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Making money from waste: The economic viability of producing biogas and biomethane in the Idaho dairy industry

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HIGHLIGHTS

- Anaerobic digestion can increase the income of (dairy) farmers.
- ≥3000 cows per farm are required for an economically viable plant operation.
- Joint, cooperative anaerobic digestion plants allows a higher manure utilization.

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ABSTRACT

Farm operations in the USA and Europe have seen a radical change in the last decades: small sized farms are disappearing, and farm size and total livestock on larger farms are increasing. The resulting spatial density of animals causes several environmental impacts. Anaerobic digestion is one promising technical solution to alleviate most of these impacts while simultaneously providing a regional energy source. This analysis assesses the economic viability of using dairy-cow manure for either (i) the on-farm production and use of biogas to generate electricity and heat or (ii) the upgrading biogas to biomethane, a natural-gas substitute. A non-linear optimization model was developed to optimize plant capacity for anaerobic digestion and maximize the net present value for each option by farm size. In this study, we used Idaho's dairy farms as a case study. The analysis implies that at least 3000 cows per farm are required for an economically viable anaerobic-digestion plant operation. For farms with up to 3600 animals, the highest net present value was achieved for the on-farm use of biogas. Farms larger than that achieved their best economic results via the production of biomethane. In total about 45% of Idaho's dairy manure could be utilized by economically feasible biogas and biomethane plants. A higher manure utilization rate could be achieved through joint, cooperative anaerobic digestion plants and manure transportation. The results can be transferred to other regions and countries, respectively, to reduce the negative impact of intensive livestock farming.

1. Introduction

The European and American dairy sectors have been subject to significant changes: The number of dairy farms has been continuously decreasing, whereas, the average number of cows per farm has been increasing [1,2]. For example, over the last three decades, Idaho has become the third largest milk-producing state in the USA. This process was characterized by two main developments: compared to 1980, the annual milk production per cow in 2012 almost doubled, and the absolute number of milk cows increased from 153,000 to 592,000 by 2017 [3,4]. Due to, among other factors, economies of scale, the state witnessed a reduction in the total number of dairy farms within the last three decades while the average farm size increased to 1240 cows per farm in 2017 [3,4]. In 2007, the average farm size in Idaho was 633 cows [5]. Besides the United States (U.S.), similar developments have been observed in Western European countries, such as the Netherlands [6].

Due to the increasing size of dairy farms and their spatial concentration, the environmental impact of intensive livestock farming has become problematic. According to [7–9], areas with dairy farms are characterized by a high mean nitrate concentration in the groundwater and soil. Besides the increasing concentration of nitrates, dairy farms may also be a health risk when water systems and soil are polluted by manure and pathogens [10]. Several sites with multiple total coliform

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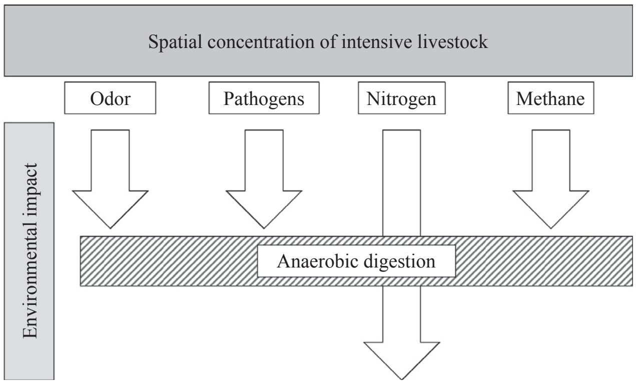

Fig. 1. The effect of anaerobic digestion on environmental impacts caused by the spatial concentration of intensive livestock.

bacteria were located near large dairy farms. In addition, the spatial concentration of livestock result in odor emissions that decrease the life quality of neighboring communities and impact human health, e.g., eye and nose irritation or headache [11].

In summary, there is an urgent need to reduce the environmental impact of intensive and spatially concentrated livestock farming. One technical option to reduce these impacts is anaerobic digestion of related effluents (Fig. 1). Anaerobic digestion reduces both odor emissions and pathogens [12,13]. Compounds of odor emissions are broken down to odorless or less-offensive odor compounds [12,14]. Anaerobic digestion of swine-manure slurry destroys 97.94–100% of total indigenous coliform populations and at least 99.67% of indigenous *Escherichia coli* populations. Similar effects on the bacteria concentration of cattle slurry were shown by [15]. Furthermore, oxygen is required to break down manure in water systems. Anaerobic digestion helps to reduce water contamination through organic material, thereby decreasing total oxygen demand (TOD) level. TOD measures the amount of oxygen needed to break down organic material [16]. However, anaerobic digestion cannot prevent the negative impact of nitrogen contamination imposed by concentrated livestock farming on water systems. Indeed, anaerobic digestion increases the value of manure due to the conversion to ammonia or nitrogen, which is characterized by a higher plant availability; however, the total concentration of nitrogen remains constant [14,16]. Besides the reduction of odor and pathogens, anaerobic digestion decreases greenhouse-gas (GHG) emission from manure used as fertilizer on fields, mainly methane [17–21]. Methane contributes to global warming with 25 times the global-warming potential of CO_2 over a period of 100 years [22]. Electricity generated by manure-based biogas reduces the GHG emission significantly; a German case study calculated a reduction about 1.45 kg CO_2e kWh^{-1} generated power due to the improved manure management and the substitution of the German electricity mix [23].[1] According to [24], the reduction of methane emissions in the U.S. can be one cost-effective measure to decrease the negative impact of climate change. In this paper, we calculate the economic viability of anaerobic-digestion plants to reduce the negative environmental impacts of dairy farms using the state of Idaho as a case study.

Anaerobic digestion plants have been slow to take off in the U.S., and a limited number of studies have analyzed the economic rationale (e.g., [25–28]). The U.S. Environmental Protection Agency (EPA) suggests that biogas plants are economically viable at a farm size of 500 dairy cows or more [29]. Klavon et al. [30] analyzed the profitability of small-scale digesters in the U.S. for farm sizes of 250 dairy cows or fewer. All digesters considered in these studies are characterized—without cost sharing—by a negative cash flow under the chosen assumptions. Similarly, Yiridoe et al. [12] carried out the effect of nonmarket co-benefits, such as odor or pathogen reduction, on the economic viability of on-farm biogas energy production. Without the consideration of nonmarket co-benefits, energy production from biogas on dairy farms for sizes up to 500 cows is not economically feasible [12]. Murray et al. [31] determined potential levelized costs and potential of biomethane (also based on manure) in the U.S., i.e., defined as biogas upgraded to natural-gas properties for the injection and substitution of fossil natural-gas in the natural-gas grid. Biomethane may cover 3–5% of the national gas market in the U.S. at a calculated price of $5–6/MMBtu. In addition, biomethane produced by manure would enter the natural-gas market if the price is above $6/MMBtu [31].

Nevertheless, the above-mentioned studies do not combine the economic viability of anaerobic digestion from the perspective of dairy farmers with the reduction of environmental concerns. In Idaho, the number of large dairy farms is comparably high relative to other states in the U.S. [32]; for this reason, anaerobic digestion may be one option to reduce the environmental impact of intensive livestock farming of dairy cows and to increase the economic viability of Idaho's dairy farmer. The present paper intends to fill this gap by using Idaho as a case study for the calculation of the economic viability of anaerobic digestion.

We assess the economic viability of two alternative (yet not mutually exclusive) technical options for anaerobic digestion: (i) the on-farm use of biogas to generate electricity and heat; (ii) the upgrading of biogas to biomethane and the injection into the grid to substitute natural gas.

The objectives are defined as follows:

i Assess the biogas potential by calculating the size class distribution of dairy farms in Idaho
ii Calculate the economic viability of on-farm biogas use and the injection of biomethane into the natural-gas grid via a non-linear optimization model to optimize the net present value of anaerobic digestion by farm size
iii Characterize the results and perform sensitivity analysis to determine alternative ways to increase the economic potential of manure utilization.

2. Methodology

2.1. Size distribution of dairy farms in Idaho

The economic viability of anaerobic digestion in Idahós dairy industry is related to the number of cows per farm. Utilizing data from the Idaho Department of Agriculture [4], we calculated the size class distribution of the farms, depending on the number of cows as well as the number of farms per size class to show the suitability of Idaho as a case study. We defined 81 size classes, each with a size of 100 cows. The largest dairy farm in Idaho has 18,000 cows compared to 8000 cows of the second largest one; consequently, we summarized the largest size class (no. 33) defined by more than 8000 cows per farm. To assess the economic potential of anaerobic digestion across the technology options, the accumulated proportion of the farms' sizes must be determined.

2.2. Economic assessment

The economic viability of anaerobic-digestion plants using manure from Idahós dairy cows depends on the economic feasibility of the project from the perspective of the operator/investor. Thus, the net present value (NPV) method was used to assess the profitability of the project from dairy farmer's perspective. The NPV method summed the annual discounted cash flow, consisting of the difference of cash inflows (benefits) and cash outflows (costs) over a certain period, resulting in the NPV. If the NPV becomes positive, the investment decision will be economically feasible based on the assumptions chosen [33]. Therefore,

[1] Further benefits of anaerobic digestion are shown, for example, in [12].

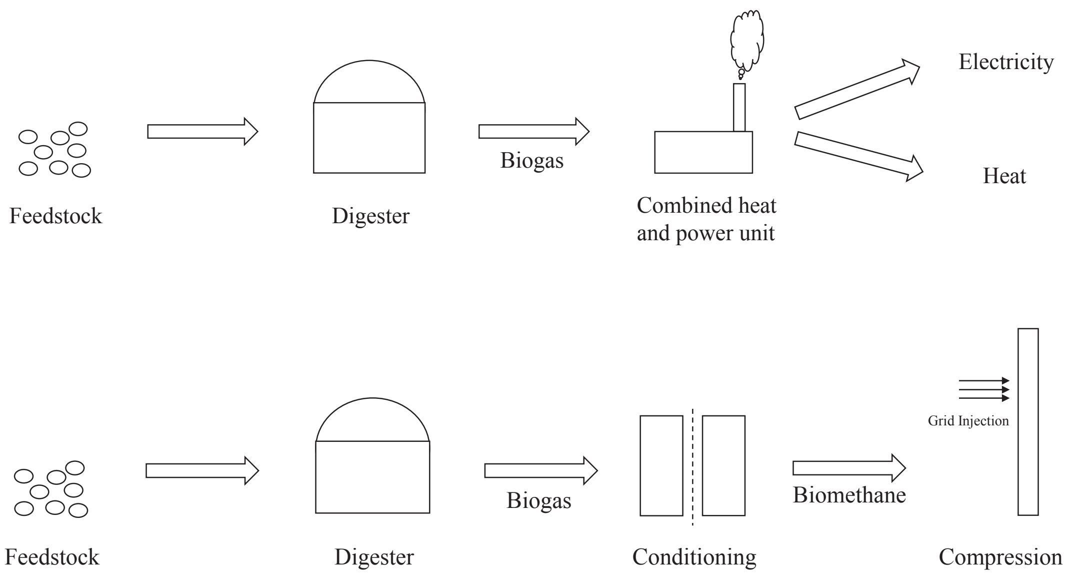

Fig. 2. Schematic representations of the on-farm use of biogas (upper figure) and the biomethane injection (lower figure).

we calculated for each technology option (on-farm use of biogas or biomethane) the net present value based on the farm size. Starting with a farm size of 100 cows and ending with 8000 cows per farm using increments of 100 cows. The largest farm with 18,000 cows was calculated separately.

