogen. The benefit is that the digestate will have higher amount of ammonia nitrogen and the use of mineral-Nitogen can decrease.

2.2.2. *Life cycle assessment*

We used life cycle assessment (LCA) to assess the potential climate impact reduction of the baseline scenario by transitioning to the biogas scenario. The change in global warming potential (GWP) in a 100-year period among the 2 scenarios was calculated based on IPCC sixth assessment values (1 for carbon dioxide (CO_2), 29.8 for fossil origin methane (CH_4), 27.2 for non-fossil origin methane, and 273 for nitrous oxide (N_2O)) (IPCC, 2021). The scope of the LCA was limited to biogas production, upgrading, transportation of manure, digestate and CBG including combustion, assuming that a biogas plant is already operating and has the capacity to utilize the manure slurry from the farm.

The amount of dairy farm products, i.e. milk and meat, as well as the feed purchase was assumed to be the same for the two scenarios and not affected by utilizing manure at biogas plant. The GWP was calculated for the main differences among the scenarios, in addition to the surplus upgraded biogas produced from the manure, which is assumed to be used outside the of farm.

The main differences between these scenarios that effect the GWP, was assumed to be the GHG emissions related to diesel consumption, manure and digestate transportation, manure and digestate storage and field application, mineral nitrogen fertiliser, biogas production, transportation and combustion of CBG (Fig. 1). The manure was assumed to be mono-digested in the biogas plant to simplify comparing the use of manure and digestate as fertiliser and to limit the nutrient flow between the biogas plant and the farm. In a real case, co-digestion of manure is recommended as viable GHG mitigation strategy (Meng et al., 2023), which can have a complex nutrients flow among the different biomass sources of the biogas plant.

2.2.2.1. Data inventory. The GHG emissions from diesel production, distribution, and usage in heavy trucks were assumed 2.8 kg CO_2, 1.2 g

CH_4 and 0.073 g N_2O per litre, based on Gode et al. (2011). The GHG emissions of mineral nitrogen fertiliser was set at 2.836 kg CO_2, 8.1 g CH_4 and 1.98 g N_2O per kg nitrogen, based on Nilsson et al. (2020). The average Swedish grid-mix emission factor of electricity consumption was considered 0.033 kg carbon dioxide equivalents (CO_2e)/kWh (Ecoinvent – high voltage), and the marginal emission factor was assumed 0.788 kg CO_2e/kWh based on Engstam et al. (2023). It was assumed that woodchips are used for providing heat in the biogas plant, with the emission factor of 0.01 kg CO_2e/MJ (Scrucca et al., 2023).

2.2.2.2. Assumptions regarding the biogas production. The energy input in form of electricity and heat were calculated for the operation of a large-scale biogas plant with slurry manure as raw material (Berglund and Börjesson, 2006). The electricity requirement for biogas upgrading, compression and dispensing was calculated based on Moghaddam et al. (2015), considering water scrubbing technology for removal of hydrogen sulphide (H_2S) and CO_2 and compressing the upgraded biogas to 200 bars.

Direct CH_4 emissions from biogas production and upgrading, refuelling, as well as operation of buses or trucks were calculated based on Göthe (2013). The surplus upgraded biogas is assumed to be used in trucks or buses that have higher CH_4 emissions compared to cars (Göthe, 2013). In addition, the direct CH_4 emissions from considering low emission facilities, in sensitivity analysis, for the production and use of upgraded biogas as vehicle fuel were calculated based on Göthe (2013), referred to as best available technologies.

2.2.2.3. Assumptions regarding storage and field application of slurry manure and digestate. It was assumed that there is no significant difference in the N_2O emissions from storing untreated manure and digestate (Kupper et al., 2020; Meng et al., 2023). The main source of GHG emissions was assumed to be CH_4 during the storage of untreated manure and digestate, and N_2O for the field application (Wulf et al., 2002; Amon et al., 2006).

