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Economic and Environmental Analysis of Small-Scale Anaerobic Digestion Plants on Irish Dairy Farms

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Abstract: The European Union's (EU) climate and energy package requires all EU countries to reduce their greenhouse gas (GHG) emissions by 20% by 2020. Based on current trends, Ireland is on track to miss this target with a projected reduction of only 5% to 6%. The agriculture sector has consistently been the single largest contributor to Irish GHG emissions, representing 33% of all emissions in 2017. Small-scale anaerobic digestion (SSAD) holds promise as an attractive technology for the treatment of livestock manure and the organic fraction of municipal wastes, especially in low population communities or standalone waste treatment facilities. This study assesses the viability of SSAD in Ireland, by modelling the technical, economic, and environmental considerations of operating such plants on commercial Irish dairy farms. The study examines the integration of SSAD on dairy farms with various herd sizes ranging from 50 to 250 dairy cows, with co-digestion afforded by grass grown on available land. Results demonstrate feedstock quantities available on-farm to be sufficient to meet the farm's energy needs with surplus energy exported, representing between 73% and 79% of the total energy generated. All scenarios investigated demonstrate a net CO_2 reduction ranging between 2059–173,237 kg CO_2-eq. yr^{-1}. The study found SSAD systems to be profitable within the plant's lifespan on farms with dairy herds sizes of >100 cows (with payback periods of 8–13 years). The simulated introduction of capital subvention grants similar to other EU countries was seen to significantly lower the plant payback periods. The insights generated from this study show SSAD to be an economically sustainable method for the mitigation of GHG emissions in the Irish agriculture sector.

Keywords: anaerobic digestion; methane production; co-digestion; combined heat and power; farm-scale; technical-economic analysis; life cycle assessment; greenhouse gas emission; Ireland

1. Introduction

The European Union's (EU) climate and energy package sets binding greenhouse gas (GHG) emission reduction targets for all EU states by 2020; these include a 20% cut in GHG emissions, to produce 20% of energy consumed from renewable sources, and a 20% improvement in energy efficiency [1]. The Republic of Ireland, in particular, has struggled to meet its emission targets, with most recent estimates projecting a 14%–15% shortfall, resulting in the country projected to pay up to €103 million in carbon credits to compensate for its lack of climate action [2,3]. Ireland's agriculture sector has consistently remained the single largest contributor, accounting for 33% of all GHG emissions in 2017, and 46% of all non-emission trading system (ETS) GHG emissions [4]. The country

now faces a dilemma, to either limit or reduce the growth of its agriculture sector (which is vital to Ireland's economy) or to disregard its environmental obligations.

A promising technology with the capacity to provide both renewable energy and GHG reduction, particularly in the agriculture sector, is anaerobic digestion (AD). AD is a natural process in which microorganisms (hydrolytic, fermentative, acetogenic and methanogenic bacteria) break down biodegradable material in the absence of oxygen, producing biogas (a mixture mainly composed of methane and carbon dioxide). These systems are beneficial for improving on-site energy generation, upgrading wastes, and producing a nutrient-rich fertiliser from the digester effluents. They can also reduce pathogenic loads, odours and greenhouse gas emissions emanating from the agricultural processes [5–8]. Furthermore, the technology has received considerable research attention, advancing its potential capability through optimisation strategies [9–14]. Despite the apparent benefits, Ireland has been slow to adopt the technology, ranking 20th in AD penetration among the EU-28 countries [15–17]. A contributing factor to the low deployment is the concentration of "large scale plants", particularly in Europe, where the siting of such centralised facilities has been based on the availability of significant quantities of biomass feedstock [18]. However, the biomass quantities in many Irish farms are currently insufficient to meet the feedstock requirements of medium-and large-scale AD plants. The situation is worsened when considering that the average dairy herd in Ireland only consists of approximately 90 cows in 2018 [19].

