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The CO_2 cutting cost of biogas from humanure and livestock manure

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A R T I C L E I N F O

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A B S T R A C T

The European Union is accelerating its rollout of sustainable energy production and promotion of a circular economy. Electricity from biogas has synergy with energy-policy and rural-development goals yet its economic value is often convoluted. This study assessed the economic potential of biogas electricity using a representative rural case and quantified the cost and level of state support required for viability. The cost of CO_2-equivalent emission reductions was determined using the recast Renewable Energy Directive (RED II). The results showed that a feed-in tariff of 0.33 € kWh^{-1} for green electricity was required for economic feasibility. This yielded a CO_2 cutting cost of 251 € t^{-1}. The methane energy potential was 78 467 kWh a^{-1} from 31 498 kg (dry mass) of substrates, 80% livestock manure and humanure and 20% plant-based. Circular use of the digestate from anaerobic digestion, enabled a nitrogen recovery potential of 1 575 kg a^{-1}. The conclusions reached are that the economic value of the avoided emissions, through the RED II framework, is significant but it does not substantially improve the cost-effectiveness of biogas as an emission-mitigation technology. For biogas plant capacities less than 500 kW, current EU feed-in tariffs do not support economic viability.

Introduction

There is widespread political intent to phase out fossil energy sources within a generation and limit the projected global temperature rise to one and a half degrees above pre-industrial levels [1]. Realisation of this goal in the European Union (EU) relies on an energy and climate policy aiming for a 40% reduction in emissions by 2030 [2], in conjunction with the Sustainable Development Goals for clean energy and climate action [3]. The European Parliament has recently proposed the European Green Deal (EGD), which will raise this target substantially in order to achieve a climate-neutral EU by 2050 [4]. The EGD will require addition investments of 260 billion euros annually by 2030 [5]. As decarbonising the economy is a costly endeavour, the choice of renewable energy technologies and their specific emission reduction costs are especially important considerations.

Biogas has some practical advantages over other renewable energy technologies. It can be stored and used to produce electricity and heat on demand [6]. This is an important benefit compared to photovoltaic arrays or wind turbines, whose generated electricity is intermittent. Additionally, biogas can be upgraded to biomethane and existing gas networks (e.g. natural gas) and infrastructure can be utilised [7]. These benefits strengthen security of supply [8]. Farm-scale anaerobic digestion (AD) of animal manures represents a large application of biogas technology in the EU and has practical utility in agriculture. Biogas contributes to EU policy on rural development and the common agriculture policy by making farming more efficient, fostering competitiveness and climate action while supporting rural employment and livelihoods [9].

AD is the microbiological conversion of organic materials (e.g. biomass substrates) to a combustible biogas. Depending on the substrate, biogas is a mixture consisting of 45–70% methane (CH_4), 30–55% carbon dioxide (CO_2), water vapour (H_2O) and nitrogen (N_2), typically less than 1% N_2 (excluding landfill gas) [10]. Small amounts of hydrogen sulphide (H_2S), ammonia (NH_3) and trace amounts of other gases are also present. Substrates used for biogas production include energy crops [11], slaughter house waste [12], animal manures [13], organic household waste [14] and industrial waste streams [15,16]. Biogas can also be extracted from wastewater streams and landfill sites [17].

An important but poorly quantified benefit of biogas is the avoidance of potentially large greenhouse gas (GHG) emissions from the non-management of would-be substrates. Livestock manures constitute a large climate action incentive because mismanagement of manure can result in large methane emissions to atmosphere and methane is a much more potent greenhouse gas than carbon dioxide. In this view, manure

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Nomenclature

A	Future annual profit (€)
AD	Anaerobic digestion
C	Capital cost (€)
C_{el}	Market value of electricity (€)
C_N	Market value of nitrogen (€)
C_{NR}	Ratio of carbon to nitrogen (unitless)
d	Year-length constant (365 day a^{-1})
DM	Dry mass = TS total solids (kg)
DM_O	Organic dry mass (a.k.a. VS volatile solids (kg)
E_{CH4}	Energy content of substrate (kWh a^{-1})
$EC_{F(el)}$	Fossil fuel comparator for electricity production (658.8 g kWh^{-1})
$f_{PV}(A)$	Present value of future annual profits A (€)
GHG	Greenhouse gas
HRT	Hydraulic retention time (day)
LHV_{CH4}	Lower heating value of methane (kWh kg^{-1})
LR	Volumetric loading rate of reactor (m^3 day^{-1})
M_i	Organic dry mass fraction (dimensionless)
m_i	Net substrate amount of substrate i (kg a^{-1})
m_N	Recoverable substrate nitrogen (kg a^{-1})
m_T	Total mass of substrate (kg a^{-1})
$\dot{m}_O$	Organic loading rate (kg day^{-1})
N	Annual recoverable nitrogen amount (kg a^{-1})
N_i	Nitrogen dry mass fraction of substrate i (dimensionless)
n	Number of livestock/humans
NF	Nitrogen fraction (unitless)
ODM	Organic dry mass
p_i	Production rate of substrate i (kg day^{-1})
Q	Annual amount of recoverable heat (kWh)
R	Annual revenue from electricity sales (€)
$RED\ II$	Renewable Energy Directive recast
SBP_i	Specific methane production of the substrate i (m^3 kg^{-1} DM)
SEP	Specific electricity production
V	Minimum reactor volume (m^3)
VS	Volatile solids
Y_{biogas}	Biogas yield, amount of biogas per kg of organic dry mass (m^3 kg^{-1})
Y_{CH4}	Methane yield, fraction of methane in biogas (%)
η_Q	Efficiency of heat recovery (dimensionless)
ρ	Density of the substrate slurry (kg m^{-3})

collection and management is an emission mitigation activity. The recast Renewable Energy Directive (RED II), the EU sustainability framework for biofuels, partly takes this perspective into account [18].