The CH_4 emission rate from storage of anaerobic digestated manure depends on storage time and method, temperature, hydraulic retention time (HRT) and organic loading rate (OLR) (Moset et al., 2019), and the emissions rate varies significantly within different studies. In this respect Rodhe et al. (2015) reported a 228 % increase in methane emissions during storage of digestated manure compared to non-digested manure. On the other hand, Amon et al. (2006) found a 66.8 % reduction in methane emissions for digestate compared with manure storage in summer. Clemens et al. (2006) reported a 67.9 % reduction in summer and a 32.3 % reduction in winter storage. Holly et al. (2017) and VanderZaag et al. (2018) demonstrated that anaerobic digestion reduces the manure CH_4 emissions by 25 % and 59 % respectively, while Meng et al. (2023) reported a 75.3 % reduction in CH_4 emissions when comparing untreated cattle slurry with digestate of cattle slurry mixed with 7.5 % grass clover. In Sweden, several studies have shown that farm slurry tanks are partly emptied two to three times a year, which results in an average storage period for slurry of about three months. The methane emissions from the storage of fresh cattle slurry, using Swedish routines in manure management, is 8.7 and 4.8 g CH_4 per kg volatile solids (VS) in summer (May-Sept) and winter (Oct-April) respectively (Rodhe et al., 2009). In this study, considering the Nordic climate of the Uppsala County and mono-digestion of cattle manure, a reduction of 50 % is considered for methane emissions during digestate storage compared to manure, while the difference in nitrous oxide emissions is not considered. The nitrous oxide emissions after field application of manure and digestate were calculated based on work by Rodhe et al. (2015).

3. Results

3.1. Farm-level economic effects

Table 6 presents the main deterministic farm-level economic effects composing the net benefit change associated with transitioning from the baseline scenario to the biogas scenario. The transition implies an increase in revenue from sales of manure to the biogas plant (115,566 SEK/year) and from the sale of the diesel tractor used in the baseline scenario recalculated as annuity (91,073 SEK/year). In terms of cost reductions, the main drivers are the reduction in cost of diesel consumption assumed in the baseline, amounting to about 265,890 SEK/year, accompanied by decrease in cost of purchased synthetic fertiliser (110,191 SEK/year). The subtotal of the total benefit change when adopting biogas systems is calculated at 640,019 SEK/year. In terms of added costs, the main drivers are the cost of purchasing biomethane from the central station with 249,964 SEK/year and the annuity associated with investing in a biomethane tractor of 137,436 SEK/year. Other important added costs are the accumulated operating costs (41,231 SEK/year), cost of purchasing digestates (135,212 SEK/year) and cost of mineral fertiliser (75,141 SEK/year). The subtotal of the total cost change is 638,984 SEK/year. The annual net benefit change is estimated at 1035 SEK/year. Since the deterministic partial budget presented in Table 6 is a single point estimates of net benefit that might vary due to variation in the considered variables, we conducted a stochastic simulation for the net benefit change based on Weibull distribution. The simulation results, presented in Fig. 2, show various percentiles, with a median net benefit (see Table E.1 in Appendix E). Consequently, the simulated net benefit is predominantly negative, particularly in the lower percentiles.

Fig. 2 shows the kernel density function of the stochastic partial budget for the net benefits associated with biogas adoption based on 5000 simulations. This density function shows the range of possible net benefit values and their corresponding probabilities. The cumulative density function (CDF) or the S-curve further shows the probability of achieving specific net benefit levels. In monetary terms, the maximum possible net benefit from adopting the biogas scenario is estimated at 68,078 SEK, while the minimum is estimated at −90,164 SEK. The simulation results indicate that a substantial proportion of outcomes are negative, with a median net benefit of −5397 SEK. This implies that more than half of the scenarios result in financial loss, highlighting a considerable risk for farmers. The CDF shows that while there is an 87.5 % probability that net benefits will exceed a positive threshold, this does not guarantee profitability, as a large share of the simulated scenarios still yield negative outcomes. The near-symmetric distribution (skewness = −0.068) implies that both gains and losses are possible, but with a slight tendency toward negative returns. This is also affirmed by a

Table 6
Deterministic effect of net benefit change in biogas scenario.

Benefits	Value (SEK per year)	Costs	Value (SEK per year)
Increased income		Cost of biomethane	249,964
Manure sale	115,566	Biomethane tractor Annuity	137,436
Diesel tractor Annuity	91,073	Operating costs	41,231
Reduced costs		Digestate cost	135,212
Reduced diesel costs	265,890	Mineral fertiliser cost	75,141
Reduced mineral fertiliser	110,191		
Reduced operating costs	57,300		
Total benefit change	640,019	***Total cost change***	638,984
Net benefit change	1035		