The application of small-scale anaerobic digestion (SSAD) plants with an electrical output of 15–100 kW_e, holds promise in overcoming the technical and economic barriers associated with treating lesser biomass quantities [18]. SSAD may be particularly useful for the Irish dairy industry, where there is a large livestock population (1.4 million dairy cows) [20], there are predictable process energy demands and reliable feedstock collection potential, its deployment is promising. Despite the potential of this technology, previous studies have largely focused on the implications of deploying medium to large scale AD plants (>100 kW_e) with relatively little focus on the Irish context [21,22]. Therefore, a lack of understanding is apparent in the applicability of SSAD plants in stand-alone agricultural environments within Ireland [23].

The goal of this study was to provide an initial assessment of the viability of SSAD on commercial Irish dairy farms. Thus, not only benefiting the reported case study but also other countries and regions, especially those with significant agricultural and livestock productivities. To achieve this goal, the following objectives were put forward:

- Examine the technical parameters associated with the operation of an SSAD plant at various capacities.
- Conduct a CO_2 balance to assess the various scenarios investigated.
- Conduct an economic analysis investigating total revenues, expenditures and financial indicators, such as net present value (NPV) and internal rate of return (IRR).

2. Materials and Methods

2.1. System Boundary

This study considered a "cradle-to-grave" system boundary, encompassing both the technical and environmental impacts in the construction and operation of SSAD plants at various scales. The system boundary, as described in Figure 1, was divided into four main parts:

1. Associated agricultural processes: (i) crop production; (ii) crop harvest and transport; (iii) manure collection and transport; (iv) storage; (v) transport to digester;
2. Biogas production: (i) digester feeding (ii) the AD process;
3. Energy conversion: (i) energy generation (production of electricity and heat); (ii) final use of energy produced;
4. End of life of digestate: (i) storage; (ii) transport and digestate spreading.

This study did not examine the processes related to the SSAD plant construction, as the material use and key manufacturing processes are unclear. Similarly, the inputs and processes related to the

disposal of the plant were also not considered and are outside the study scope. Additionally, the inputs related to the production of farm equipment (e.g., tractors, machines) were not included in the system boundaries, due to the uncertainty regarding their energy input. All simulations were created and run using the software package Microsoft Office Excel (Microsoft Office 2016, Microsoft Corporation, Redmond, WA, USA).

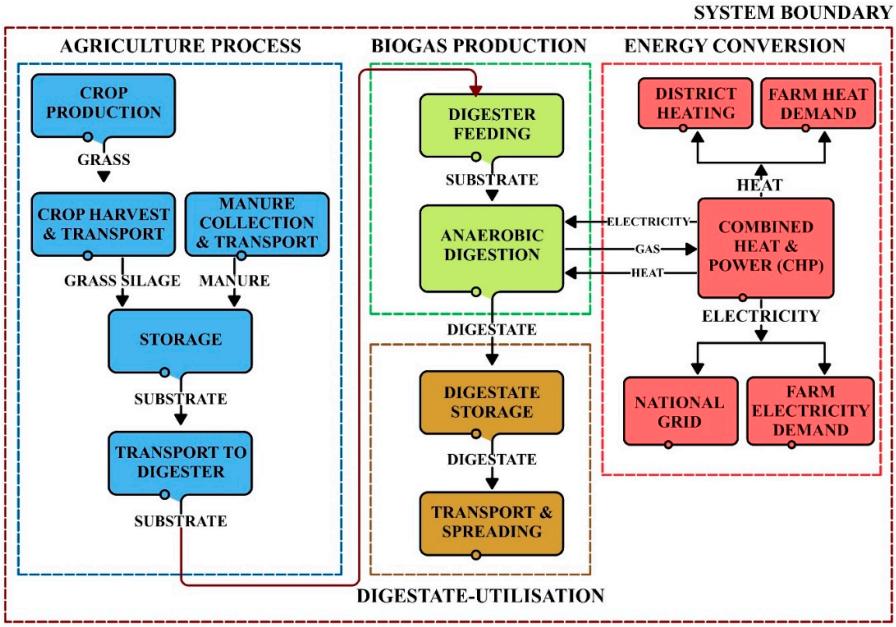

Figure 1. System boundary.