A common use of biogas is to combust it directly in a gas engine, generating electricity and heat. An example of an AD biogas electricity plant is in Fig. 1. Substrates are loaded from storage into a mixing chamber with water to form the correct consistency. The mixture is pumped to the main digester where it is further mixed by recirculation of biogas from the storage tank into the bottom of the digester. A small amount of substrate from the main digester circulates (i.e. inoculant) to the mixing chamber to inoculate the mix with bacteria. The mixing chamber, digester and post digester are sealed and fitted with gas collection piping to the main biogas storage tank. In its simplest configuration, there is no biogas cleaning. The biogas is fed to a gas engine, which drives an alternating current (AC) electric generator. Some of the generated heat is utilised in maintaining the temperature of the main digester tank, typically less than 55 °C, through a submerged heat exchanger.

The second product of the AD process is the digestate, the remaining part of the biomass substrate. The digestate exits the main digester through a pump and is mechanically separated into a solid and liquid fraction. Being rich in nitrogen (N), phosphorus (P) and potassium (K), it is a valuable organic fertiliser and its reuse in agriculture helps close the resource loop by reducing reliance on mineral fertilisers of fossil origin.

Biogas yields from different substrates have a large range with manure slurries generally showing the lowest potential and energy crops or select industrial by-products the highest. For example, the volume of biogas from manures to cereal grains and rape seed cake substrates varies from 0.020 to 0.612 m^3 kg^{-1} (wet weight), a 30 fold range [20]. The methane content of biogas is less variable. The methane fraction at farm scale biogas plants in Sweden, operating primarily with manures (cow and pig), had a range of 54 to 66% [21]. Their specific methane production had a range of 0.178–0.191 m^3 kg^{-1} volatile solids (VS). For manures augmented with other substrates, production increased to

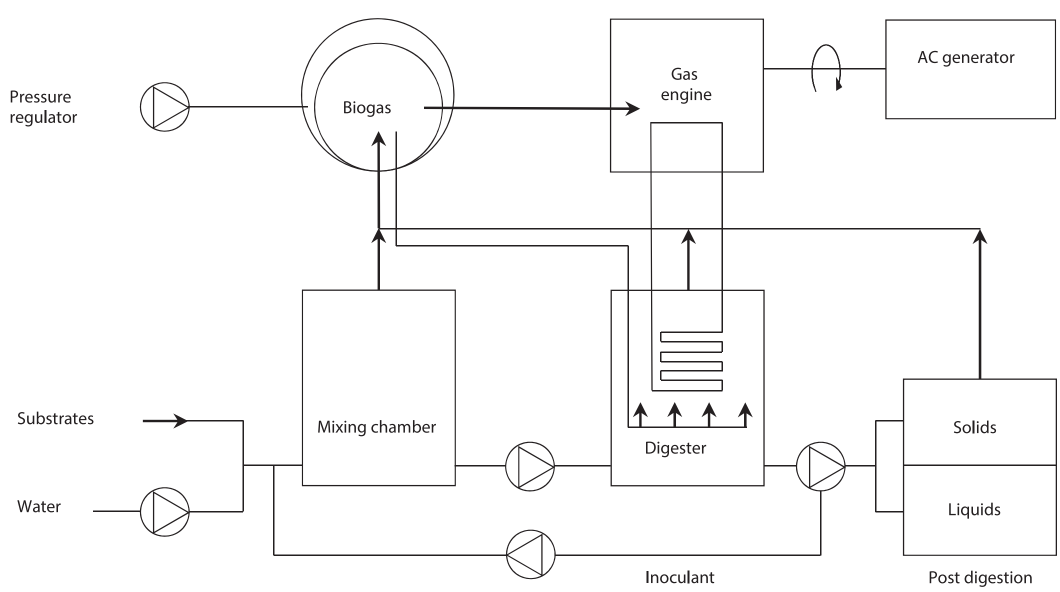

Fig. 1. An example of an anaerobic digestion biogas electricity plant [19].

0.224–0.289 m^3 kg^{-1} VS. *Humanure* (or *night soil*) and urine are abundant resources associated with agrarian communities [22]. However, they are commonly viewed as waste streams due to a human culture of aversion to these by-products. Flush toilets rely on exploitation of utility drinking water as a carrier thereby necessitating treatment at wastewater treatment plants. Bioaccumulation and potential health risks therefrom has limited the re-use of wastewater sludge [23] making the water treatment sector a challenging exception to society's transition to a circular economy. Humanure demonstrates a relatively high specific methane potential [24–26]; up to 0.327 m^3 kg^{-1} organic dry mass (ODM). This is comparable to the specific methane yields of grasses (cocksfoot, tall fescue, reed canary grass and timothy) which range from 0.253 to 0.394 m^3 kg^{-1} VS [11]. Lignocellulosic (woody) substrates, however, have poor gas potential by comparison. Consider, for example, that vineyard stems had a specific methane yield of 0.054 m^{-3} kg^{-1} VS [27] while winery residues from grapes can have up to 0.36 m^{-3} kg^{-1} VS [28]. These relevant examples capture the natural variability of biomass substrates but also to a lesser extent reflect differences in AD process configurations.