2.3. Assumptions on the economic assessment

2.3.1. Components

The two technology scenarios required different components, resulting in different total investment costs. In both cases, a digester produces biogas, and a flare prevents the release of methane. When the biogas production is comparably higher than the biogas consumption of the plant over a certain time, and the biogas cannot be stored in the on-plant biogas storage, excess biogas is flared. Three different digester types were considered: covered lagoon (CL), complete-mix (CM), and plug-flow (PF) digester.

Covered lagoons are ponds, covered by impermeable plastic film to capture the methane. They are usually used for liquid materials with a solid content up to 2% and a hydraulic-retention time (HRT) of 35–60 days. Solid material has to be removed pre-digestion [34]. Typical feedstocks of covered-lagoon systems are dairy and swine manure, collected by flush systems. Components of these digester type are well-established [35].

Complete-mix digesters consist of steel tank reactors, where the digestion is mixed by agitators. The HRT is between 20 and 25 days, and these digester types allow a solid material content of 3–10%. Solid materials can be removed pre- and post-digestion [34]. Complete-mix systems are especially used in dairy, beef, and swine operations. The manure is collected by flush or scrape collection systems [35].

Plug-flow digesters are horizontal tanks; the feedstock flows intermittently into the reactor. Consequently, the content of solid materials can be higher (i.e., 10–14%). The HRT is similar to that of complete-mix digesters, 20–30 days. Solid material is separated post-digestion [34]. A higher share of solid material is needed to maintain a homogenous mixture in the digester without the use of agitators. Due to the optimal characteristics of dairy manure, plug-flow digesters are predominantly used on dairy farms (in the U.S.) [35].

In the biogas scenario, a hydrogen-sulfide treatment is needed before the biogas can be used in a combined heat and power unit (CHPU) to generate electricity and heat. By contrast, in the biomethane scenario, biogas is upgraded to a natural-gas substitute, compressed, and injected to the grid. In order to produce biomethane, a conditioning plant to reduce the concentration of carbon dioxide and hydrogen sulfide, as well as a compression plant, must be installed (Fig. 2).

All components were defined as cost functions based on the number of cows per farm and/or the hourly biogas production (Table 1).[2] Table A1 and Table A2 (see Appendix) provide an overview of all sets, indices, variables and parameters that are used in the model.

Where *cows* are the number of cows per farm, *I* is capital investments in varying components defined by the set $dig \in DIG$, that describes the different digester types: covered lagoon *CL*, complete-mix *CM* and plug-flow *PF*. Capital investments in other components are described by the indices *flare* (flare), *H2S*, for hydrogen-sulfide treatment unit, *CHPU*, combined heat and power unit, *cond*, conditioning unit, *comp*, compression unit, and SSN, solid separation unit. *RPI_CI* is the annual rate of price increase of capital investments, *opt_cap* is the optimal installed capacity of the anaerobic digestion plant, cap_CHPU is the installed capacity of the CHPU, *BCH4* is the hourly biogas production, *max_cap_CHPU* is the maximum installed capacity of the CHPU, *max_BCH4* is the maximum hourly biogas production, *biogas_cow* is the daily biogas production per cow, η_{dig} is the manure collection efficiency of the digester type, η_{biogas} is the efficiency of the biogas control system and *CH4_biogas* is the concentration of methane in biogas, *CH4_energy* is the energy content of methane, η_{el} is the electrical efficiency of the CHPU, *flh_bm* are the annual full load hours of the conditioning and compression unit, *year* is the commissioning year of the plant and η_{cond} is the efficiency of the conditioning unit.

For each digester type, the total capital cost per additional cow decreases, exhibiting economies of scale in farm size. Furthermore, the cost functions of the digesters also include the investments in the CHPU (1–3); we subtracted these costs for the biomethane scenario (9) from the digester cost formulas. The capital investments in digesters (and digestion solid separation) depend on the optimal capacity of the biogas or biomethane plant (4–6), which is calculated by the non-linear optimization model. To calculate the optimal capacity the maximum biogas production of the farm, depending on the farm sizes, has to be taken into account. The optimal capacity is defined by the capacity with the highest NPV that considers the maximum biogas potential of the farm size. According to the cost functions of the digester type, the capital investments in plug-flow digester types are the highest for each farm size (between 100 and 8000 cows). Covered lagoon digesters are characterized by the lowest capital investments; however, their

[2] All capital and annual costs were converted to 2017 US$.

Table 1
Capital investments in components needed for the operation of the biogas and biomethane plant.

Component	Biogas	Biomethane	Source/Comment
Digester			
Covered lagoon (CL)	$I_{CL} = (\text{"\$"}400 \times cows + \text{"\$"}599{,}566) \times (1 + RPICI)^{(year-2010)} \times optcap$ (1)		The cost functions including the digester and the CHPU are modified from [36]
Complete-mix (CM)	$I_{CM} = (\text{"\$"}563 \times cows + \text{"\$"}320{,}864) \times (1 + RPICI)^{(year-2010)} \times optcap$ (2)		
Plug-flow (PF)	$I_{PF} = (\text{"\$"}617 \times cows + \text{"\$"}566{,}006) \times (1 + RPICI)^{(year-2010)} \times optcap$ (3)		
$optcap = \begin{cases} \frac{max\ cap\ CHPU}{cap\ CHPU}(biogas) \\ \frac{max\ BCH4}{BCH4}(biomethane) \end{cases}$ (4)			
$\text{max}capCHPU = biogascow \times \eta_{dig} \times \eta_{biogas} \times CH4biogas \times CH4energy \div 24 \times \eta_{el} \times cows$ (5)			
$\text{max}BCH4 = biogascow \times \eta_{dig} \times \eta_{biogas} \times cows \div 24 \div \frac{flh\ bm}{8760}$ (6)			
Flare	$I_{flare} = I_{dig} \times 0.033$ (7)		[36]
Hydrogen sulfide treatment	$I_{H2S} = I_{dig} \times 0.031$(8)		
CHPU	$I_{CHPU} = (\text{"\$"}1642 \times BCH4^{1.17}) \times (1 + RPICI)^{(year-2013)}$ (9)		Own equations according to data by [37]
Conditioning		$I_{Cond} = (-\text{"\$"}0.076 \times BCH4^2 + \text{"\$"}1534.7 \times BCH4 + \text{"\$"}10^6) \times (1 + RPICI)^{(year-2013)}$ (10)	
Compression		$I_{Comp} = (-\text{"\$"}0.0077 \times (BCH4 \times \eta_{Cond})^2 + \text{"\$"}122.6 \times BCH4 \times \eta_{Cond} + \text{"\$"}111{,}872) \times (1 + RPICI)^{(year-2013)}$ (11)	
Solid separation (SSN)	$I_{SSN} = (\text{"\$"}29.11 \times cows + \text{"\$"}55{,}584) \times (1 + RPICI)^{(year-2007)} \times optcap$ (12)		Own equation according to data by [38]

manure-collection efficiency is also lower compared to complete-mix and plug-flow digesters. We assume that turnkey plants can be provided at any size. The digestion solid separation allows the reuse of solid materials that substitute current bedding materials (2). The operational life of the biogas and biomethane plants was set to 15 years based on [35].

2.3.2. Biogas production and capturing

The daily biogas production varies across publications. For instance, [27] found values between 1.5 and 3.9 m^3 per cow and day. In this study, we assumed 2 m^3 of biogas per cow and day, in-line with [30]. According to [35], the manure collection efficiency from cows depends on the digester type: 75% for covered-lagoon digester and 90% for complete-mix and plug-flow digesters. Furthermore, we considered an efficiency of 98% for the biogas control system. This assumes that 2% of the annual biogas production is released into the atmosphere.

2.3.3. Annual costs

2.3.3.1. Operating and maintenance. To operate the biogas or biomethane plant, cost for labor and new parts occur and are summarized in operating and maintenance (O&M). We defined cost functions for the annual O&M of the components used for anaerobic digestion (Table 2). Table 2 also shows the internal energy consumption of the anaerobic digestion plant for heating the digester (to maintain the biological process) and operating components such as pumps and agitators. In contrast with biogas plants, biomethane plants need an external energy supply.

Where *t* is the year of operation, *OM* are the annual operation and maintenance costs, *OMF* is the annual O&M costs factor, *RPI_OM* is the annual rate of price increase of O&M, *Demand_ht* is the proportion of the CHPU's generated heating that has to be used for the digester, *Int* is the internal electricity consumption of the biogas plant, *U* is the annual utility rate of the biomethane plant and *UC* is the annual utility charge.

2.3.3.2. Transport of biomethane. In this paper, biomethane is compressed and injected into the natural-gas grid, which must be extended by the operator or a third party to connect the biomethane plant. According to [31], it is assumed that a third party will invest in and operate the distribution lines. Hence, the operator has to pay a transmission tariff to transport the biomethane to the end-user:

$$Trans_t = Injectbm \times fee \times (1 + RPITR)^{(year-2014+t-1)} \quad (20)$$

$$Injectbm_t = BCH4 \times \eta_{Cond} \times \eta_{Comp} \times flhbm \quad (21)$$

where $Trans_t$ are the annual costs of the biomethane transportation, *Inject_bm* is the annual amount of biomethane that is injected into the natural gas grid, *fee* is the marginal costs of the pipeline transportation, *RPI_TR* is the annual rate of price increase of the biomethane transport and η_{Comp} is the efficiency of the compression unit.

2.3.4. Annual revenues

2.3.4.1. Electricity substituted. To calculate the substituted electricity, the hourly demand of the dairy farm was calculated by using a standard load profile, which is used by network operators to estimate the electricity demand of a specific consumer. Hourly values of the standard load profiles are normalized to an annual sum of 1; consequently, we had to multiply them with the consumption of the farm depending on the number of cows. The standard load profile differentiates between the four seasons and working days, Saturdays and Sundays/holidays. According to their numbers per year, these days were weighted. To determine the annual demand of the farm, we defined an equation depending on the farm size (22) using the data of [40]. This study was published in 1994, thus, we took an annual decrease of the electricity demand by 1% into account starting with the second year of operation. This factor describes the increasing energy efficiency of dairy farms.

Table 2
Annual operating and maintenance of components needed for the operation of the biogas and biomethane plant.