2.2. Feedstock Yield

The farms simulated in this study were selected based on their ability to collectively provide a full representation of the Irish dairy industry, which consists of mainly small to medium-sized farms, as illustrated in Figure 2. The study used a co-digestion feedstock of both dairy cow manure and grass silage. Grass silage was selected because of its popularity in Ireland, where 80% of agriculture land is devoted to pasture, hay and grass silage [24]. Furthermore, Ireland has ideal climate conditions for grass production, experiencing mild and moist conditions, an abundance of rainfall and a lack of extreme temperatures [25,26].

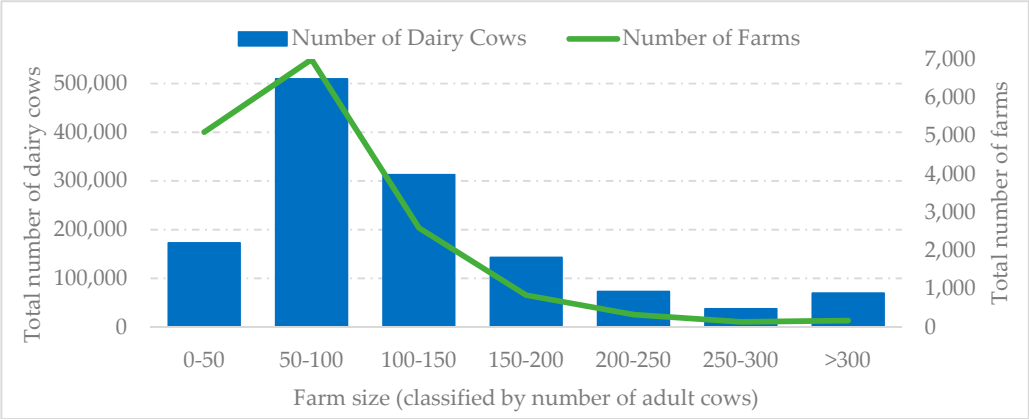

Figure 2. Distribution of total farms and dairy cows by farm size in Ireland [27]

Five dairy farm sizes were selected, these relate to the assumed herd sizes of 50 dairy cows (Scenario 1); 100 dairy cows (Scenario 2); 150 dairy cows (Scenario 3); 200 dairy cows (Scenario 4); and 250 dairy cows (Scenario 5). The number of dairy cows refers to the number of female bovine dairy cows, which had already calved and were kept exclusively to produce milk.

The dairy enterprise is based on a self-contained Holstein–Friesian herd [28], retaining pure-bred replacements and selling beef crosses at three weeks. Dairy cows are culled, on average, after five lactations (i.e., annual replacement rate of 18%), which is common in Ireland [29,30]. Manure is predominantly collected from the milking parlour and the cattle housing units (mainly slatted sheds) [31]. The quantity of manure produced per adult cow, heifer, and calve is presented in Table 1. Over the 16 week winter period, it was assumed all manure produced was collected for digestion as the cows are housed [32]. It was more difficult to estimate manure collection over the grazing period (remainder of the year) as collection mainly occurs when the cows are being milked. Based on a milking rate of two times per day and the increased metabolic rate during this period, a 20% manure collection rate was assumed in comparison to Table 1 figures, i.e., 10.4 kg fresh weight (FW) day^{-1} for adult cows, 7.44 kg FW day^{-1} for heifers, and 3.72 kg FW day^{-1} for calves.

Table 1. Characteristics of dairy livestock [32,33].

Livestock	Livestock Weight Target	Total Manure Production (FW day^{-1})
Adult cows (<24 months)	550 kg	52.2 kg
Heifers (12 to 24 months)	406 kg	37.2 kg
Calves (>12 months)	175 kg	18.6 kg

In the model, it was assumed that the dairy enterprise was the primary source of income, with revenue from biogas production being a supplementary income stream. Consequently, the needs of the dairy herd were prioritised, with only surplus crops used for biogas production. The area of farmland available to grow feedstock was estimated by subtracting Ireland's mean farm size (based on herd size) from the area of land required to sustain the dairy herd. The mean farm sizes for the scenarios considered corresponded to 43.51 (Scenario 1), 68.74 (Scenario 2), 93.96 (Scenario 3), 119.19 (Scenario 4), and 144.41 hectares (Scenario 5) [27]. The area of farmland required to sustain the dairy herd was based on a recommended ratio of 2.8 cows per hectare with an additional 20% margin of safety added, to account for seasonal variations and unusable land [32]. Silage yields in Ireland are typically between 11 and 15 t dry solids (DS) ha^{-1}; yields are generally higher in the southwest and decrease towards the northeast [25,34]. The model assumed an average yield of 13 t DS ha^{-1} to enable it to represent the majority of Irish dairy farms.