Electricity from biogas has earlier been recognised as a high-cost technology [29] and this rationalises the need of subsidies if biogas use is to be promoted. EU subsidies for biogas vary widely across EU Member States and take the form of feed-in tariffs, premiums and tenders for the promotion of biogas electricity [30]. Consider, for example, the renewable energy support mechanisms in Hungary, Austria and Germany [31]. Feed-in tariffs generally depend on plant capacity and substrate type (e.g. livestock manures, agricultural substrates) while the duration of support is a fixed term (e.g. 15–20 years or plant lifetime). Levels of support reflect national differences in labour costs and market price of electricity but also echo the political will of national policy [32,33].

Two decades of experience from biogas farm installations have provided numerous data on operation and production efficiency [21,34]. Despite the pioneering experience, the final energy costs and economic attractiveness of AD plant investments are not transparent based on existing literature. The purpose of this paper is to present a general method for assessing the economic feasibility of biogas technology and for determining the required level of subsidy to achieve economic feasibility. It also aims to put a price tag on the cost of emission reductions through biogas electricity. The case examines both the economic and environmental feasibility of biogas electricity production. The key objectives are to determine the present value of electricity from biogas and determine what level of subsidy (if any) is needed to make biogas electricity production a feasible enterprise and to determine the emission-cutting cost using this technology.

Materials and methods

This study assessed the implementation of biogas electricity for a village in Hungary, located in the outlying areas of Budapest. The village is representative of countless others throughout the EU and the world. The following is a general description.

There are approximately 70 households (224 inhabitants) in the village, centred on vineyards and small land holdings. Each household maintains a vegetable plot (100 m^2) and a garden area (250 m^2). The village land consists of vineyard (20 ha), agricultural fields for cereal crops (20 ha), uncultivated meadow (20 ha) and small plots of pastureland (15 ha) for livestock (Figure S1). Several families own a section of the vineyard and produce wine from the grape harvest. The average number of livestock kept throughout the year include pigs (50), laying hens (250) and dairy cows (10). Pigs and hens reside in fenced, partly open paddocks year round whereas the cows are at pasture from April until October. Forested areas border the village and deciduous trees and shrubs surround the dwellings.

Household bio wastes are passively managed using aerobic composting in outdoor bins along with garden wastes and cuttings. Residents rely on a combination of communal wastewater treatment (flush toilets), septic fields and pit latrines for managing humanure. Seasoned livestock manure and compost are utilised via land spreading on fields and as a top soil in vegetable plots. Village activities revolve around the fully centralised winery operations and are highly cooperative among households using a centralised wine cellar and bottler. Agricultural machinery (e.g. tractors and trailer-staged equipment) operate collectively and there are usually two to seven seasonal employees working, for example, in vine pruning, selection and winery tasks.

Substrate inventory and management

An inventory of biomass substrates was compiled and these fall into two categories; manures and plant-based biomass originating from livestock, agriculture and individual households (Table 1). The annual supply of substrates was calculated based on number of livestock and land areas with details in the description column of the table.

Substrate collection, storage and handling require careful planning and organisation to ensure routine operation of the AD plant. To some extent, these tasks will be realised using existing facilities and machinery in the village but there will also be a need to acquire appropriate storage tanks and associated infrastructure. For example, several bins or tanks will be necessary for collection of biomass generated at each household. Among seasonal substrates, the winery residues are significant and consist of grape stems, peels and seeds. Residues are generated following autumn harvest and after four and eight months when a large amount of sludge is produced from the fermentation step. Sufficient storage facilities are therefore required to manage these substrates, which were formerly disposed of using the communal wastewater system.

Anaerobic digestion plant overview

The AD biogas plant is modelled as a black box whose material inputs are substrates and water (potable) (Fig. 1). The outputs are renewable electricity, heat and digestate. The biogas is directly combusted in a gas-fired engine to generate electricity, which is sold directly to the electricity grid. The electricity and the recovered value of nitrogen, present in the digestate, have revenue potential. The liquid digestate will be stored in tanks and applied to agricultural land as a fertiliser. The solid fraction is stored in covered windrows and, after stabilisation through composting, can be applied to fields and vegetable plots. The recovered nitrogen content in the digestate offsets the cost of commercial fertilisers used in agriculture.