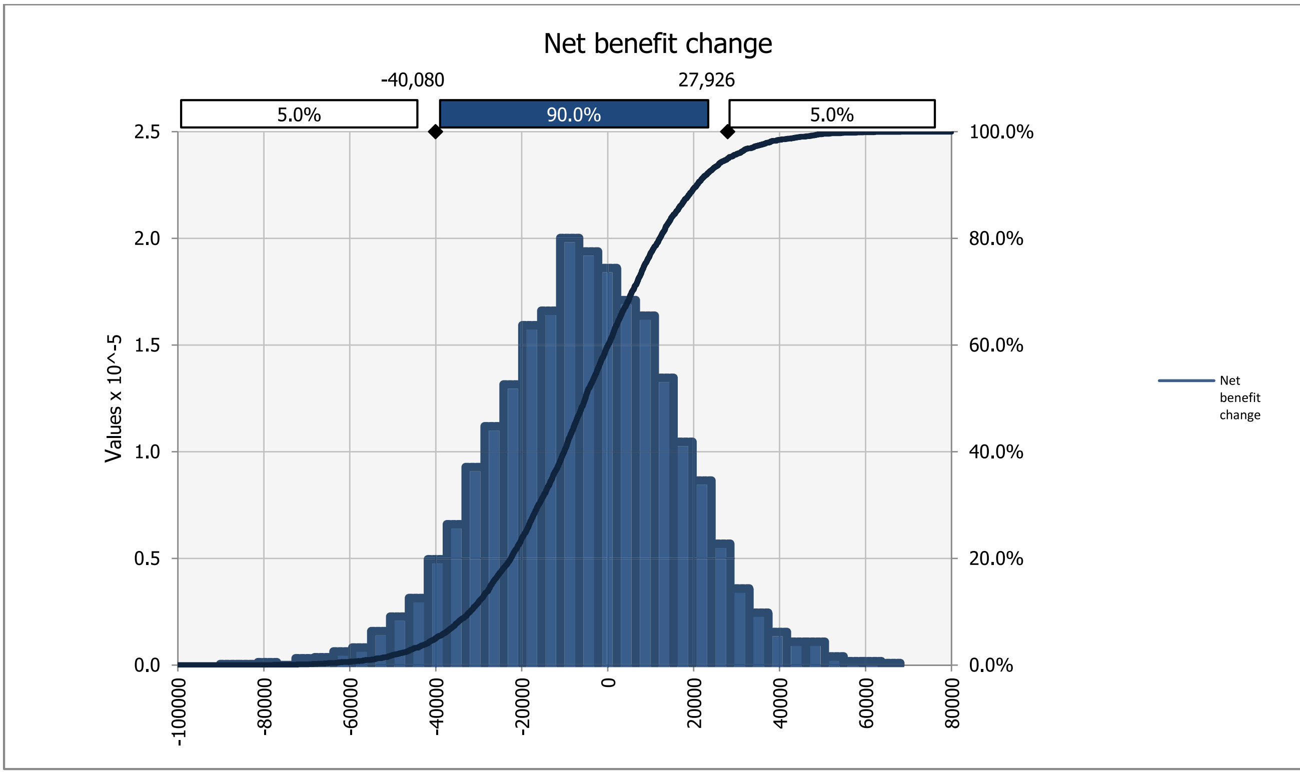

Fig. 2. Kernel Density of Weibull Distribution of the net-benefit outcome.

quite broad confidence interval which shows a considerable uncertainty about the true mean of the net benefit change (see Table S1 in supplementary material).

Appendix C contains details on the model used for calculating the standardised stepwise regression coefficients. In Fig. 3, the result of the regression coefficients is displayed on a tornado chart. The coefficient is a numerical value which implies that increasing/decreasing the input variable by one-unit will significantly increase/decrease the outcome variable. In the chart, longer bars are accompanied by larger coefficient which signifies the importance of the input variable on the output. The interpretation is that larger bars to the right denote increasing the input variable will significantly increase the outcome variable. Conversely, negative coefficient extending to the left will adversely decrease the outcome variable. This is same way of saying the bar and sign of the tornado chart relates to sign and magnitude of a simple regression. The price of diesel with coefficient of 0.59 is the single most impactful of the input variable. For example, a 1 % increase in diesel price will increase the net benefit of this scenario by 12,317 SEK (0.59*20,885.66) per