Component	Biogas	Biomethane	Source/Comment
Digester	$OM_{dig,t} = I_{dig} \times OMF \times (1 + RPIOM)^{t-1}\ \forall\ dig$ (13)		Annual O&M costs according to [35,36]
Flare	$OM_{H2S,t} = I_{H2S} \times OMF \times (1 + RPIOM)^{t-1}$ (14)		
Hydrogen sulfide treatment	$OM_{H2S,t} = I_{H2S} \times OMF \times (1 + RPIOM)^{t-1}$ (15)		
Conditioning		OM_{Cond} = "\$"$249.57 \times BCH4^{0.9317} \times (1 + RPIOM)^{t-1}$ (16)	Own equations according to data by [37]
Compression		OM_{Comp} = "\$"$27.90 \times (BCH4 \times \eta_{Cond})^{1.0728} \times (1 + RPIOM)^{t-1}$ (17)	
Solid separation (SSN)	$OM_{SSN,t} = I_{PD} \times OMF \times (1 + RPIOM)^{t-1}$ (18)		Annual O&M costs according to [35,36]
Internal consumption/ utility	1/3 of the energy equivalent of the produced biogas for heating (*Demand_ht*)[N1] and 7% of the electrical CHPU generation (*Int*)[N2]	$U_t = I_{PD} \times UC \times (1 + RPIel)^{t-1}$ (19)	[N1] [30]; [N2] according to [39]; *U* according to [36]

$$Demandel_t = (0.3024\ \text{kWh} \times cows^2 + 41.584\ \text{kWh} \times cows + 33{,}469\ \text{kWh}) \times (1-\eta_{increase})^{t-1} \quad (22)$$

where *Demand_el* is the electricity demand of the farm and $\eta_{increase}$ is the annual reduction of the electricity demand of the farm.

The hourly electricity demand can be calculated by the following equation:

$$Demandel_{h,t} = Demandel_t \times SLP_h \quad (23)$$

where *h* is one hour within the operational year *t* and *SLP* is the hourly value of the standard load profile.

The electricity substituted results from the hourly electricity consumption of the farm and the net hourly electricity generation of the CHPU that is defined as the gross electricity generation less the internal consumption of the anaerobic digestion plan (24). To calculate the annual electricity substituted, the hourly values will be summed (28).

$$Substel_{h,t} = \begin{cases} Demandel_{h,t} \times Purchaseel_t, \text{ if } Demandel_{h,t} \leqslant NetCHPU_{h,t} \\ NetCHPU_{h,t} \times Purchaseel_t, \text{ if } Demandel_{h,t} > NetCHPU_{h,t} \end{cases} \quad (24)$$

$$NetCHPU_{h,t} = GrossCHPU_{h,t} - Int \times GrossCHPU_{h,t} \quad (25)$$

$$GrossCHPU_{h,t} = capCHPU \times flh/8760 \quad (26)$$

$$Purchaseel_t = Purchaseel_0 \times (1 + RPIel)^{(t-1)} \quad (27)$$

$$Substel_t = \sum_h Substel_{h,t} \quad (28)$$

where *Subst_el* is the electricity substituted, *Purchase_el* the costs for electricity purchased, *RPI_el* is the annual rate of price increase of purchased electricity, *Net_CHPU* is the net electricity generation of the CHPU, *Gross_CHPU* is the gross electricity generation of the CHPU and *flh* are the annual full load hours of the CHPU.

2.3.4.2. Electricity sold. Likewise, the electricity sold depends on the electricity demand of the farm and the net generation of the CHPU and can be described as follows:

$$Soldel_{h,t} = \begin{cases} (NetCHPU_{h,t} - Demandel_{h,t}) \times (Priceel + REC), \text{ if } Demandel_{h,t} < NetCHPU_{h,t} \\ 0, \text{ if } Demandel_{h,t} \geqslant NetCHPU_{h,t} \end{cases} \quad (28)$$

$$Soldel_t = \sum_h Soldel_{h,t} \quad (29)$$

where *Sold_el* is the excess electricity that is fed into the electricity grid, *Price_el* is the hourly wholesale price of electricity and *REC* are Renewable Energy Certificates.

An hourly wholesale price of \$0.03 kWh^{-1} over the whole operational life was taken into consideration. In addition, we assume that the biogas plant operator receives a Renewable Energy Certificate (REC) for each MWh that is fed into grid. These are purchased by companies to reduce their environmental impact [41]. RECs are sold to a utility company and generate an additional revenue source; for the purpose of this study, we set the value for each REC constant over the simulation period at \$0.03 kWh^{-1}.

Besides the REC, the state of Idaho enables customers to offset the electricity purchased from the grid by the use of net metering. Net metering allows the operators of renewable energy plants to offset their electricity consumption through these generators. If excess electricity on the dairy farm is fed into the grid, the operator receives a credit per kWh to offset the electricity consumption. However, the net metering system is limited to a maximum installed capacity of 100 kW [42]. Compared to the combination of the hourly wholesale price and REC, the costs for electricity purchased from the grid are higher; therefore, small biogas plants (≤100 kW) may choose the net metering system. However, due to the credit system, the amount of electricity that is fed into the grid is limited to the electricity consumption that is not substituted by the CHPU electricity generation of the dairy farm. The optimization model, described in Section 2.4, calculates the most cost-effective way to sell the biogas plant's electricity.

2.3.4.3. Heating substituted. Due to the use of manure as feedstock the majority of generated heat is used to maintain the biological process in the digester. Nevertheless, surplus heat can be used to substitute the demand for generated heat on the farm. In contrast with the electricity substituted, we calculated the heating substituted without the consideration of a thermal load profile. Nevertheless, heating from biogas plants can also be used to substitute for heating demands for hot water during the summer. Consequently, we took the wholesale natural-gas price into consideration to avoid the overestimation of the revenues from heating substituted. The annual heating substituted by the biogas plant is defined by the following equations:

$$Substht_t = \frac{capCHPU}{\eta_{el}} \times (\eta_{th} - Demandht) \times flh \times Prodht_t \quad (30)$$

$$Prodht_t = Pricegas_t \times \eta_{Prodht} \div CH4energy \div CH4NG \quad (31)$$

where *Subst_ht* is the substituted annual heating, η_{th} is the thermal efficiency of the CHPU, *Prod_ht$_t$* is the annual price of generated heat by the farm (natural gas), η_{Prod_ht} is the efficiency of the heating generation of the farm (gas heating) and *CH4_NG* is the concentration of methane in natural gas.

2.3.4.4. Animal bedding substituted. A digestion solid separation extracts reusable solids pre- or post-digestion that can be used to substitute for animal bedding material. According to [43], reused solid material can be sold at the local level. The amount of substituted bedding depends on the optimized capacity of the biogas or biomethane plant (33). Consequently, the revenues from animal bedding substituted can be calculated by the following equations:

$$Substbed_t = Rebed \times cows \times Pricebd_t \times optcap \tag{33}$$

$$Pricebd_t = Pricebd_0 \times (1 + RPIbd)^{(year-2011)+(t-1)} \tag{34}$$

where *Subst_bed* is the annual revenue from substituted bedding, *Re_bed* are the reusable solids per cow and day from the digester, *Price_bd* is the annual price of animal bedding material (Table A2), *biogas_cow* is the daily biogas production per cow, η_{dig} is the manure-collection efficiency of the digester type, η_{biogas} is the efficiency of the biogas control system and *RPI_bd* is the annual rate of price increase of animal bedding.

2.3.4.5. Biomethane sold. The biomethane plant operator receives two revenues by compressing the natural-gas substitute into the grid: the natural-gas price and the so-called Renewable Identification Number (RIN) that is used as a certificate to trade biofuels in the U.S. We used RIN revenues of $1 per gallon gasoline equivalent by $1 [44]; this corresponds to $0.2815 N m^{-3}$ for compressed biomethane. The revenues from biomethane sold are described by the following equations:

$$Soldbm_t = Injectbm \times (Pricegas_t + RIN) \tag{34}$$

$$Pricegas_t = Pricegas_0 \times (1 + RPIgas)^{(t-1)} \tag{35}$$

where $Sold\_bm_t$ is the annual revenue from biomethane sold, $Price\_gas_t$ is the annual average natural-gas price, *RIN* is the price for each certificate of the RIN and *RPI_gas* is the annual rate of price increase of natural-gas.

2.4. Optimization model

In order to optimize the NPV for each farm size and scenario we programmed a non-linear optimization model, which maximizes the NPV with regard to the maximum biogas yield of the dairy farm depending on their number of cows. The optimization model was implemented in MATLAB (R2017b) using the interior-point algorithm (fmincon). Details of the model are given in the following equations and inequalities. The code and the input data of the model are published in the supplementary material section.

$$\max NPV = I_{0,scenario} + \sum_t \frac{(Rev_{t,scenario} - Costs_{t,scenario})}{(1+i)^t} \ \forall \ scenario \tag{36}$$

$$I_{0,scenario} = \begin{cases} I_{dig} + I_{H2S} + I_{flare} + I_{PostD}, \ if \ I_{0,biogas} \\ I_{dig} - I_{CHPU} + I_{flare} + I_{PostD} + I_{Cond} + I_{Comp}, \ if \ I_{0,biomethane} \end{cases} \tag{37}$$

$$Rev_{t,scenario} = \begin{cases} Substel_t + Soldel_t + Netmetel_t + Substht_t + Substbed, \ if \ I_{0,biogas} \\ Soldbm_t + Bed, \ if \ I_{0,biomethane} \end{cases} \ \forall \ t \tag{38}$$

$$Costs_{t,scenario} = \begin{cases} OM_{dig,t} + OM_{H2S,t} + OM_{flare,t} + OM_{DS,t}, \ if \ I_{0,biogas} \\ OM_{dig,t} - OM_{CHPU,t} + OM_{flare,t} + OM_{DS,t} + OM_{Cond,t} \ \forall \ t \\ \quad + OM_{Comp,t}) + U_t + Trans_t, \ if \ I_{0,biomethane} \end{cases} \tag{39}$$

subject to

on-farm use of biogas

$$\sum_h Netmetel_{h,t} \leqslant \sum_h Demandel_{h,t} \frac{\sum_h Substel_{h,t}}{Purchaseel_t} \tag{40}$$

$$Netmetel_t = 0, \ if \ capCHPU > 100 \tag{41}$$

$$capCHPU \geqslant 0 \tag{42}$$

$$capCHPU \leqslant maxcapCHPU \tag{43}$$

biomethane

$$BCH4 \geqslant 0 \tag{44}$$

$$BCH4 \leqslant maxBCH4 \tag{45}$$

where *i* is the discount rate for the calculation of the NPV, based on the interest rate of farmers.

The optimization model takes the investments and the discounted annual revenues and costs (present value) into account (37). According to the scenario considered, the capital costs are varying on the components required (38). In contrast to the biomethane scenario, electricity and heat can also be used on-farm to substitute energy (39). Due to the production of biomethane, the electricity demand has to be purchased (40). Annual credits for net-metering are limited to the electricity demand on the farm that is not substituted by the CHPU electricity generation (41). Furthermore, in Idaho the net metering system is limited to a maximum installed capacity of 100 kW (42). The maximum capacity is defined by the biogas production of the cows and the efficiency of the digester type, the CHPU, and the biogas control system, as well as the energy and methane content of the biogas (44). Likewise, in the biomethane scenario, the maximum hourly biogas production is also limited by the biogas production of the cows and the efficiency of the biomethane plant (46).

2.5. Effect on the income of Idaho's farmers

To calculate the annual effect on the income of Idaho's dairy farmers, we chose, for each economically feasible farm size, the scenario (on-farm use of biogas/biomethane) and digester type characterized by the highest NPV. Those NPV were converted to the annuity *A* by the following equation [33]:

$$A = NPV \times \left(\frac{i \times (i+1)^n}{(i+1)^n - 1} \right) \tag{46}$$

where *NPV* is the net present value and *n* is the operational life of the anaerobic digestion plant.