2.3. Pre-Digestion Farm Activities

This study considered the direct and indirect energy inputs for the co-digestion feedstock prior to digestion. For the grass silage feedstock, energy inputs in cultivation, harvesting, recovery and digester feeding were accounted for and are described in Table 2 and Table 3. The calculations used in Table 2 were based on the land being ploughed every seven years to maintain grass productivity. For the dairy cow manure feedstock, the energy inputs related to its collection, loading and transportation from the farm's cattle housing and milking parlour to the digester were also accounted. According to Berglund [35], the energy input in loading and transporting liquid manure is 2.5 MJ t^{-1} km^{-1}. The model used this figure and an estimated distance of 500 m between the manure storage and digester to calculate energy consumption. The system boundary assumed that the digestate produced from the AD process was spread as fertiliser on the farms' own land.

Table 2. Fuel consumption by machinery in grass cultivation (Reproduced from Gerin [36]).

Operation	Average Diesel Fuel Consumption (l ha^{-1} y^{-1})
Crop production	
Soil ploughing and crumbling	4.67
Sowing and maintenance	6.9
Weed control	0.24
Transport and spreading of fertiliser	18
Crop collection and transport	
Harvest	47.20
Harvest transport	25.49
Silo compaction	8.80
Digester feeding (grass)	23.57

Table 3. Energy consumed and CO_2 emitted from raw materials [36–38].

	Application Rate (kg ha^{-1} yr^{-1})	Energy Consumed (MJ kg^{-1})	CO_2 Emitted (kg CO_2 kg^{-1})
Mineral fertiliser			
Nitrogen	82	70 ± 34	2.5 ± 0.1
Phosphorus pentoxide	11	12 ± 4	1.1 ± 0.4
Potassium oxide	29	7.5 ± 2.5	0.67 ± 0.19
Other raw materials			
Diesel	N/A	56.3 ± 5.6	3.64 ± 3.6
Weed control	0.11	200 ± 20	15.45 ± 1.5

2.4. Operation of the Biogas Plant

The biogas available for potential recovery in an AD plant is largely dependent on the fraction of volatile solids (VS) in the feedstock, high fractions of VS correlate to higher biogas production [39]. The VS content represents the portion of organic solids that can be digested in the feedstock, while the remainder of the solids is fixed [40]. Using the feedstock physical and chemical properties described in Table 4, the biogas flowrates per kg of VS were quantified using the Boyle–Buswell stoichiometric relationship described in Equation (1) [41]. This methodology assesses the biogas potential of organic solids through the AD process. As this methodology considers the total content of VS to be biologically degraded, it can lead to an overestimation of the biogas produced from the feedstock in comparison to real-world case studies [42]. Nevertheless, Boyle–Buswell has been commonly applied in literature as an effective indicator to gauge biogas potential [21,43,44]. The subsequent methane yield was 0.6376 m^3 CH_4 kg^{-1} VS from dairy cow manure and 0.822 m^3 CH_4 kg^{-1} VS from grass silage.

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + dNH_3 + eH_2S \quad (1)$$

Table 4. Physical and chemical properties for dairy cow slurry and grass silage [21,41,45].

Physical Properties	Dairy Cow Manure	Grass Silage
DS (g kg^{-1}) [a]	87.5 ± 2.1	292.7 ± 3.4
VS (g kg^{-1}) [b]	66.9 ± 1.8	87.5 ± 2.1
VS DS^{-1} (%) [a b]	76.5	91.7
Carbon (%)	58.62	46.43
Hydrogen (%)	7.69	6.43
Oxygen (%)	30.50	44.72
Nitrogen (%)	2.92	2.36
Sulphur (%)	0.27	0.06

[a] DS is dry solids; [b] VS is volatile solids.