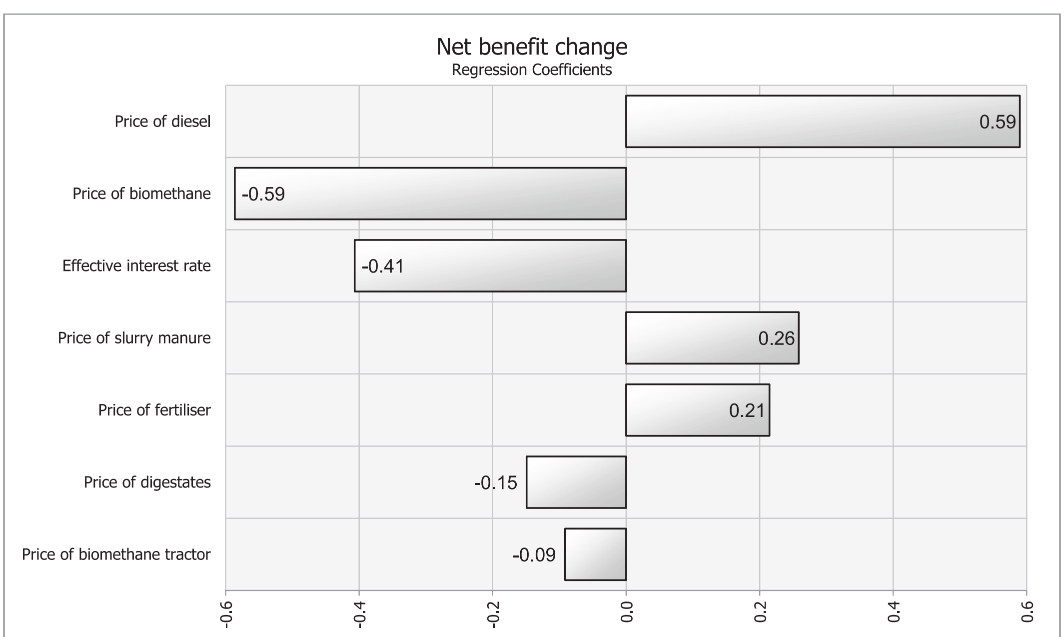

Fig. 3. Tornado plot with regression coefficients for net benefit change in biogas implementation.

year. Conversely, the price of biomethane is also associated with a larger impact whereby a 1 unit increase in its price will decrease the net benefit change associated with biogas implementation by 12,242 SEK/year. A unit increase in effective interest rate will eventually decrease the net benefit by 8492 SEK/year.

Similarly, the price of slurry manure depicts a unit increase is accorded with a 5399 SEK increase in net benefit of biogas adoption. Accordingly, a 1 % increase price of synthetic fertiliser in baseline is accompanied by 4485 SEK increase in net benefit of adoption. Price of digestates is also followed by a negative impact on benefit precisely a 1 unit increase in price of digestates will decrease net benefit by 3113 SEK/year. Finally, the increase in price of biomethane tractor would result in increase in net benefit although by insignificant amount of 1910 SEK/year. This sign is against our a priori expectation but the magnitude is correct. A simple explanation why this might have undesirable sign may be related to annuity payment. Appendix D shows the scatter plots for the individual sensitivity of the input variables in relation to the net benefit change.

In this study, we assumed a dairy farm with 300 milking cows and 325 ha of cropland using the equivalent of one tractor. In practice, a dairy farm of this size would use multiple tractors to manage various tasks simultaneously, while tractors would be idle part of the day. If we assumed multiple tractors, the farm would sell two or more diesel tractors and purchase an equivalent number of biomethane tractors. The total fuel consumption would remain unchanged, as one tractor could operate longer hours, while multiple tractors would result in more idle hours for the tractors. For simplicity, we assume one tractor in our main results.[1]

3.2. Effects on greenhouse gas emissions

3.2.1. Climate impact

Overall, the biogas scenario resulted in a GWP reduction of 218.4 tons carbon dioxide equivalent (CO_2e) compared to the base scenario (Fig. 4). This implies a 28.35 kg CO_2e reduction per ton of slurry manure used in the biogas production. The most contributing factor to this reduction is the substitution of diesel with CBG in buses and trucks. Specifically, it reduces the GWP from 242.8 tons CO_2e to 93.5 tons CO_2e, representing a decrease of 149.2 tons CO_2e.

The biogas scenario causes emissions from transportation of manure, digestate and CBG that do not apply to the base scenario. With the assumption of a 25 km distance between the farm and the biogas, GWP of these transportations resulted in 13.4 tons CO_2e. The reduction in mineral nitrogen fertiliser use resulted in 17.9 tons CO_2e emissions reduction in the biogas scenario. Storage and field application of anaerobically digested manure had less emissions compared to untreated manure, a reduction of 27.1 tons CO_2e and 6.5 tons CO_2e respectively.