The annuities per farm size were multiplied by the number of farms per size class and then summed. In contrast to the maximization of the NPV, we counted the number of farms per size class by the use of a range of ± 50 cows for each size class considered. The range was used to avoid the overestimating of anaerobic digestion plants on the additional income of farmers and the GHG emission savings in Idaho.

2.6. GHG emission savings

In this paper, we give an overview about potential GHG-emission savings. To calculate the GHG-emission savings in a more detailed way, a lifecycle assessment of the scenarios and different farm sizes would need to be carried out. As a consequence, in our analysis, the environmental impact of the whole anaerobic digestion plant was not taken into account; e.g., we did not account for transport emissions or potential road improvements. We approximate the GHG-emission savings through a comparison of methane emission from dairy cows and the amount of methane that could theoretically be captured and converted to CO_2 through anaerobic digestion, taking the methane capture efficiency of the varying digester types and the methane losses of the biogas production process into account. Both parameters describe the quantity of methane captured, i.e., the fraction that does not enter the atmosphere directly. The captured methane in the varying digester types is converted to CO_2. To calculate the CO_2 emissions of the combustion of methane, we considered a methane density of 0.6797 kg m^3 (1 atm, 288 K) [45] and multiplied the annual methane emissions [kg] with the quotient of the molecular mass of CO_2 and methane (2.75). As a result, the combustion of 1 m^3 methane leads to CO_2 emissions of about 1.87 kg.

2.7. Cooperation scenario

To increase the economic potential of anaerobic digestion, in this scenario, various dairy farmers cooperate to invest in a biogas or biomethane plant [46,47]. As a consequence, the manure must be transported by truck or pipeline to the anaerobic digestion plant. According to [48], the transport of manure by truck is more economically feasible than by pipeline up to the manure production of 90,000 beef cattle. This is why we took the transport of manure by trucks into account. We investigated for each farm size and every scenario the maximum proportion of manure that can be transported 5 and 10 km. Due to the environmental impact, higher transport distances were not considered. To do so, we calculated the NPV for the chosen transport distances and divided the result by the NPV of the scenario. The resulting proportion can be interpreted as the maximum manure proportion that can be economically transported.

We took a daily total manure production of 36.29 kg cow^{-1} into account[3] [50]. The transport costs were calculated by the cost formula of [48] and those costs were converted to 2017 dollars by an annual cost increase of 1%, which was also used for the calculation of future biomethane transport costs. The calculation, based on slurry and lagoon manures is characterized by a moisture content between 95 and 99%, respectively. Furthermore, the manure is transported by 40-ton trucks with an average utilization rate of 85% [48].

3. Results

3.1. Idaho's dairy farms

To visualize the class size distribution of Idaho's dairy farms, the class size distribution depending on the number of cows per farm (Fig. 3) and depending on the number of farms per size class (Fig. 4) were divided into increments of 250 cows. In Fig. 3, besides the class size distribution of number of cows per farm, the proportion of cows less than or equal the mentioned farm size is shown. Idaho is characterized by a high proportion of large dairy farms. The two farm sizes with the highest number of cows per size class are farms with 1251–1500 and 2751–3000 cows. In general, the size class distribution of Idaho's dairy farms allows a comparably high use of the manure potential by a low number of anaerobic digestion plants. For example, farms with 2000 and more cows represents about 55% of the total manure potential in Idaho. Although, more than 50% of the total dairy farms in Idaho are represented by farms with a maximum of 750 cows (Fig. 4); even one third of the farms have a maximum of 250 cows.

3.2. On-farm use of biogas and biomethane

The net present value depending on the farm size and the digester types of the on-farm biogas use are shown in Fig. 5 A. At least, 3000 cows per farm are needed for an economically feasible use of dairy manure for the production of biogas. Thus, the covered-lagoon digester type is characterized by low capital costs, representing the highest NPV for farms with 2600 cows and more. Below 2500 cows, the complete-mix digester achieves a higher NPV, but does not allow an economically feasible use of the manure potential. The most cost-intensive digester type, namely plug-flow, becomes economically feasible without co-digestion on farms with 6600 cows and more. Due to the highest NPV for the covered-lagoon digester type, the results assume that in the biogas scenario, lower capital-costs have a lower impact on the NPV than the higher methane-capture efficiency of complete-mix and plug-flow digester types. Furthermore, in all scenarios (on-farm use of biogas and biomethane), the highest NPV was achieved when the whole manure potential of the farm was used to maximize the production of biogas or biomethane. From the perspective of the operator or investor, the payback period of anaerobic digestion plants has a major influence on the investment decision. Depending on the chosen digester type, the payback period in the biogas scenario varies between 5 and 8 years (Fig. 5B). The plug-flow digester has the highest payback period of 8 years, whereas the complete-mix digester differs between 6 and 7 years. Depending on the number of cows per farm, the payback period of the covered lagoon digester is between 5 and 8 years.

In contrast to the biogas scenario, upgrading biogas to biomethane requires a higher number of cows per farm to make the operation economically feasible (Fig. 5C). The complete-mix digester up to farms of 5900 cows shows the highest NPV. For larger farms, the covered-lagoon digester achieves higher NPVs. At least 3200 cows per farm are needed, under the assumptions taken into account, to operate the biomethane plant economically. Furthermore, the NPV difference between the digester types is smaller than the same difference for the on-farm use of biogas. The most cost-intensive digester type, plug-flow, becomes economically feasible on farms with 4600 cows and more. As a result, the methane-capture efficiency has a higher impact on the NPV than in the biogas scenario. This is why the complete-mix digester is often the more cost-effective solution to capture methane for the injection into the natural gas grid. As a consequence the variation of the payback period between the digester types is lower than in the biogas scenario (Fig. 5D). Overall, the payback period is characterized, with the exception of the plug-flow digester, by a period of 4–8 years. Furthermore, the NPV increase is more sensitive in the biomethane scenario. The NPV is higher for large dairy farms, and the payback period can be reduced up to 4 years on farms with a maximum of 8000 cows.

3.3. Combined analysis of the scenarios

3.3.1. Optimal combination of biogas and biomethane plants

Results with the highest NPV in the biogas and biomethane scenario are summarized in Fig. 6. Up to a farm size of 3600 cows, the on-farm use of biogas and the covered-lagoon digester type achieve the highest NPV. The conversion to biomethane becomes more economically feasible on farms with 3700 and more cows. Between farm sizes of 3700 and 5900 cows, the complete-mix digester achieves better results than the covered-lagoon type. Farms larger than 6000 cows are characterized by the highest NPV when the covered-lagoon digester type is used. If farms with 3000 and more cows operate anaerobic digestion plants, about 45% of Idaho's total manure potential can be used.

3.3.2. Effect on the income of Idaho's farmers

Based on the optimal combination of biogas and biomethane plants, the annual additional income of Idaho's farmers using manure to produce biogas or biomethane is about $93.53 M. However, Idaho's largest dairy farm (with 18,000 cows) is characterized by an annuity of $20.2 M yr^{-1} and contributes to more than one fifth of the additional income. Without the cooperation of farms to construct and operate an anaerobic digestion plant together, the effect on the income of Idaho's farmers would especially be concentrated on very large farms that already benefit from the economies of scale (Fig. 7).

3.3.3. GHG emission savings

The total annual methane emissions of dairy cows in Idaho are equivalent to 4.39M t CO_2 yr^{-1} (Table 3). If the manure is captured in

[3] In this study, the average weight of a mature dairy cow was calculated by 450 kg [49].

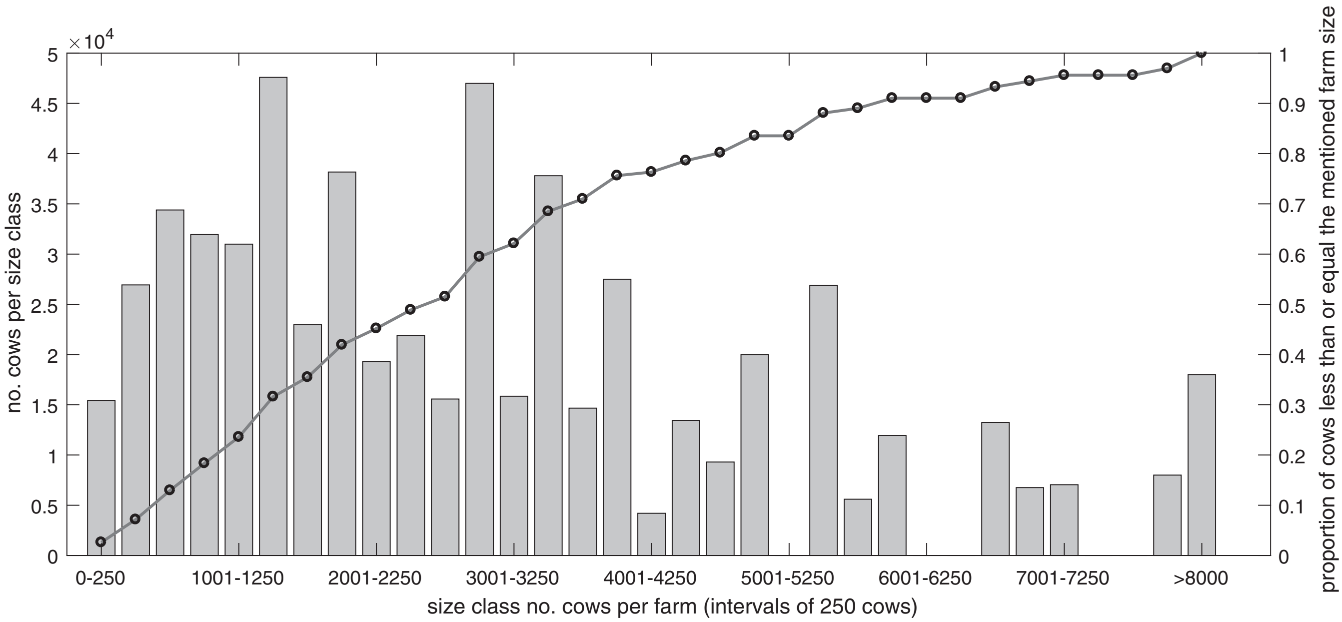

Fig. 3. Size class distribution and their proportion of Idaho's dairy farms depending on the number of cows per size class (based on data of [4]).