Methane and nitrogen recovery potential

The annual methane potential E_{CH4} (kWh a^{-1}) from anaerobic digestion of the substrate mixture is estimated from the lower heating value of methane LHV_{CH4} (kWh kg^{-1}), the specific methane production of the substrate SBP_i (m^3 kg^{-1} DM), the organic dry mass fraction M_i (dimensionless) and the net substrate amount m_i (kg a^{-1}) according to Equation (1).

$$E_{CH4} = LHV_{CH4}\sum_i SBP_i \bullet \mathrm{M_i} \bullet \mathrm{m_i} \tag{1}$$

Minimum and maximum values of *SBP*, obtained from literature, were used to estimate the methane potential of the substrates (Table 1). The amount of recoverable heat Q *(kWh* a^{-1}*)* is determined (Equation (2)) by the efficiency of heat recovery η_Q (dimensionless).

$$Q = E_{CH4} \bullet \eta_Q \tag{2}$$

The amount of recoverable substrate nitrogen m_N (kg a^{-1}) is determined from the nitrogen dry mass fraction of the substrate N_i (dimensionless) using Equation (3).

Table 1
Inventory and description of village substrates.

Substrate	Description	Annual availability	Supply (kg/a)	VS fraction (as received)	Specific Methane Production range (m^3 kg^{-1} ODM)	Nitrogen fraction (dry mass)	C/N ratio	Ref.
Humanure	Collected in household dry toilets. Each inhabitant produces 0.20 kg per day.	Continuous	16 352	0.250	0.178–0.327	0.06	8	[22,24,35]
Urine	Collected in household dry toilet at 0.5 L (0.5 kg) per person per day.	Continuous	40 880	0.0171	0.178–0.327	0.17	0.8	[22,35]
Pig manure	Collected from piggery, 5.88 kg per day per pig, 80% of the manure can be collected.	Continuous	85 848	0.149	0.178–0.289	0.037	13	[22,35]
Cow manure	Collected from cow house, 29 kg per day per cow, only 50% of the manure can be collected due to pasturing.	Continuous	52 925	0.124	0.178–0.289	0.029	25	[20,22,35]
Hen manure	Collected from the hen house and enclosures, 0.13 kg per day per hen, 80% of the manure can be collected.	Continuous	9 490	0.154	0.178–0.289	0.063	10	[22,35]
Kitchen biowaste	Household food waste estimated at 0.10 kg per person per day.	Continuous	6 541	0.10	0.253–0.394	0.02	5	
Winery sludge	Grape pomace (stems, skins, seeds) from winemaking. Estimated at 11% of the average grape harvest (12 000 kg/ha) consisting of peel (6%) and fermentation sediment (5%).	Sept–Oct	26 400	0.136	0.253–0.360	0.01[a]	13[a]	[28,36]
Vine cuttings	Leafy and woody seasonal cuttings from the vineyard, estimated at 0.5 kg per grape vine (1 200 vines/ha).	May–June	12 000	0.05	0.054–0.253	0.01	41	[27]
Grass cuttings	Cuttings from gardens and common areas (1.75 ha total from 250 m2 gardens) assuming 1 500 kg per hectare green weight.	May–Oct	2 625	0.101	0.253–0.394	0.024	19	[35]
Leaf fall	Fallen party dry leaves from gardens and hedges, estimated at 30 kg per household.	Oct–Nov	2 100	0.05	0.253–0.394	0.009	54	[22,37]
Garden residues	From household vegetable plots, estimated at 100 kg green weight per household.	May–Oct	7 000	0.05	0.253–0.394	0.005	27	
Cereal straws	Representing straw mixed and collected with manures as well as that used for mixing with other substrates before AD. Assumed to be a local surplus from cereal crops.	Continuous	4 921	0.06	0.054	0.005	128	[35]

Symbols refer to: a = estimated as apple pomace from [22], the specific methane production of the substrates was taken to be within the range of those established for manure based biogas plants (0.178 to 0.289 m^3 kg^{-1} VS [21].

$$m_N = \sum_i N_i \bullet M_i \bullet m_i \tag{3}$$

The volumetric loading rate LR (m^3 day^{-1}) of the primary AD reactor is estimated using the total annual substrate mass m_T (kg a^{-1}), the assumed density of the substrate slurry ρ (kg m^{-3}) and the year-length constant d (365 day a^{-1}) (Equation (4)). The minimum required reactor volume V (m^3) depends on the hydraulic retention time HRT (day) of the process using Equation (5) [19].

$$LR = m_T \bullet \rho \bullet d \tag{4}$$

$$V = LR \bullet HRT^{-1} \tag{5}$$

Revenue, capital and economic indicators

The annual revenue R (€) generated from the AD plant depends on the methane potential E_{CH4} (kWh a^{-1}), the efficiency of electrical generation η_{el} (dimensionless), the efficiency of heat recovery η_Q (dimensionless), the electricity price c_{el} (€ kWh^{-1}), the heat price c_Q (€ kWh^{-1}), the annual recovered nitrogen N (kg a^{-1}) and the market value of nitrogen c_N (€ kg^{-1}) (Equation (6)).

$$R = E_{CH4}\left(\eta_{el} \bullet c_{el} + \eta_Q \bullet c_Q\right) + (N \bullet c_N) \tag{6}$$

Annual profit A (€) is the difference between R and the annual operational costs C_o (€) which includes labour cost C_L (€), maintenance cost C_m (€) and insurance cost C_i (€) (Equation (7)) [38].

$$A = R - C_o = R - C_L - C_m - C_i \tag{7}$$

The capital cost C (€) is estimated at 8 800 € per kW electricity (British pound-to-Euro exchange rate of 1.0 £ = 1.1 €) installed capacity based on previous models of small biogas plants (sizes up to 500 kW) [39]. Annual labour cost is 500 h per year at a rate of 9.90 € per hour (2019) [32]. Plant maintenance and insurance costs are 2.5 and 1.0% of the capital costs per year. Due to the generic specifications on the AD plant, the on-site use of electricity for size reduction, mixing and pumping etc. is not included in the operational cost estimate, although these costs can be significant [40], especially for lignocellulosic substrates [41].