The plant simulated consisted of a mesophilic continuously stirred tank reactor (CSTR) with all biogas produced used in a combined heat and power (CHP) unit. The annual operating time of the plant was assumed to be 8000 hours (91% of the year), allowing for routine maintenance and repair, as reported in the literature [46–48]. The hydraulic retention time of the plant was 25 days [49]. Based on the rate of biogas flow, it was possible to size the required CHP unit using Equation (2) [50]. The CHP unit was assumed to have an electrical efficiency of 30% and a thermal efficiency of 55%, which is typical for similar sized systems [35,48,51,52].

Berglund and Börjesson [35] reported that the primary power consumption in the operation of an AD plant is the pumping and stirring of feedstock (7.2 kWh t^{-1}). The net electricity produced via the CHP unit was first used to meet the electrical demand of the farm, with surplus electricity exported to the national grid. The energy required to heat and maintain the digester's temperature was calculated using Equation (3). The plant's heat losses (hl) were estimated using Equation (4). The heat transfer coefficients of the plant's construction materials correspond to the following: floating cover (1.0 W m2.°C); 6mm steel plate "sandwich" with 100mm insulation (0.35 W m2.°C); 300mm concrete floor in contact with earth (1.7 W m2.°C)(Zhang, 2013). Equation 5 describes the energy required to heat the digester feedstock (q). The operating temperature of the digester was assumed to be constant at 40 °C, with the temperature of the incoming feedstock at 10 °C [53].

$$CHP\ capacity\ (kW_e) = \frac{Biogas\ production\ (m^3)\ x\ [Calorific\ value\ of\ biogas\ (\frac{MJ}{Nm^3}/3.6)}{Operational\ full\ load\ \left(\frac{h}{yr}\right)} x\ Electrical\ efficiency\ (\%), \quad (2)$$

$$\text{Total heat requirement for the process} = hl + q, \quad (3)$$

$$hl = U\ A\ \Delta T, \quad (4)$$

where hl is heat loss (kJ s^{-1}); U is the overall coefficient of heat transfer (W m^{-2} K); A is the cross-sectional area through which heat loss occurs (m^2); ΔT is temperature drop across the surface area (°C).

$$q = C\ Q\ \Delta T, \quad (5)$$

where q is the energy required for heating feedstock (kJ s^{-1}); C is the specific heat of the feedstock (kJ kg^{-1} $°C^{-1}$); Q is the volume to be added (m^3); ΔT is the outside and inside temperature difference (°C).

2.5. Final use of Energy Produced

The energy produced in the form of electricity and heat via the CHP unit was used in four main areas. These include: (i) the operation of AD plant; (ii) satisfying the dairy enterprises energy demand; (iii) exported to the national grid (electricity); (iv) exported to district heating system (thermal energy). The energy demand of the farm was calculated by using the energy requirements per litre of milk, as reported in the literature [54]. The average yield of an Irish dairy cow was assumed to be 5000 litres [55]. The thermal energy generated by the CHP unit was understood to displace kerosene, which is the primary heating fuel on Irish farms [54].

The heat produced that exceeds the needs of the plant and the farm has a number of potential local applications, such as drying woodchips, use in the horticulture sector, or in local industry. Another promising option is its use in a district-heating scheme, where heat generated is distributed from a central location through a network of insulated pipes to nearby residential and commercial energy users. Although these systems are not common in Ireland, this study has selected this technology to demonstrate its potential applicability. The study assumed that the thermal energy supplied to the scheme displaces kerosene, which is commonly used to heat residential homes in Ireland [54]. Equation (6) was used to describe the heat transfer capacity of the pipework utilised, with the subsequent heat losses calculated using Crane's methodology [56]. An average distance of 300 m was assumed between the CHP unit and the residential housing for this study.

$$Q = \pi\ r^2\ \text{v}\ \Delta T\ C \quad (6)$$

where Q is heat transfer capacity of pipe (kW); *r* is internal pipe radius (mm); v is the fluid velocity (m^3 s^{-1}); ΔT is temperature difference between the flow and return (°C); C is the specific heat of fluid (kJ kg^{-1} $°C^{-1}$).