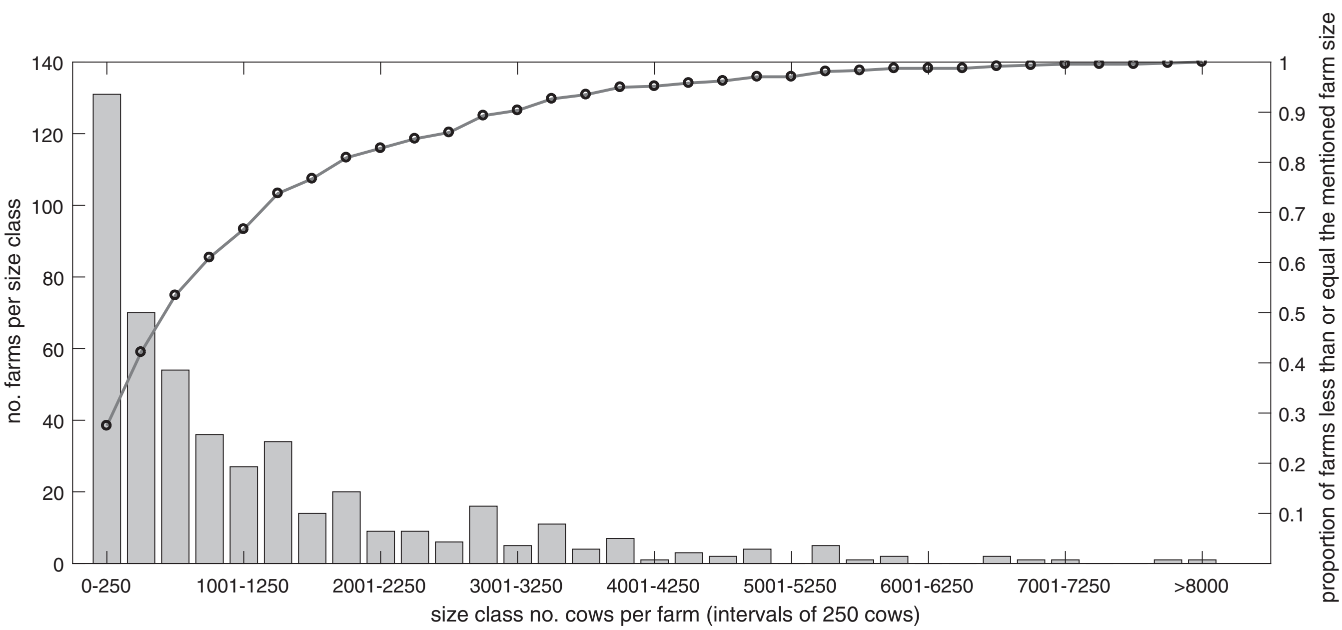

Fig. 4. Size class distribution and their proportion of Idaho's dairy farms depending on the number of farms per size class (based on data of [4]).

the considered digester types, according to the achieved NPV in the Sections 3.2 and 3.3, and the produced methane is converted to CO_2 through combustion, the GHG emissions can be reduced up to 33%. As a result, the total GHG emissions regarding to anaerobic digestion might be about 2.95M t CO_2e yr^{-1} in the state of Idaho by the consideration of the economic potential of dairy manure.

In this paper, we analyzed the economic viability of the mono-digestion of dairy manure. In the case of mono-digestion, with the exception of soil sealing through the installation of anaerobic digestion plants, we do not estimate further negative environmental impacts when biogas is produced (compared to the use of manure for soil amendment). However, the increase of the biogas production through co-digestion can lead to increasing GHG emissions, marine eutrophication, and land-use changes [51]. The negative impacts of co-digestion are lower if waste or residues, instead of energy crops (e.g. maize silage), are used [51].

4. Discussion

4.1. Sensitivity analysis

The calculation of the NPV in the biogas and biomethane scenario indicates a different influence of capital costs and methane-capture efficiency on the economic viability of an anaerobic-digestion plant. To show the impact of the parameters on the NPV in both scenarios, we carried out a sensitivity analysis for (i) the on-farm use of biogas, a covered-lagoon digester with a farm size of 3500 cows (Fig. 8) as well as for (ii) the biomethane scenario, a complete-mix digester with a farm size of 4000 cows (Fig. 9). In the biogas scenario, the capital costs, the bedding price, and the gas yield per cow are the most sensitive parameters. In particular, the capital costs show the highest impact on the NPV. In this study, we calculated the capital costs and the bedding revenues, the two most sensitive parameters, conservatively. Depending

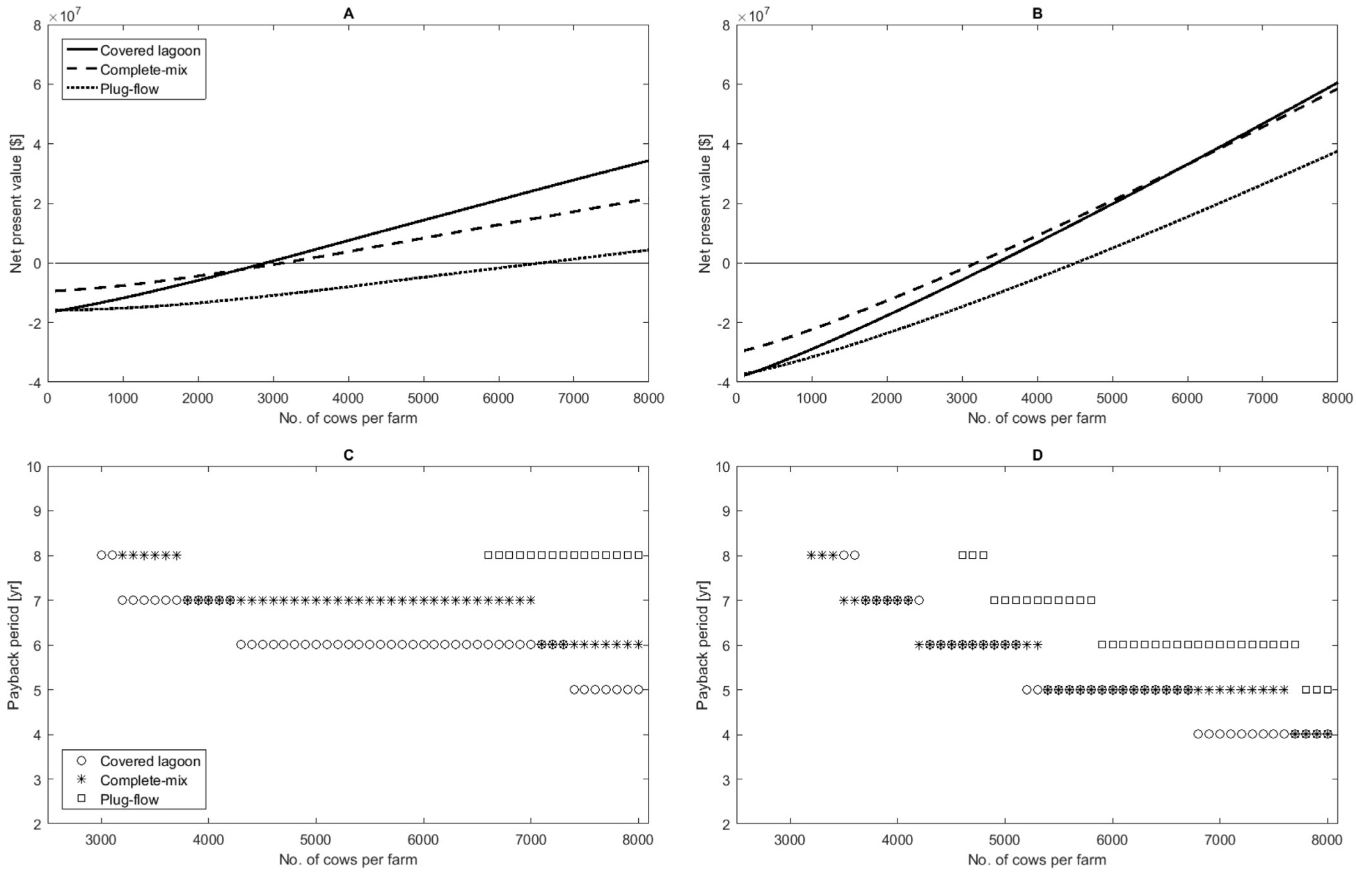

Fig. 5. Net present value and payback period of the on-farm use of biogas (A|C) and biomethane (B|D) depending on the farm size.

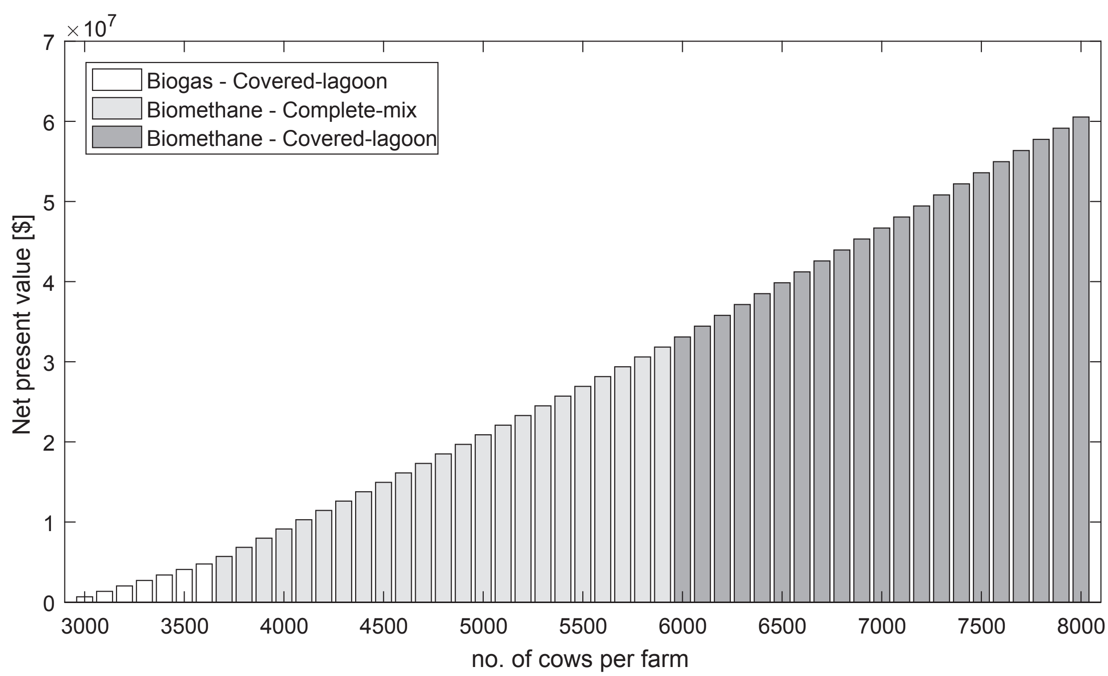

Fig. 6. Combination of biogas and biomethane use characterized by the highest NPV depending on the number of cows per farm.

on the regional conditions of the planned biogas plant, the capital costs can be lower, e.g. through synergy effects if another biogas plant is planned in proximity. In addition, the spatial concentration of intensive livestock farming may increase the price of local bedding material, and the biogas plant may become economically feasible with a lower number of cows per farm. Furthermore, the sensitivity analysis underlines the low influence of REC and the discount rate on the NPV.