The simple payback period t_p (a) of the invested capital is calculated from capital cost and annual cash flow R_a (€ a^{-1}) (Equation (8)) [38], which is the sum of annual profit A and the annual depreciation (linear C n^{-1}).

$$t_p = C \bullet R_a^{-1} = C \bullet (A + C \bullet n^{-1})^{-1} \tag{8}$$

The return on investment ROI depends on annual profit and the capital cost (Equation (9)) [38].

$$ROI = A \bullet C^{-1} \tag{9}$$

If the annual profit remains constant, the present value $f_{PV}(A)$ (€) of future profits A (€) over n (a) years at a discount rate i (%) is calculated from Equation (10) [42].

$$f_{PV}(A) = A \bullet [(1+i)^n - 1] \bullet [(1+i)^n]^{-1} \tag{10}$$

The cost of capital i_c (%) is unique and used as the discount rate. It depends on the debt ratio DR (dimensionless) of the project, the interest rate of the debt i_d (%) and the cost of equity i_e (%) (Equation (11)) [42].

$$i_c = (DR \bullet i_d) + [(1 - DR) \bullet i_e] \tag{11}$$

To determine the two unknown variables in Equation (6), R and c_{el}, a graphical solution is used to find the minimum level of feed-in tariff to make the project economically feasible. This is done by selecting a selling price of electricity c_{el} and observing the condition when the difference between present value and capital cost is zero (Equation (12)) [38].

$$f_{PV}(A) - C = 0 \quad (12)$$

Plotting the generated data points (c_{el}, $f_{PV}(A)$-C) will result in a straight line that crosses the x-axis. The x-axis value at the point of intersection with the line is the value of c_{el} when Equation (12) is satisfied and is equal to the minimum required feed-in tariff.

Cost of CO_2 emission reduction

The mass of carbon dioxide equivalent reductions m_{CO2} (g) through use of biogas electricity is estimated from Equation (13). It uses the framework of RED II [18] in which S_{el} (%) is the GHG emission savings from biogas electricity, $EC_{F(el)}$ (g kWh^{-1}) the fossil fuel comparator for electricity production and E_{el} *(kWh)* the electricity produced from biogas.

$$m_{CO2} = S_{el} \bullet \mathrm{EC_{F(el)}} \bullet \mathrm{E_{el}} \quad (13)$$

RED II quantifies the avoidance of emissions through S_{el}, whose value can be larger than 100%, reflecting the negative emission component of biogas in its definition. The default and typical values of S_{el} are 85 and 136% respectively for biogas for electricity for wet manure substrates (Case 2) and open digestate management [18].

The specific cost of CO_2 reductions C_{CO2} *(€ t^{-1})* from biogas electricity is defined as the cost of replacing grid electricity *Δh (€)* (derived from fossil fuels) with biogas electricity divided by m_{CO2} (Equation (14)) [38].

$$C_{CO2} = \frac{\Delta h}{m_{CO2}} \quad (14)$$

In this case, the numerator is the difference between the annual market value of produced electricity (assumed to be generated from fossil fuels) and the annual amount of feed-in tariff paid to the producer.

Assumptions and model inputs

The techno-economic analysis used production and economic inputs described in Table 2.

In addition, the study used the following assumptions.

- The cost of the substrates are modelled at zero
- The potable water (e.g. existing well water available in the village) used in the plant is available at no cost
- Taxes are set a zero for the profitability assessment

Table 2
Selected production and economic inputs for the study.

Variables	Symbol	Units	Value
Lower heating value methane	*LHV*	MJ m^{-3}	35.7 [43]
Hydraulic retention time	*HRT*	day	30
Slurry density	ρ	kg m^{-3}	1000
Efficiency of heat recovery	η_Q	%	50
Efficiency of electricity generation	η_e	%	45
Nitrogen price	c_N	€ kg^{-1}	0.29–0.41 [44]
Heat price	c_Q	€ kWh^{-1}	0.00
Electricity selling price (feed-in tariff)	c_{el}	€ kWh^{-1}	**To be determined**
Tax rate	r	%	0.00
Cost of equity	i_e	%	0.20
Interest rate of debt	i_d	%	0.04
Debt ratio	DR	%	0.50
Cost of capitol	i_c	%	0.120
Duration	n	year	20
Discount rate	i	%	0.120

- On-site use of electricity for size reduction, mixing and pumping etc. is not included in the operational cost estimate, although these costs depend on specific plant configuration and are significant [40]
- Cereal crops are effective biogas substrates but they are not considered in this assessment (Competition between food and non-food biomass etc.)
- Cost of labour 9.9 € (includes all social benefits) [32] but may not reflect real salaries for unskilled labour (i.e.) real labour may be lower cost
- Recoverable heat (not including utilised process heat) is not included in revenue expectations

Results and discussion

The results are presented in two parts, the biogas potential from available substrates followed by the economic results.