2.6 *Environmental Considerations*

As depicted in the system boundary (Figure 1), all energy requirements for the operation of the AD plant were met internally via the CHP engine, where no CO_2 emissions were assumed. Surplus heat was fully used on-site with the understanding that it displaces kerosene, which is a conventional heating fuel on farms in Ireland [54]. According to Upton [57], the energy output from kerosene is 36.4 MJ l^{-1}, with CO_2 related emissions at 0.25 tCO_2 MWh^{-1}. All electricity generated that exceeds the energy demand of the AD plant and farm was exported to the national grid. The subsequent CO_2 savings were calculated based on the average emissions produced by the current energy mix of 0.367 t CO_2 MWh^{-1} [58].

The study accounted for the release of CO_2 in the combustion of biogas, at a rate of 83.6 kg GJ^{-1} [59]. Furthermore, the study included a "do nothing scenario", which incorporated the GHG emission savings in comparison to a no AD plant scenario. This included the emissions released from manure storage and application to land. Calculations follow guidelines from an OECD report, where emissions during storage are based on 20% potential biogas production over a 2-month period. Emissions from land application were calculated based on 10% remaining biogas potential [60]. The emission factor of biogas was calculated to be equivalent to be 11.9 kg CO_2 based on global warming potential (GWP) of 28 for methane [61].

2.7 *Establishment and operating costs*

As a new enterprise, establishment costs have to be accounted for within the model. The capital cost for the AD plant was quantified by compiling the capital costs and associated CHP electrical capacity of several SSAD plants (Figure 3). The data gathered gave an estimation of the average establishment costs for the model. Figure 3 correlates with similar studies [48], seeing a reduction in capital costs as the capacity of the plant increased.

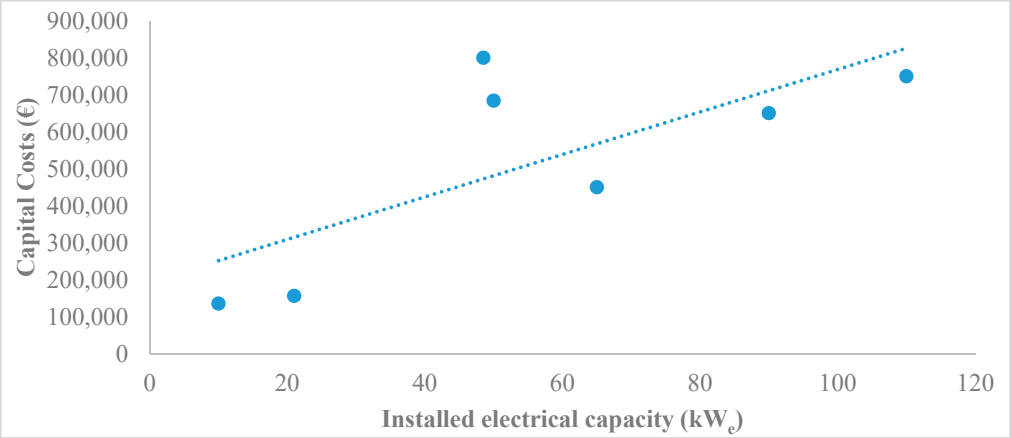

Figure 3. Establishment cost for farm-scale anaerobic digestion plants [62–69].

The published data available on the running of Irish farm-scale AD plants are quite limited, mainly due to the relatively low number of plants in operation [16]. Considering these limitations, this study puts forward a list of annual expenditures to provide an appropriate representation of the Irish context.

- The plants incur an annual maintenance cost of 2.5% of the total capital cost, as reported in the literature [70].
- Insurance costs are typically 1% of total capital costs, which was observed in the model [71].

- The time required to operate the AD plant is a minimum of 8.5 working hours (net) per kW_e capacity installed [67]. The cost of labour for a staff member in this position is estimated to be €15 hr^{-1}, which is considered standard in Ireland for this position [67].