In the biomethane scenario, the gas yield per cow has the highest

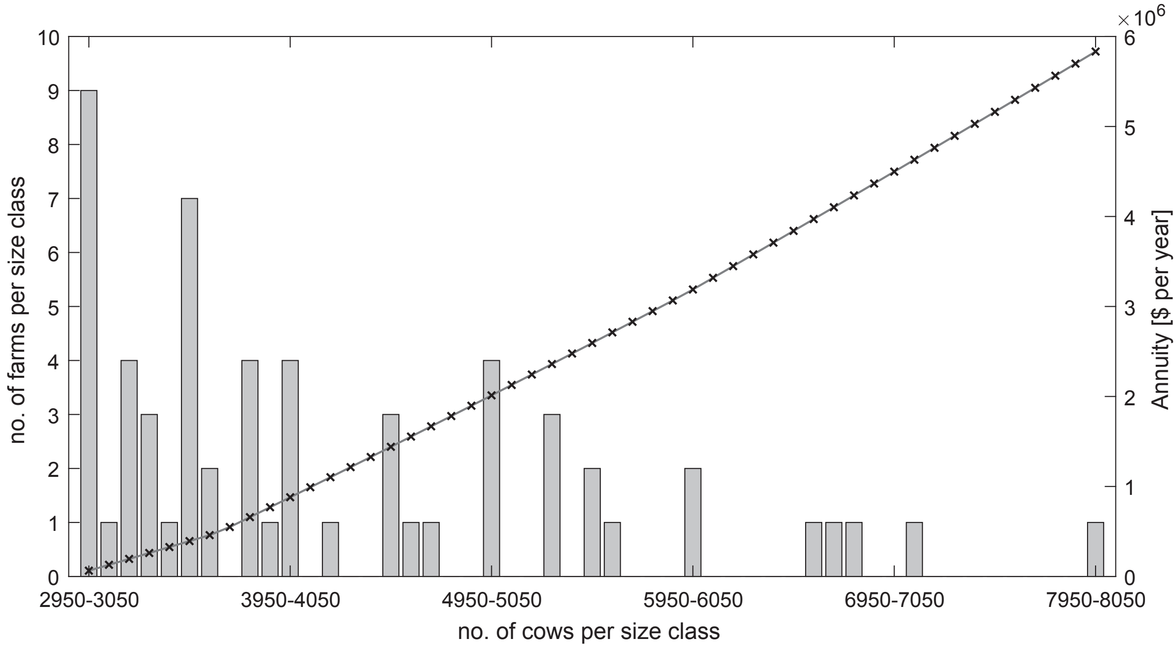

Fig. 7. The highest achieved annuity of economic feasible farm sizes of the technologies considered and the number of farms per size class.

Table 3
Comparison of GHG emissions with and without anaerobic digestion in Idaho [t CO2e yr^{-1}].

Total methane emissions without anaerobic digestion	4,388,225
Savings through conversion of methane to CO_2	1,436,698
Total emissions with anaerobic digestion	2,951,527

impact on the NPV in the considered combination of digester type and farm size. This was also true in results of economic viability; in contrast to the biogas scenario and due to higher methane-capture efficiency, the complete-mix digester was characterized by a higher NPV. However, the capital costs and bedding price are also sensitive parameters in the biomethane scenario. Moreover, the RIN is more important for the economic feasibility of a biomethane plant than the REC in the biogas scenario. Biomethane has to be transported to the end-user; however, the pipeline transportation fee belongs among the less sensitive parameters. In addition, a higher or lower natural-gas price is also characterized by a low impact on the NPV. To summarize, in the biogas scenario, the substituted heat and electricity have a higher effect on economic feasibility than does purchased electricity. Conversely, the

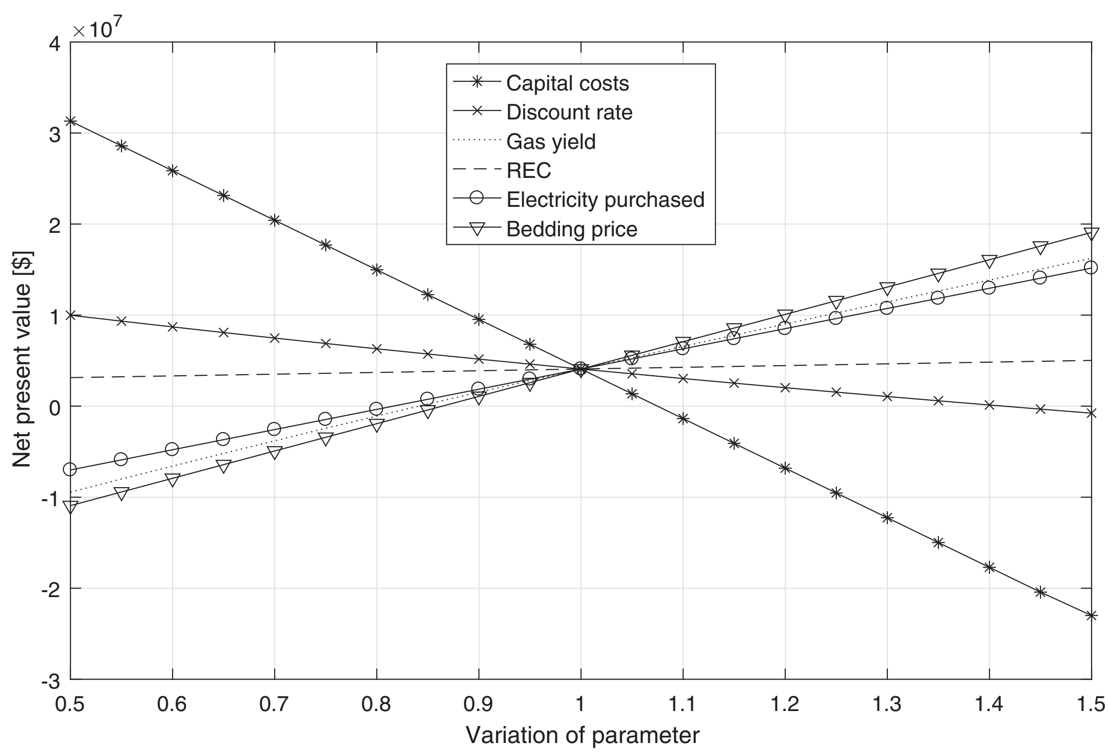

Fig. 8. Sensitivity analysis in the biogas scenario considering a covered lagoon digester and a farm size of 3500 cows.

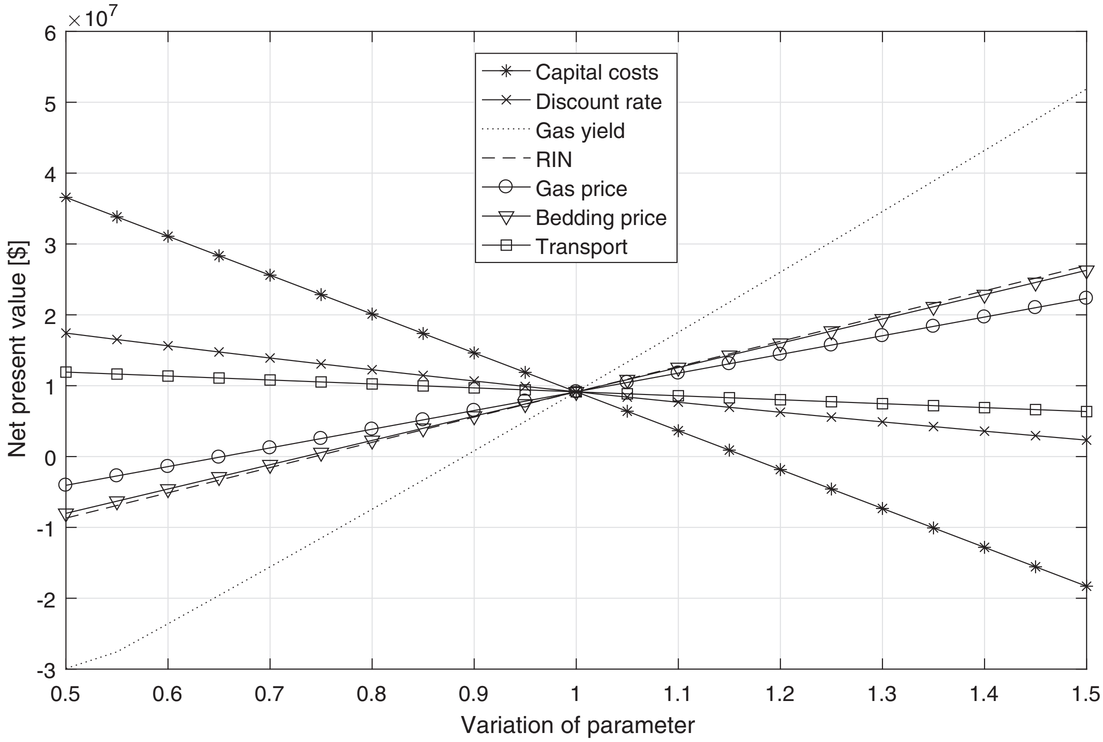

Fig. 9. Sensitivity analysis in the biomethane scenario considering a complete-mix digester and a farm size of 4000 cows.

biomethane scenario is defined by one product and is, therefore, more sensitive to the RIN or the gas yield per cow.

4.2. Cooperation scenario

The transport of manure and the cooperation of farmers to invest and operate an anaerobic-digestion plant allows a smaller average farm size and can increase the economic viability of Idaho's use of dairy manure. Table 4 gives an overview of the results in a biogas scenario. In each case (farm size and digester type), the maximum proportion of transported manure, which allows an economically feasible operation of the plant, is shown. For example, the maximum transported proportion of manure (5 km) for the cooperation of farms with a total of 3000 cows and a covered-lagoon digester type is 0.42. A smaller summed farm size does not allow an economically feasible operation. Larger cooperation (≥3300 cows) using the same digester type can theoretically transport up to 100% of their needed manure. In general, the transport costs are comparably low, so that the transport of manure becomes useful for a large number of cows. In addition, in the biogas scenario, the economic feasibility of biogas plants is based on the substitution of electricity and heat use on the farm. In the cooperation scenario, however, we neglected the changed farm sizes. Therefore, economic feasibility is dependent on the location of the digester, which should be located on the farm with the highest demand for electricity and heat.

Similar results were achieved for the biomethane scenario (Table 5). Due to a different NPV depending on farm sizes, the combined farm size and the maximum proportion of transported manure vary. According to the chosen digester type above, the operation of a covered-lagoon digester type requires at least a summed farm size of 3500 cows when manure is transported 5 km and biomethane is injected to the grid. In contrast to the biogas scenario, the transport of manure in the complete-mix digester type is more efficient (≥3200 cows), and the plug-flow digester allows an economically feasible cooperation with smaller summed farm sizes.

Compared to large dairy operations, smaller-sized farms have a weaker negotiating position for planned cooperation, requiring a comparably higher share of investments in joint, cooperative anaerobic-digestion plants. Therefore, smaller dairy farms make a profit by co-operating when a larger dairy farm needs additional manure for to ensure economically viable operation of an anaerobic-digestion plant. However, a better position for smaller farms could be achieved by incentives provided by policy makers; for example, if regulation required manure of smaller farms be pretreated in anaerobic-digestion plants before it could be used as soil amendment.

To summarize, due to the comparably high number of large dairy farms in Idaho, the transport of manure is one option to increase the economic viability of anaerobic-digestion operation in the state. Nevertheless, to calculate the potential for improvement through the transport of manure, the spatial distribution of Idaho's dairy farms has to be taken into account. In general, the negative impact of manure transport on the environment should also be part of a final evaluation.

4.3. Comparison to Germany

Germany is the world leader of anaerobic digestion technologies [52]. Since the introduction of a remuneration system for renewable energies, including biogas plants, in 2000, the number of biogas plants has continuously increased. In 2016, more than 8500 biogas plants, with an installed capacity of about 4400 MW and an average size of 530 kW, were operating in Germany [53]. Furthermore, a minority of farmers joins a cooperative to operate a biogas plant. The most important feedstocks are corn and grass silage, as well as manure [54]. In contrast to Idaho, Germany's average dairy farm size is about 23 times

Table 4
Farm sizes and digester types characterized by an economically feasible proportion of transported manure in the biogas scenario.