Methane, electricity and nitrogen potential

The methane, energy and nitrogen recovery potentials (Equations (1) through (3)) of available substrates (Table 1) are presented as minimum and maximum values (Table 3). The methane potential from 31 498 kg DM of organic substrate ranges from 5 988 to 9 837 m^3 annually, with a corresponding energy potential of 59 386 to 97 548 kWh a^{-1}. The nitrogen recovery potential from the digestate is 1 575 kg a^{-1}.

Of the relative substrate contributions to the methane potential, 80% derives from manures and 20% from plants (Fig. 2a). Pig manure has the largest contribution (38%), followed by cow manure (19%) and humanure (19%). Winery sludge (14%) and the combined potential of grass and vineyard cuttings, garden residues etc. have relatively low potential (6%) due to their low organic dry mass fraction (Table 1).

Approximately 80% of all recoverable nitrogen in the substrates (Fig. 2b) originates from humanure and urine (34%), pig manure (29%) and plant substrates (17%). This shows that the greatest value of humanure and urine substrate is derived from their nitrogen recovery potential.

Table 4 contains the calculated production amounts (Equation (1)). The methane from the biogas can enable an average electricity production of 35 310 kWh annually with 39 234 kWh of recoverable heat (Equation (2)). The specific electricity production (i.e. amount of produced electricity divided by the total organic dry mass of substrate, SEP) of the biogas plant is 1 121 kWh t^{-1} ODM.

Profitability analysis and feed-in tariff

To satisfy the condition of Equation (12), an electricity price (feed-in tariff) of 0.33 € kWh^{-1} is required for the average value of generated electricity. The minimum and maximum values are 0.30 and 0.37 € kWh^{-1} for maximum and minimum potentials respectively. The generated annual revenue is 12 792 € from electricity (11 593€) and recoverable nitrogen value (1 199 €) (Table 5).

The present value (Equation (10)) of the biogas project over a ten-year plant lifetime is 36 992 € (Table 6). This is the maximum amount an investor should spend on the project in order that it make economic sense. The min and max range results in a present value range of 21 681 to 52 303 €. An average cash flow of 10 246 € a^{-1} enables a payback period 3.6 years with a return on investment of 17.7%. That these values indicate a good project economy is not surprising because the feed-in tariff (0.328319 € kWh^{-1}) is the solution to satisfy the condition that *V - C* is zero.

The sale of excess recoverable heat, from the AD process, part of which is used internally to regulate reactor temperature, has potential to raise project revenue and in large-scale urban applications would contribute positively to plant economy. In the present case, the sale of heat at 0.03 € kWh^{-1} would generate an additional 1 125 € annually, raising the present value to 40 832 €, an increase of 26%. Heat utilisation

Table 3
Methane, energy and nitrogen recovery potential of substrates.

Substrate	Organic dry mass (kg a^{-1})	Min. methane production (m^3 a^{-1})	Max. methane production (m^3 a^{-1})	Min. energy (kWh a^{-1})	Max. energy (kWh a^{-1})	Recovered nitrogen (kg a^{-1})
Humanure	3 974	707	1 299	7 014	12 885	238
Urine	1 799	320	5 88	3 175	5 833	306
Pig manure	12 791	2 277	3 697	22 579	36 659	473
Cow manure	6 563	1 168	1 897	11 584	18 808	190
Hen manure	1 461	260	422	2 580	4 188	92
Kitchen biowaste	654	116	189	1 155	1 875	13
Winery sludge	3 590	908	1 293	9 008	12 818	36
Vine cuttings	600	32	152	321	1 505	120
Grass cuttings	265	67	104	665	1 036	63
Leaf fall	105	27	41	263	410	19
Garden residues	350	89	138	878	1 368	38
Cereal straw	305	16	16	163	163	20
Total	**31 498**	**5 988**	**9 837**	**59 386**	**97 548**	**1 575**

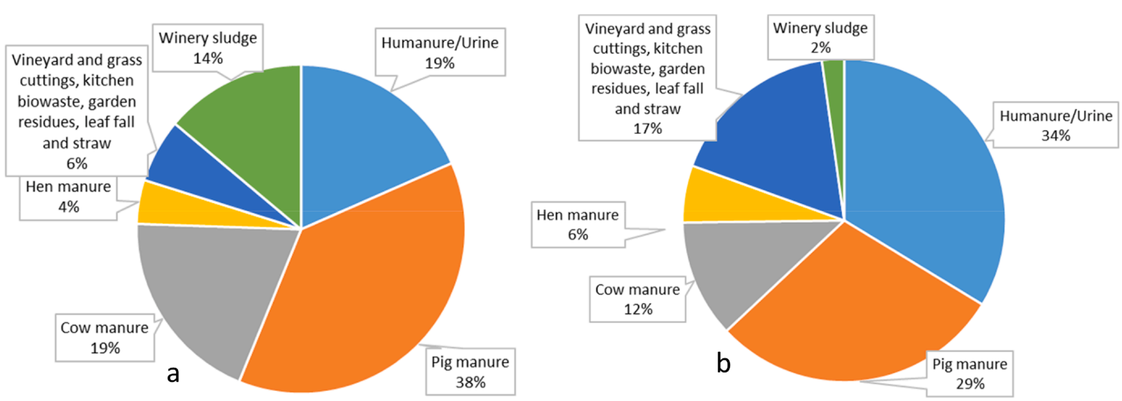

Fig. 2. Relative contribution of substrates to a) methane potential and b) recovered nitrogen.