3.3. Sensitivity analysis

The input data were varied to evaluate the impact of different parameters on the GWP reduction in the biogas scenario compared to the base scenario, as well as the change in the regression coefficient. Using the primary assumptions, the biogas scenario resulted in a GWP reduction of 218.4 tons of CO2e compared to the base scenario. Table 7 summarizes the changes in this reduction.

Using the Swedish marginal emission factor for electricity consumption in the biogas plant had the most effect on the climate impact results. The biogas scenario resulted in a total GHG emissions reduction of 68.1 tons CO_2e compared to the base scenario, equivalent to 8.84 kg CO_2e per ton of slurry manure. Followed by using low emission facilities for biogas production, upgrade and use, which yielded a the total GHG emissions reduction of 302.9 tons CO_2e, or 39.3 kg CO_2e per ton slurry manure.

4. Discussion

Previous research has demonstrated the environmental feasibility of biogas systems on farms and recorded positive effects on energy balance, acidification and eutrophication, although with considerable storage cost and extensive tractor modifications (Fredriksson et al., 2006 Hansson et al., 2007; Ahlgren et al., 2009; Ahlgren et al., 2010). In this study, we suggest biogas scenario for dairy farms which allows farmers to become fossil free in their input use by switching to a biogas-system for fuel and fertiliser use. We evaluate the economic (farm-level) and climate consequences of transitioning from a conventional fossil-based system to the suggested biogas-based system. Our contributions emanated from building a stochastic partial budget to analyse the farm-level economic consequences from transitioning. The analysis is a typical example of "what if" scenario and what might happen, if certain decisions are embarked upon (Owusu-Sekyere et al., 2023). Partial budget is a coherent financial instrument for decision analysis under uncertainty and economic examination in situations especially where extensive empirical data of farms or other businesses are lacking (Ahmed et al., 2021). Second, LCA was used to assess the climate impact of the same system. The combined farm-level economic and climate analysis of the same system is the second contribution of our paper.

In this paper, our approach involves a scenario with a collaboration between farms and central biogas plant. Since many farms are incapable of investing in biogas plants independently, we aimed to investigate a more feasible scenario from the farmers' perspective. In this scenario, the municipality assumes responsibility for building and operating a biogas plant, sourcing inputs from multiple suppliers, including slurry manure from farmers, and supplying biomethane to various customers, including the farmers themselves. Hence, central the biogas plant is considered exogenous because it operates as an external entity, independent of farmers' ownership and operational control. This approach reflects a realistic scenario where a municipal biogas plant collaborates with multiple farms, allowing farmers to benefit without the financial and managerial responsibilities of running the plant. By modelling the biogas plant as exogenous, we can analyse how such collaborations impact farm economic outcomes and contribute to societal climate change mitigation. Furthermore, we treat the prices of slurry manure and biomethane as exogenous variables, meaning they are determined by external market conditions rather than individual farm operations. This assumption aligns with economic modelling practices, where exogenous variables are those influenced by factors outside the model's scope. By setting biomethane prices in line with compressed natural gas (CNG) and pricing digestates at two-thirds the cost of mineral fertilisers, we aim to provide stable and predictable costs for farmers. This pricing strategy reduces potential feedback effects, ensuring that fluctuations in a single farm's slurry supply do not disproportionately impact prices.

Our results point to that the hypothetical farm considered here would experience a deterministic positive net benefit change of 1035 SEK/year if transitioning from its conventional production to the suggested biogas-based production. Simulating the net-benefit change while taking variation in variables into consideration yields a maximum value of 68,078 SEK/year and a minimum of −90,165 SEK/year. If this same procedure were repeated across multiple farms, we would expect that 90 % of the calculated confidence intervals would contain the true mean of the net benefit change. In this case, the confidence interval in Fig. 2 ranges from −40,080 to 27,926 SEK/year, suggesting that the 90 % confidence interval contain the true mean of net benefit. However,

[1] For sensitivity analysis (see the supplementary material Table S3 and S4), we assumed instead that two diesel engine tractors were replaced with two biomethane tractors. This resulted in a deterministic net benefit of −45,328. However, assuming instead that the farm operates multiple tractors and replaces them with more efficient biomethane models, the deterministic net benefit improves, ranging from 45,745 onward.