Covered lagoon			Complete-mix			Plug-flow		
Combined farm size [cows]	Max. proportion of manure transported		Combined farm size [cows]	Max. proportion of manure transported		Combined farm size [cows]	Max. proportion of manure transported	
	5 km	10 km		5 km	10 km		5 km	10 km
						6600	0.03	0.02
						6700	0.11	0.08
						6800	0.19	0.15
						6900	0.28	0.21
						7000	0.36	0.27
						7100	0.43	0.33
						7200	0.51	0.38
						7300	0.58	0.44
			3200	0.17	0.13	7400	0.65	0.49
			3300	0.41	0.31	7500	0.72	0.54
			3400	0.64	0.48	7600	0.79	0.59
3000	0.42	0.32	3500	0.86	0.65	7700	0.85	0.64
3100	0.83	0.62	3600	1.00	0.80	7800	0.91	0.69
3200	1.00	0.92	3700	1.00	0.95	7900	0.97	0.74
≥3300	1.00	1.00	≥3800	1.00	1.00	8000	1.00	0.78

Table 5
Farm sizes and digester types characterized by an economically feasible proportion of transported manure in the biomethane scenario.

Covered lagoon			Complete-mix			Plug-flow		
Combined farm size [cows]	Max. proportion of manure transported		Combined farm size [cows]	Max. proportion of manure transported		Combined farm size [cows]	Max. proportion of manure transported	
	5 km	10 km		5 km	10 km		5 km	10 km
			3200	0.06	0.04	4600	0.36	0.27
3500	0.28	0.21	3300	0.69	0.53	4700	0.77	0.58
3600	0.94	0.71	3400	1.00	0.98	4800	1.00	0.87
≥3700	1.00	1.00	≥3500	1.00	1.00	≥4900	1.00	1.00

smaller (54 dairy cows in 2013) [55] and the co-digestion of energy crops and manure is required for economical operation [56]. For small biogas plants (< 75 kW), the German Renewable Energy Sources Act guarantees a remuneration up to \$0.27 kWh^{-1} for electricity that is fed into the grid when at least 80% mass of the feedstock is manure [57]. Thus, significant gas-emission reductions are stated [23]. The remuneration for biogas plants with a higher installed capacity is lower, but the proportion of energy crops in the feedstock mix generally increases. In this paper, we show that, in contrast to Germany, the size class distribution of Idaho's dairy farms allows a higher economic potential from the use of manure (without co-digestion) under the assumptions considered. Furthermore, our results indicate that an improvement of the investment conditions of anaerobic-digestion plants, through either political instruments or increasing revenue, may enhance the economic potential of manure use in Idaho and reduce negative impacts of intensive livestock farming significantly.

5. Conclusions

The size of farms operating in the USA and Western Europe has been increasing. The concentration of intensive livestock causes several environmental and human-health concerns. Anaerobic digestion can partially address these problems, and the spatial concentration of farming operations would allow for a significant use of the accumulated effluents from intensive livestock farming. We used a non-linear optimization model to calculate the economic viability of anaerobic digestion in Idaho by farm size, considering the on-farm use of biogas and the production of biomethane. We find that at least 3000 cows per farm are required to make the operation of an anaerobic digestion economically feasible. Furthermore, covered-lagoon and complete-mix digester types achieved the best results. Due to the high number of large dairy farms, about 45% of total manure potential can be used in anaerobic digestion plants. Furthermore, we show that the use of anaerobic digestion may increase the income of farmers and decrease greenhouse-gas emissions through the use of manure as fertilizer.

Although electricity and gas prices in Idaho are comparably lower than obtains in other states in the U.S. and other countries, especially in Europe [58,59], we conclude that anaerobic digestion is an economically viable solution to decrease the negative environmental impacts of intensive livestock farming. Consequently, the results of this paper can be easily transferred to other countries characterized by a similar spatial concentration of manure, but with higher energy prices. Furthermore, the results of this analysis are of relevance for the following target groups:

- Farmers: Additional income through owned anaerobic-digestion plants (for larger farms) or jointly operated cooperative plants (for smaller farms) can be achieved.
- Scientists: The newly developed non-linear optimization model can be further improved and adapted for additional research questions.
- Policy makers: The results can be used to increase manure utilization and to reduce negative environmental concerns, for example,

by a targeted support of smaller farms through encouraging co-operation.

However, anaerobic digestion does not reduce the increased concentrations of nitrogen in the surface and groundwater caused by the spatial concentration of livestock. To reduce this impact, anaerobic digestion has to be combined with wastewater treatment units that allow recycling of nutrients and reduce their concentration in the digestate that is used as soil amendment. Under the assumptions considered, the use of manure as feedstock for anaerobic digestion is already economically feasible. Consequently, universities, research institutes and biogas associations may improve the exchange of information and provide similar results to policy makers to use the existing economic potential to reduce the negative impact of spatially concentrated livestock farming and their resulting external costs. Another approach might be the involvement of existing anaerobic-digestion plants in the U.S. (and other countries) to present best-practice examples in operation and detail the advantages of these technologies from the operator's point of view.

For future research, we suggest analysis of the economic feasibility of combination wastewater-treatment units and anaerobic-digestion plants that would reuse nutrients (especially nitrogen) as well as to reducing their negative impact on water quality. This might monetize the impact of anaerobic-digestion plants on the reduction of environmental and human-health problems, as well as verify the improvement of business conditions for anaerobic-digestion plants in Idaho. In addition, a lifecycle assessment is needed for a comprehensive analysis of the greenhouse and other gas emissions in the scenarios considered.

Declaration of interest

None.

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Financial & conflicts of interest disclosure

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Appendix A

See Tables A1 and A2.

Table A1
Sets, indices and variables considered in the optimization model.

Type	Range	Description	Unit, Instance
Sets and indices			
t ∈ T	1:15	Time	Years
h ∈ H	1:8760	Time	Hours
dig ∈ DIG		Digester type	Covered lagoon, complete-mix, plug-flow
Variables			
BCH4	R ≥ 0	Hourly biogas production	[$Nm^3\,h^{-1}$]
cap_CHPU	R ≥ 0	Installed capacity of the CHPU	[kW]

Table A2
Assumptions on the parameters used in the optimization model.

Parameter	Value	Description	Unit	Source/note
biogas_cow	2.0	Daily biogas production per cow	[m^3_{biogas} d^{-1} cow^{-1}]	[30]
CH4_biogas	0.6	Concentration of methane in biogas		Own assumption according to [39]
CH4_energy	9.97	Energy content of methane	[kWh $m^{-3}_{methane}$]	[39]
CH4_gas	0.9	Concentration of methane in natural gas		Own assumption according to [60]
cows	100–8,000; 18,000	No. of cows per farm		Increments of 100 cows between the farm size of 100 and 8,000 cows
Demand_el		Annual electricity demand of the farm	[kWh yr^{-1}]	See formula (22)
Demand_ht	1/3	Is the proportion of the CHPU's generated heating for internal consumption		[30]
fee	0.041	Marginal costs of the pipeline transportation	[$ Nm^3 h^{-1}]	[61]
flh	8,000	Annual full load hours of the CHPU	[h yr^{-1}]	[62]
flh_bm	8,000	Annual full load hours of the conditioning and compression unit	[h yr^{-1}]	Own assumption
η_{biogas}	0.98	Efficiency of the biogas control system		Own assumption according to [63,64]
η_{Cond}	0.56	Efficiency of the conditioning unit		Own calculations according to data by [37]
η_{Comp}	0.95	Efficiency of the compression unit		
η_{dig}	0.75 (CL); 0.9 (PF, CM)	Manure collection efficiency of the digester type		[35]
η_{el}	0.37	Electrical efficiency of the CHPU		[56]
η_{ht}	0.48	Thermal efficiency of the CHPU		Own assumption according to [39]
$\eta_{increase}$	0.01	Annual reduction of the electricity demand of the farm		Own assumption
η_{Prod_ht}	0.8	Efficiency of the heating generation of the farm (gas heating)		
Int	0.07	Internal electricity consumption of the biogas plant		Own assumption according to (FNR, 2018)
i	0.05	Discount rate		Own assumption according to [65]; weighted average interest rate of large farm lenders
OMF	0.04	Annual operation and maintenance costs factor		[36]
$Price\_bd_0$	27	Price of animal bedding t = 0	[$ t^{-1}]	Own assumption according to [43] and [38]
Price_el	0.03	Hourly wholesale price of electricity	[$ kWh^{-1}]	Own assumption
$Price\_gas_0$	0.2	Natural gas price t = 0	[$ Nm^{-3}]	EIA [66]; U.S. Natural Gas Citygate Price (average January 2008 – October 2017)
$Purchase\_el_0$	0.0809	Costs for electricity purchased t = 0	[$ kWh^{-1}]	EIA [59]; average retail price in Idaho 2015
Re_bed	0.009	Reusable solids per cow from digester	[t cow^{-1} day^{-1}]	[43]
REC	0.03	Renewable Energy Certificate	[$ kWh^{-1}]	Own assumption
RIN	0.2815	Renewable Identification Number	[$ Nm^{-3}]	Own calculations according to [44]
RPI_CI	0.027	Annual rate of price increase of capital investments		BLS [67]; average annual increase of non-building related engineering projects between 2007 and 2016
RPI_bd	0.011	Annual rate of price increase of animal bedding		Own assumption according to [68]; prices received for hay in the U.S.
RPI_el	0.01	Annual rate of price increase of purchased electricity		Own assumption
RPI_gas	0.01	Annual rate of price increase of natural gas		
RPI_OM	0.065	Annual rate of price increase of operation and maintenance costs		Due to a neglected exchange of the CHPU (operational life of 10 years [62]), we took a higher price increase of O&M costs into account
RPI_TR	0.01	Annual rate of price increase of the biomethane transport		Own assumption
SLP	See supplementary material	Standard load profile of dairy farms		[69]
UC	0.053	Annual utility charge		[36]
Year	2017	Commissioning year of the plant		

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2018.04.026.