Table 4
Production amounts.

Item	Symbol	Units	Min	Max	Ave
Methane produced	V_{CH4}	m^3	5 988	9 837	7 913
Energy of methane	E_{CH4}	kWh	59 386	97 548	78 467
Heat produced	Q	kWh	29 693	48 774	39 234
Electricity generated	e	kWh	26 724	43 897	35 310
Specific electricity production	SEP	kWh t^{-1} ODM	848	1 394	1 121
Recovered nitrogen	N	kg a^{-1}	1 575	1 575	1 575

Table 5
Annual revenue.

Item	Symbol	Units	Min	Max	Ave
Nitrogen recovery	C_N	€ a^{-1}	993	1 404	1 199
Electricity sales	C_{el}	€ a^{-1}	8 774	14 412	11 593
Heat sales	C_Q	€ a^{-1}	0	0	0
Total revenue	R	€ a^{-1}	9 767	15 816	12 792

is a requirement in some Member States to fully unlock existing biogas subsidies [30]. In practice, heat utilisation has limited potential for generating revenue because AD plants are often in rural locations, far from potential consumers and lacking the conduits required to supply district heating networks [39].

The determined methane, electricity and nitrogen potentials are valid across EU Member States as these potentials depend on process control. Member State subsidies vary greatly across the EU. Germany's support of biogas technology is recognised as one of the most generous in the EU. Its feed-in tariffs for biogas electricity (from biomass substrates) range from 0.0583 to 0.277 € kWh^{-1} for a 20-year plant duration [30]. The tariff is reduced by 0.002 € per kWh of plant capacity along with a quarterly 0.5% reduction. In the present case, with a plant size of 35 310 kWh a^{-1}, the maximum first year tariffs, including capacity reduction, would be 9 710 € (9 781–70.62 €) with the annualised quarterly reduction of 195.62 € a^{-1}.

If the feed-in tariff for the biogas project corresponded to the maximum in the German policy (0.277 € kWh^{-1}) [31], the present value is reduced from 36 992 to 26 753 €, a decrease of 28%. Equation (12) then results in a value of −10 238 €. The negative value is an economic loss over the project lifetime, indicating a poor investment. Table 7 shows how the loss ($f_{PV}(A) - C$), ROI and payback period vary with project duration and feed-in tariff.

With the German tariff and a 20-year duration, the economic loss (after the first year) is lowest (- 1 624 €). The ROI is the same for 10, 15 and 20 years but the duration of the return is longer. The payback period becomes longer with duration because the annual cash flow is affected by the lower tariff.

Due to their generally lower support mechanisms, other national subsidy systems will result in poorer economic performance than in the German case. This is evident from their lower subsidies. For example, the Hungarian feed-in tariffs, although available for the plant lifetime, are significantly lower, ranging from 0.04 to 0.12 € kWh^{-1} and are linked to time of day for plant capacities less than 20 MW [31]. In Austria, support is limited to 15 years and tariffs range from approximately 0.13 to 0.19 € kWh^{-1}.

There may also be qualitative benefits to the proposed AD plant at

Table 6
Profitability analysis at conditions $f_{PV}(A)$ - C = 0 (c_e = *0.328319 € kWh^{-1}*).

Row	Description	Units	Row Operation	Minimum	Maximum	Average
A	Capital cost	€		27 996	45 987	36 992
B	Operational cost	€ a^{-1}		5 930	6 560	6 245
C	Revenue	€ a^{-1}		9 767	15 816	12 792
D	Profit	€ a^{-1}	C-B	3 837	9 257	6 547
E	Tax	€ a^{-1}	D * r	0	0	0
F	Depreciation	€ a^{-1}	A/n	2 800	4 599	3 699
G	Cash flow	€ a^{-1}	D + F	6 637	13 855	10 246
H	Present value	€	f_{PV} *(D)*	21 681	52 303	36 992
I	Payback period	a	A/G	4.2	3.3	3.6
J	Return on investment	%	100 * D/A	14	20	18

Table 7
Variation in economic indicators as a function of feed-in tariff.

Feed-in tariff (€ kWh^{-1})	Duration (a)	Present value (€)	Variation in feed-in tariff, c_{el} (%)	$f_{PV}(A)$ – *C* (€)	ROI (%)	Payback period (a)
0.328	10	36 992	0.0	0.0	17.7	3.6
0.277	10	26 753	−28	−10 238	12.8	4.4
0.277	15	32 249	−13	−4743	12.8	5.1
0.277	20	35 367	−4	−1624	12.8	5.6

the community level. Access to digestate and recovered nutrients assist in closing the resource loop and enhance the autonomy of village agriculture. For example, the local supply of digestate may save time and resources for farmers. The digestate also acts as a buffer to insulate farmers from external service and market uncertainties of fertiliser costs and top soil for gardens.