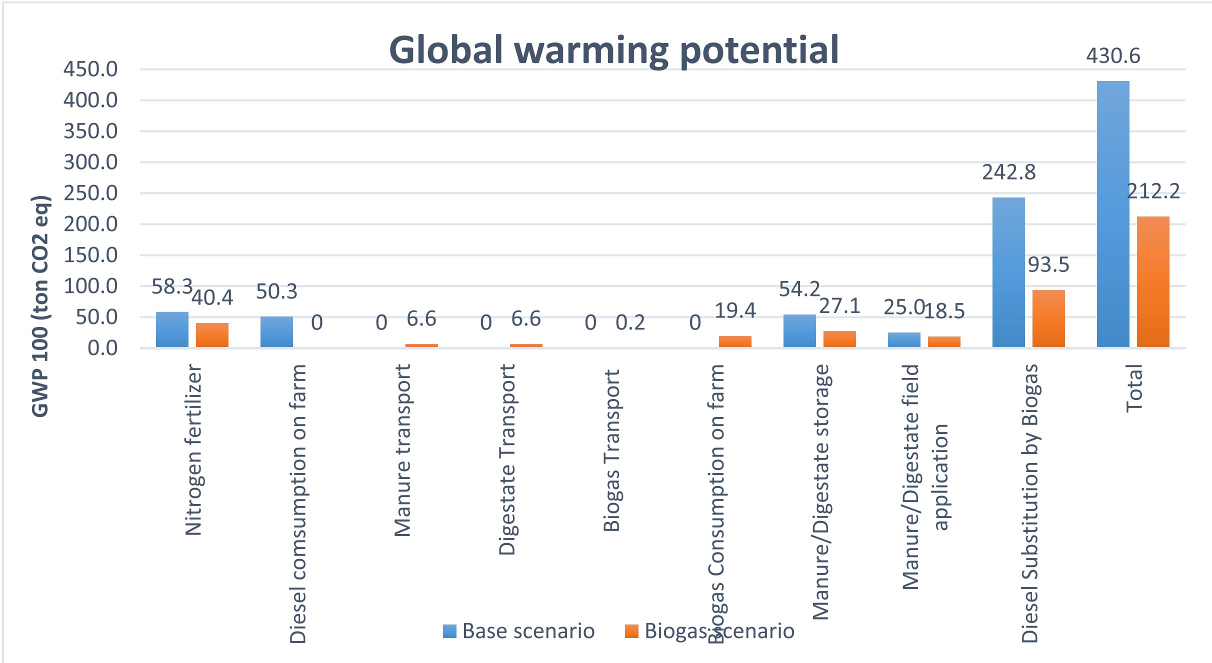

Fig. 4. Results for global warming potential (GWP) impact for the base scenario and biogas scenario

Table 7
Summary of variations in input data and their effects on GHG emissions reduction and regression coefficient.

Change in the input data	GWP reduction of Biogas scenario vs. Base scenario (ton CO_2e)	Change in GWP reduction, compared to the primary assumptions (%)	Change in regression coefficient
Primary assumptions	218.4		0.69
Marginal electricity mix	68.1	−68.8	Not applicable
Biogas production, upgrade and use in low emission facilities	302.9	38.7	Not applicable
Both diesel and biogas engines 10 % more efficient	218.4	0.0	0.49
Biogas engines 10 % more efficient	247.7	13.4	−0.49
Tractor biogas engine more efficient	223.0	2.1	−0.49
More biogas per substrate	236.4	8.2	0.65
Shorter transport distances	219.8	0.6	Depends

because this include both negative and positive values, it indicates uncertainty about whether the true mean net benefit is negative or positive. Yet, given the size of the virtual farm (300 dairy cows) changes in the net-benefit can be practically considered as close cost-neutral. The results further point to that the price of diesel and biomethane are the main drivers of the net benefit change, contributing to variance of net benefit change with 35.3 % and 34.1 % respectively. Consequently, a decrease shock in the price of diesel can also render the system prohibitive. Similarly, if diesel price increases, the positive net benefit associated with the system increase significantly. The price of biomethane is assumed to be pegged at the price of CNG and ethanol to ensure a uniform price and a long-term contract between the farmers and biogas plant. Changes in these settings will also impact the economic effect of the system. In addition, the effective interest rate and price of slurry manure jointly contribute 22.9 % variation to the net benefit. Notably, our study points to that the price of fertiliser and digestates and annual investment cost for the biomethane tractor do not significantly influence the result.