References

[1] Zimmermann A, Heckelei T. Structural change of European dairy farms – a cross-regional analysis. J. Agric. Econ. 2012;63(3):576–603.
[2] Dong F, Hennessy DA, Jensen HH, Volpe RJ. Technical efficiency, herd size, and exit intentions in U.S. dairy farms. Agric. Econ. 2016;47(5):533–45.
[3] Watson P, Brown A, Lewin P, Taylor G. The Contribution of the Dairy Industry to the Idaho Economy: 2011 and 2012. University of Idaho; 2014.
[4] ISDA. Active Producers with Inspections dated 10/25/2016 – 10/25/2017, Estimated Mature Animal Summary, Report ran 10/25/2017. Idaho Department of Agriculture – Bureau of Dairying; 2017.
[5] Gould BW. Consolidation and Concentration in the U.S. Dairy Industry. CHOICES 2010; 25(2).
[6] Jaarsma R, Hermans T, Rienks W, de Vries J. Enlarging of scale in dairy farming: Consequences for farm-bound traffic flows in the countryside. NJAS – Wageningen J Life Sci 2013;64–65:67–75.
[7] Ecology. Effects of Land Application of Manure on Groundwater at Two Dairies over the Sumas-Blaine Surficial Aquifer Implications for Agronomic Rate Estimates. Washington State Department of Ecology; 2002.
[8] Almasri MN, Kaluarachchi JJ. Assessment and management of long-term nitrate pollution of ground water in agriculture-dominated watersheds. J Hydrol 2004;295(1–4):225–45.
[9] Andrews WJ. Nitrate in ground water and spring water near four dairy farms in North Florida, 1990–1993. Florida: Tallahassee; 1994.
[10] Côté C, Massé DI, Quessy S. Reduction of indicator and pathogenic microorganisms by psychrophilic anaerobic digestion in swine slurries. Bioresour Technol 2006;97(4):686–91.
[11] Schiffman SS. Livestock odors: Implications for human health and well-being. J Anim Sci 1998;76(5):1343.
[12] Yiridoe EK, Gordon R, Brown BB. Nonmarket cobenefits and economic feasibility of on-farm biogas energy production. Energy Policy 2009;37(3):1170–9.
[13] Wright PE, Perschke SP. Anaerobic digestion and wetland treatment case study: comparing two manure odor control systems for dairy farms. Orlando, Florida: ASAE Annual International Meeting; 1998.
[14] Lusk P. Methane Recovery from Animal Manures: The Current Opportunities Casebook; 1998.
[15] Kearney TE, Larkin MJ, Levett PN. The effect of slurry storage and anaerobic digestion on survival of pathogenic bacteria. J Appl Bacteriol 1993;74(1):86–93.
[16] Nelson C, Lamb J. Final Report: Haubenschild Farms Anaerobic Digester: Updated; 2002.
[17] Bacenetti J, Sala C, Fusi A, Fiala M. Agricultural anaerobic digestion plants: what LCA studies pointed out and what can be done to make them more environmentally sustainable. Appl Energy 2016;179:669–86.
[18] Mezzullo WG, McManus MC, Hammond GP. Life cycle assessment of a small-scale anaerobic digestion plant from cattle waste. Appl Energy 2013;102:657–64.
[19] O'Shea R, Wall DM, Murphy JD. An energy and greenhouse gas comparison of centralised biogas production with road haulage of pig slurry, and decentralised biogas production with biogas transportation in a low-pressure pipe network. Appl Energy 2017;208:108–22.
[20] Murphy JD, McKeogh E, Kiely G. Technical/economic/environmental analysis of biogas utilisation. Appl Energy 2004;77(4):407–27.
[21] Horschig T, Adams PWR, Röder M, Thornley P, Thrän D. Reasonable potential for GHG savings by anaerobic biomethane in Germany and UK derived from economic and ecological analyses. Appl Energy 2016;184:840–52.
[22] Boucher O, Friedlingstein P, Collins B, Shine KP. The indirect global warming potential and global temperature change potential due to methane oxidation. Environ Res Lett 2009;4(4):44007.
[23] Oehmichen K, Thrän D. Fostering renewable energy provision from manure in Germany – where to implement GHG emission reduction incentives. Energy Policy 2017;110:471–7.
[24] Hayhoe K. Climate change policy: costs of multigreenhouse gas reduction targets for the USA. Science 1999;286(5441):905–6.
[25] Wright P, Inglis S. An economic comparison of two anaerobic digestion systems on dairy farms. Las Vegas, Nevada, USA: ASAE Annual International Meeting; 2003.
[26] Martin JH jr. A comparison of dairy cattle manure management with and without anaerobic digestion and biogas utilization; 2003.
[27] Mehta A. The economics and feasibility of electricity generation using manure digesters on small and mid-size dairy farms. SSRN J 2002.
[28] USDA. An analysis of energy production costs from anaerobic digestion systems on U.S. livestock production facilities. U.S. Department of Agriculture; 2007.
[29] EPA. Market opportunities for biogas recovery systems at U.S. livestock facilities. U. S. Environmental Protection Agency; 2011.
[30] Klavon KH, Lansing SA, Mulbry W, Moss AR, Felton G. Economic analysis of small-scale agricultural digesters in the United States. Biomass Bioenergy 2013;54:36–45.
[31] Murray BC, Galik CS, Vegh T. Biogas in the United States: estimating future production and learning from international experiences. Mitig Adapt Strateg Glob Change 2017;22(3):485–501.
[32] NASS. Statistics by State. United States Department of Agriculture, National Agricultural Statistics Service. [November 04, 2017]; Available from: < https://www.nass.usda.gov/Statistics_by_State/ > .
[33] Newnan DG, Lavelle JP, Eschenbach TG. Engineering economic analysis op 12 New York [etc.]: Oxford University Press; 2014.
[34] Wilkie AC. Anaerobic digestion of dairy manure: design and process considerations. Dairy manure management: treatment, handling, and commuity relations; 2005 (NRAES-176). p. 301–12.
[35] ICF International. Greenhouse gas mitigation options and costs for agricultural land and animal production within the United States; 2013.
[36] EPA. AgSTAR fact sheet: anaerobic digestion capital costs for dairy farms. U.S. Environmental Protection Agency; 2010.
[37] Cooley D, Murray B, Ross M, Lee M-Y, Yeh K. An economic examination of north carolina's landfill biogas development potential; 2013.
[38] Leuer ER, Hyde J, Richard TL. Investing in methane digesters on Pennsylvania dairy farms: implications of scale economies and environmental programs. Agric Resour Econ Rev 2008;37(2):188–203.
[39] FNR. Faustzahlen: Fachagentur Nachwachsende Rohstoffe e. V. [January 10, 2018]; Available from: < https://biogas.fnr.de/daten-und-fakten/faustzahlen/ > .
[40] Peebles RW, Reinemann DJ. Demand-side management/energy conservation potential for Wisconsin dairy farms. International Winter Meeting of the American Society of Agricultural Engineers; 1994.
[41] Critchfield J. Understanding renewable energy certificates (RECs) and the green power procurement process; 2015.
[42] Idaho Power. Net Metering. [November 25, 2017]; Available from: < https://www.idahopower.com/energy/renewable-energy/green-choices/net-metering/ > .
[43] Kramer J. Wisconsin Agricultural Biogas Casebook – 2009; 2009.
[44] S&P Global Patts. US RIN prices jump in early trading; 2017 D6s top $1/RIN. [November 25, 2017]; Available from: < https://www.platts.com/latest-news/agriculture/houston/us-rin-prices-jump-in-early-trading-2017-d6s-21354598 > .
[45] Gas Encyclopedia. Methane. [December 20, 2017]; Available from: < https://encyclopedia.airliquide.com/methane > .
[46] Yazan DM, Fraccascia L, Mes M, Zijm H. Cooperation in manure-based biogas production networks: an agent-based modeling approach. Appl Energy 2018;212:820–33.
[47] Lantz M. The economic performance of combined heat and power from biogas produced from manure in Sweden – a comparison of different CHP technologies. Appl Energy 2012;98:502–11.
[48] Ghafoori E, Flynn P, Feddes J. Pipeline vs. truck transport of beef cattle manure. Biomass Bioenergy 2007;31(2–3):168–75.
[49] Purdue University. Dairy Facts. [November 27, 2017]; Available from: < http://www.ansc.purdue.edu/faen/dairy%20facts.html > .
[50] USDA. Agricultural Waste Management Handbook. Natural Resources Conservation Service, United States Department of Agriculture; 1992.
[51] de Vries JW, Vinken TMWJ, Hamelin L, de Boer IJM. Comparing environmental consequences of anaerobic mono- and co-digestion of pig manure to produce bio-energy – a life cycle perspective. Bioresour Technol 2012;125:239–48.
[52] Lora Grando R, Souza Antune AMde, da Fonseca FV, Sánchez A, Barrena R, Font X. Technology overview of biogas production in anaerobic digestion plants: a European evaluation of research and development. Renew Sustain Energy Rev 2017;80:44–53.
[53] Daniel-Gromke J, Rensberg N, Denysenko V, Trommler M, Reinholz T, Völler K, et al. DBFZ Report Nr. 30: Anlagenbestand Biogas und Biomethan – Biogaserzeugung und -nutzung in Deutschland. Leipzig: Deutsches Biomasseforschungszentrum gemeinnützige GmbH; 2017.
[54] Scheftelowitz M, Rensberg N, Denysenko V, Daniel-Gromke J, Stinner W, Hillebrand K, et al. Stromerzeugung aus Biomasse (Vorhaben IIa), Zwischenbericht Mai 2015; 2015.
[55] BMEL. Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten: Tabellen Kapitel C, H.II und H.III des Statistischen Jahrbuchs, Kapitel C Landwirtschaft, 142. Betriebe mit Milchkuhhaltung nach Bestandsgrößenklassen. German Federal Ministry of Food and Agriculture; 2016.
[56] Scheftelowitz M, Thrän D. Unlocking the energy potential of manure—an assessment of the biogas production potential at the farm level in Germany. Agriculture 2016;6(2):20.
[57] Bundestag. Renewable Energy Sources Act (EEG) 2017; 2016.
[58] Johannesson Lindén Å. Unit Energy costs in Europe, Member States and international partners; 2017.
[59] EIA. State Electricity Profiles. U.S. Energy Information Administration. [January 15, 2018]; Available from: < https://www.eia.gov/electricity/state/ > .
[60] Mango FD. The light hydrocarbons in petroleum: a critical review. Org Geochem 1997;26(7–8):417–40.

[61] Murray BC, Galik CS, Vegh T. Biogas in the United States: an assessment of market potential in a carbon-constrained. Future 2014.
[62] Lauer M, Dotzauer M, Hennig C, Lehmann M, Nebel E, Postel J, et al. Flexible power generation scenarios for biogas plants operated in Germany: impacts on economic viability and GHG emissions. Int J Energy Res 2017;41(1):63–80.
[63] Jørgensen L, Kvist T. Methane emission from Danish biogas plants: Quantification of methane losses; 2015.
[64] Jacobs A, Auburger S, Bahrs E, Brauer-Siebrecht W, Christen O, Götze P, et al. Greenhouse gas emission of biogas production out of silage maize and sugar beet – an assessment along the entire production chain. Appl Energy 2017;190:114–21.
[65] Federal Reserve Bank of Kansas City. Agricultural Finance Databook: Section A: Amount and Characteristics of Farm Loans Made by Commercial Banks; 2017.
[66] EIA. Natural Gas Prices. U.S. Energy Information Administration. [January 15, 2018]; Available from: < https://www.eia.gov/dnav/ng/xls/NG_PRI_SUM_DCU_NUS_M.xls > .
[67] BLS. PPI Industry Data: Industry: Engineering services; Product: Non-building related engineering projects. U.S. Bureau of Labour Statistics; 2017.
[68] Gould B. Prices Received for Hay > Hay, All, Baled - Price Received. [December 20, 2017]; Available from: < http://future.aae.wisc.edu/data/annual_values/by_area/2080?tab=feed > .
[69] Stadtwerke Herborn. Regelung zur Anwendung von Lastprofilen: Lastprofil L1: Landwirtschaftsbetriebe mit Milchwirtschaft. [January 15, 2018]; Available from: < https://www.stadtwerke-herborn.de/marktpartner/netzbetrieb/strom/lastprofile.html > .