The project will also place resource constraints on the community. It will require input and contribution from individuals for the construction, operation and maintenance throughout the lifetime of the project. Although existing equipment (e.g. tractors and tools) can be used, there will be greater expenses (e.g. diesel fuel) and dedication of time. Individual responsibility for the management tasks and routines will be necessary. Moreover, there may be administrative responsibilities will consume time and resources due to construction and electricity grid connection.

Humanure is not commonly viewed as a resource at a community level but rather a managed waste product of municipal wastewater treatment plants (WWTP). Utilisation of sludge generated at WWTPs (e.g. through land spreading on agricultural land) is challenging due to real and perceived health risks from potential contaminants [45]. Waterborne conveying and municipal treatment of humanure places considerable energetic and environmental load on WWTPs and threatens the availability of potable water [46].

Dry toilet collection of humanure reduces water use and can significantly augment the biogas and nitrogen recovery potential of village-scale anaerobic digestion, thereby reducing the load on WWTPs. However, dry toilets shift “waste” management responsibilities upstream to the individual and local community. These are important considerations when planning an AD plant using these substrates.

CO_2 cutting cost based on RED II

According to RED II, the typical and default costs of CO_2 reductions (Equation (14)) for electricity produced from biogas are 251 and 402 € t^{-1} respectively, with the corresponding avoided CO_2-equivalent emissions ranging from 31.6 to 19.8 t a^{-1}. This assumes that the produced electricity from the biogas plant replaces EU fossil-fuel generated electricity with a comparator value of 183 g MJ^{-1} (0.0006588 t kWh^{-1}) and a Hungarian household electricity market price of 0.1031 € kWh^{-1} [33]. The CO_2 reduction costs have a higher range than recently reported by Wang et al. who found a range of 134 to 385 € t^{-1} (1 CAD = 0.67 €) for AD of waste streams with no quantification of avoided emissions from unmanaged alternatives [29]. The RED II framework considers the avoided emissions through the value assigned to the emission savings (S_{el}), whose typical value is 136%. Wang et al. classified AD as a high-cost emission reduction technology compared to low-cost technologies, which included wood residue fuels in combustion. For comparison, wood pellets, which are an upgraded fuel made from wood industry by-products have an emission cutting cost (RED) of 107 € t^{-1} in co-firing applications [38]. This exemplifies how there can be significant differences in emission reduction costs depending on the renewable technologies in question. The costs are much higher than the price of carbon on the EU emission trading system, which at the time of writing has moved to above 40 € t^{-1} after a decade of being below 20 € t^{-1}.

How representative are the results for biogas production in real farm-scale plants throughout Europe? A meaningful measure of AD plant utility is its specific electricity production (SEP), whose average value in this study is 1 071 kWh t^{-1} ODM (Table 4). Experiences from hundreds of biogas plants in Switzerland, Germany and Austria over recent decades have generated good data on technical performance [34]. For plant capacities less than 500 kW, specific electricity production ranges from 650 to 1600 kWh t^{-1} in these regionally comparable countries. These plants also operate primarily on manure substrates, with minor fractions of agricultural residues, and the large SEP range is due to the number of reactors and hydraulic retention time, not to significant differences in biogas potential. One can conclude that the results herein are well within observed performances in Europe and this provides strong evidence that the assumptions and input used in this study are generally accurate. Capital cost is a function of AD plant size so that the results are valid for plant sizes up to 500 kW electrical capacity [39].

Due to the benefits often associated with economy of scale (i.e. decrease in specific investment costs), there is a need to study the economic performance of larger biogas-to-electricity plants (>500 kW), especially at sites where produced heat can generate revenue. The benefits from such cases, will likely lower the specific subsidy needs (as reflected in national subsidy systems) and corresponding CO_2 cutting cost. As an energy storage technology, this feature of biogas is perhaps the most attractive element (compared to wind and solar) and therefore large plants located close to natural gas networks should be a natural priority in subsidy development. Finally, the direct combustion of biogas (e.g. in 100% heating applications) may also have great utility from an emission savings perspective, due to the possibility to utilise the total thermal power of the generated biogas.

Conclusions

Biogas electricity production is a high-cost renewable energy technology, which supports rural development and employment. In this study, the economic feasibility of biogas electricity was assessed for a representative Hungarian village case. Biogas production via anaerobic digestion was primarily based on available livestock manures, humanure and agricultural residues. In terms of nitrogen recovery potential, humanure punches above its weight class. A general method was presented for assessing the required level of renewable energy subsidy to achieve economic feasibility. The results showed that biogas production from the considered substrates has economic potential as long as substantial support mechanisms (e.g. feed-in tariffs) are available over the lifetime of the investment. For this case, representative of plant capacities less than 500 kW, the required feed-in tariff for economic feasibility was found to be in the range of 0.30 to 0.37 € kWh^{-1}. According to the recast Renewable Energy Directive (RED II), this resulted in typical and default CO_2 cutting costs of 251 and 402 € t^{-1} respectively.

The magnitude of feed-in tariff for the considered case exceeds the present levels in the EU. For the first time, the avoided emissions of unmanaged livestock manure has been quantified in economic terms using the recast Renewable Energy Directive (RED II) framework. The conclusion is that the economic value of the avoided emissions is significant but it does not substantially improve the cost-effectiveness of biogas as an emission-mitigation technology. These findings will have significance in future prioritisation of renewable energy subsidies in EU energy and climate policy.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2022.102381.

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