Furthermore, our findings support the implementation of the biogas-based scenario as a step in reducing negative impacts on climate from agricultural production. Besides, the implementation of biogas system for self-sufficiency of farm energy systems in Sweden has been revealed in previous work (Fredriksson et al., 2006; Hansson et al., 2007; Gunnarsson et al., 2008). The LCA results point to that switching to the biogas-based system will result in reduction of 218.4 t CO_2 e. emissions compared to the fossil-based baseline. In this regard, results point to an opportunity for farmers to use the reduction in CO_2 emissions (in whole or in part depending on individual agreements with the biogas plant) from transitioning to the biogas-based system as a form of investment in carbon sequestration in voluntary market. There are several opportunities for farmers to do so. For instance, Svensk Kolinlagring, a Swedish carbon storage initiative, provide investment opportunities for farmers with more than four hectares to invest in carbon credits, in line with European commission's objective to foster biodiversity and ecological concerns, reduce GHG emissions from agricultural land and keeping the global temperature at 1.5 degrees limit (Svensk Kolinlagring, 2024). The carbon storage initiative offers farmers 1800 SEK /tonne of CO_2 eq. investment in carbon credits for accomplishing on-farm sustainable practices (Svensk Kolinlagring, 2024). This initiative is only available for farmers who engage in planting crops that trap carbon in the soil, not dairy farmers. It is therefore interesting that such opportunities exist for sustainable farms which can potentially be extended for dairy farms. Nevertheless, farmers are eligible to benefit from methane reduction from carbon credits traded daily in the European carbon credit market.[2] The European carbon pricing is volatile based on demand and supply and based on mandatory compliance market and voluntary market. The average daily price of carbon credit hovers around 74 euros, which

[2] Retrieved from Live Carbon Prices Today, Carbon Price Charts • Carbon Credits

provide a significant opportunity for the farmers to trade in forward market. Based on our estimation, reducing GHG emissions by 218.4 units implies that farmers could earn carbon credit up to 16,162 euros, which depends on market dynamics, certification and compliance practices. Given the carbon credit, the augmented true economic net benefit can, therefore, be estimated as net benefit plus carbon credit amounting to 186,035 SEK/year. However, since this is in collaboration with the central biogas plant, it is possible that all the credit will not be accorded to the farmer and will instead be shared. Similarly, if we incorporate 218.4 t of CO_2 in 516,500 t of fossil CO_2 emissions caused by agricultural machinery and heating agricultural premises (Swedish Environmental Protection Agency, 2023a, 2023b), the society will experience an estimated share of CO_2 depletion by 42 % (218.4/516,500).

While there is no established market for slurry manure and digestates, our result shows that there is a potential, both for the economic and climate benefits. For example, having such established market not only increases the amount of ammonia nitrogen needed for plant growth, but also increases farmers' willingness to pay for digestates albeit through provision of information to farmers (Roberta et al., 2021). In fact, Feiz et al., (2022) established that the practical success of biogas business performance in Sweden relies on suitable site-selection that take account of supply and demand, infrastructure and synergy, land-use and zoning, and socio-political settings. Some assumptions were therefore made for this study, which do not necessarily reflect the real market outcome. This is because the data were rescaled to fit into Swedish context and rely heavily on expert elicitations. Therefore, estimations like ours may compound the evaluation of costs and benefits especially when market alters frequently. Using data for Sweden, our simulation approach evaluated the system for a 15-year period without taking into account how disruption in prices, costs or interest rate can have a medium-term impact on the system. Therefore, future research would have an important task in examining the impact of structural interruptions that can arise from unforeseen circumstances. Reasonable examples which can cause structural interruptions include impacts from new discoveries of cheap marginal oil fields, a new global pandemic or the geopolitical tensions following recent crisis in Eastern Europe and in the Middle East.

The calculated climate effects are expected to scale linearly with the number of cows and the farm size. Manure and digestate volumes—along with their storage, field application, and transportation—are determined by the number of animals, and therefore the biogas production potential. On the other hand, nitrogen fertiliser requirements, as well as diesel or biogas consumption, depend on both the herd size and the farm area. Milk production per cow varies between breeds and farms, but for this study, we assumed an average yield of 10,000 ECM per cow per year, which is a typical estimate for Swedish dairy farms. Assuming higher milk production per cow leads to changes in the feed, which in turn affects the amount of manure produced. With a greater volume of manure, more biogas can be generated, contributing to a reduction in GHG emissions in the biogas scenario. However, the increased feed may also result in higher fuel consumption, either diesel or biogas, on the plant farm, leading to more emissions of the farm. The overall impact of these changes depends on factors such as feed efficiency and nutrient utilization, which were not explicitly quantified in this study but remain important considerations for future research.

Our findings have clear implications for initiatives aiming at supporting uptake of climate friendly technologies in society at large. Since the agglomeration of global agricultural emissions are deciding the effects, the whole society will benefit if biogas transition is achieved. For instance, the biogas scenario is built on the assumption of a larger scale central biogas production plant with several categories of end-users, our findings highlight the need to build working biogas plants that can collaborate with farmers. Since Swedish board of agriculture have been supporting on-farm anaerobic digestion facilities (Swedish board of agriculture, 2023), it is only coherent to consolidate the collaboration between farmers, cooperatives and municipalities. Thus, there is a need to support policies that focuses on increasing self-sufficiency of biogas on farms and production of least substrate on a small or industrial scale. Besides, the intricate concerns about farming agricultural land for energy crops, agricultural commodities prices and displacement of food systems has been focus of debate (Kimming et al., 2011; Vasilea et al., 2016; Reid et al., 2019). The production of biogas from farm waste is particularly interesting, as it would not compete with agricultural land uses to the same extent as other biofuel production types which might be problematic due to the availability of agricultural land, crop rotation needs and competition with food crops (Raslavičiusa et al., 2012). The biogas system we propose here suggests an investment in technological advancement, which can drive the rise in supply of biogas, without compromising the farmer's economic incentive. The technologically feasible system suggested here is cost-neutral at the farm level, while significantly contributing to reducing GHG emissions. It remains an open question if the net benefit and carbon credit investment is enough for risk averse farmers, or if additional incentives would be needed to encourage uptake. These findings indicate that even though biogas adoption has potential financial benefits, the high variability in net benefit suggests that the investment is not without risk. Factors such as energy price fluctuations, farm-specific operational efficiency, and initial capital investment all contribute to this uncertainty. Specifically, the initial capital outlay needed for the transition might discourage action, and future research has an important task in investigating farmers' sensitivity in this respect. Especially, farmers' risk preferences would be relevant to study in this respect. While there are numerous examples of municipality-owned biogas plants in Sweden, estimating the investment and operating costs from the municipality's perspective is beyond the scope of this study, but is a potential area for future research, particularly with a focus on the farm– municipality-owned biogas plant operation set up suggested here.

5. Conclusion

This study developed a scenario in which dairy farms can become fossil-free in their fuel usage by transitioning to a biogas-based system and compared the economic and climate consequences of doing so. Through this study, we provide a model that enables farmers to examine costs and benefits associated with the transition and taking into consideration the risk and uncertainty in the economic variables. We compared the farm-level economic consequences of transitioning to the biogas scenario and climate impacts from doing so, with the fossil-based baseline scenario.

The findings point to that investment in the considered biogas system can be feasible from both an economic and climate perspective without requiring additional agricultural land to produce or by compensating farmers through higher farm output prices and thus higher food prices. Whilst the biogas system has potential upside, more than half of the simulated point estimates lead to a loss, suggesting that the investment is not without financial risk. Specifically, factors such as fluctuations in diesel prices, biomethane price, effective interest rates, and initial capital outlay all contribute to this uncertainty. Despite potential climate benefits, given the possibility of negative returns, risk-averse farmers may hesitate to adopt the biogas scenario.

The findings reveal how market internalisation of the transition to fossil-free dairy farming can be achieved through the creation of economic and business incentives that encourage trading between farmers and centralised biogas plants. However, a functioning biogas plant is necessary for the biogas scenario to materialise, whether established through a private organisation, a cooperative, or municipal initiatives. This can be achieved through the continued establishment of biogas plants in collaboration with farmers and other stakeholders to spur farmers' interest in owning more anaerobic digestion (AD) plants. This can be facilitated through better pricing, information sharing, suitable site locations, encouragement in the use of digestates on farms, and innovation in digestate spreading machinery.

By presenting statistically simulated input and output parameters, we provide novel evidence that farmers can be incentivised to transition to fossil-free agriculture and drive adoption using market indicators, contingent upon the existence of such a biogas plant.

CRediT authorship contribution statement

Nasir Adam: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ashkan Tayebi:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Vivian Wei Huang:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Gordana Manevska-Tasevska:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Åke Nordberg:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Per-Anders Hansson:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Helena Hansson:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2025.104358.

Data availability

Data will be made available on request.

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