Taxes and interest were not considered in the financial assessment of the plants. Taxes are calculated based upon the company's total profits or loss; therefore, including taxes would not reflect the actual revenue generated by the project. Interest was also not considered, as it would give a distorted representation of the cost of financing, because of its reliance on fluctuations in the financial market.

2.8. Revenue streams and financial indicators

Electricity exported to the national grid is sold according to the Renewable Energy Feed-in Tariff (REFIT), introduced by the Irish Government in May 2010 [72]. These tariffs were offered for a period of 15 years with indexation, including a rate of 15.8 c€ kWh^{-1} for electricity exported from an AD plant with a CHP capacity of less than or equal to 500 kW. The current Irish REFIT schemes have since closed as of December 2015. It is presumed that this support will reopen in the coming years with a new funding round at the same rates for a period of 20 years. Revenue is calculated at the point that exported electricity enters the national grid, with subsequent transmission and distribution losses not considered.

Energy used to satisfy the farm's on-site power demand was based upon Ireland's business electricity rates from July to December 2017 [73]. The farm scenarios considered under this study were compatible with two rates: energy users consuming less than 0.02 GWh yr^{-1}, a purchase rate of 19.9 c€ kWh^{-1} applies; for energy users consuming between 0.02 to 0.5 GWh yr^{-1} a rate of 15.1 c€ kWh^{-1}.

The thermal energy produced via the CHP engine was understood to displace kerosene heating oil as a fuel at a cost of 8 c€ l^{-1} [74]. In addition, the simulated plants take advantage of the "*Support Scheme for Renewable Heat*" launched in mid-2019 [75]. The scheme provides a tariff of 2.95 c€ kWh^{-1} for a period of 15 years for AD plants producing less than 300 MWh yr^{-1} [75]. Accounting for the cost of infrastructure, the revenue generated from the sale of thermal energy via the district heating system was estimated to be €0.03 kWh^{-1}.

The financial indicators used to assess and compare the economic performance of the different plant scenarios included the net present value (NPV), internal rate of return (IRR), simple payback period, and discounted payback period. The NPV gives an indication of whether the project is profitable, taking into account the value of cash flows at different times, as shown in Equation (7). The IRR is a discount rate that makes the NPV of all cash flows equal to zero. The discount rate indicates the risk an investor takes in investing in a project. The higher the risk, the larger the discounted rate expected in compensation. This study used a discount factor of 5% and a project lifespan of 20 years, which is deemed appropriate for an AD project of this scale as reported in the literature [76–78]. The payback period refers to the number of years it takes to generate enough revenues to pay the investment back. The discounted payback period makes the same calculation but includes the time value of money.

$$NPV = \sum_{t=0}^{n} \frac{NCF_t}{(1+r)^t}, \quad (7)$$

where NCF_t is the expected net cash flow, t is time and r is the discount rate.

Government supports through capital subvention grants have proven effective in increasing the deployment of AD plants by significantly lowering establishment costs. Grants of up to 50% have been adopted in countries such as Sweden, France, Wales and England [68]. This study incorporated a government subvention grant of 50% to provide an understanding of its implications.

3. Results

3.1. Technical Results

The technical parameters of the SSAD plants under study are presented in Table 5. These parameters provide an overview of the plant's operation in terms of feedstock used, plant specifications, resulting methane yield and application of energy. The cow manure available increased linearly, as it was directly proportional to the number of livestock on the farm. Interestingly, the farmland available for biogas production increased by just 35.4% between the smallest and largest farm sizes, showing that a larger proportion of farmland is potentially available for biogas production in farms with smaller herd sizes. Consequently, the grass feedstock represented a much larger percentage of total methane production in Scenario 1 (51%) in comparison to Scenario 5 (23%).

All scenarios examined exhibited a net energy generation, which was used to supply external applications, as shown in Figure 4. The farm's energy demand represented a relatively small portion of the total energy generated, ranging from 3.08% to 4.66%. The majority of the energy generated was exported off-site, representing between 73.04% and 79.13% of the total energy generated, demonstrating the need for external applications at the plants' planning stage.

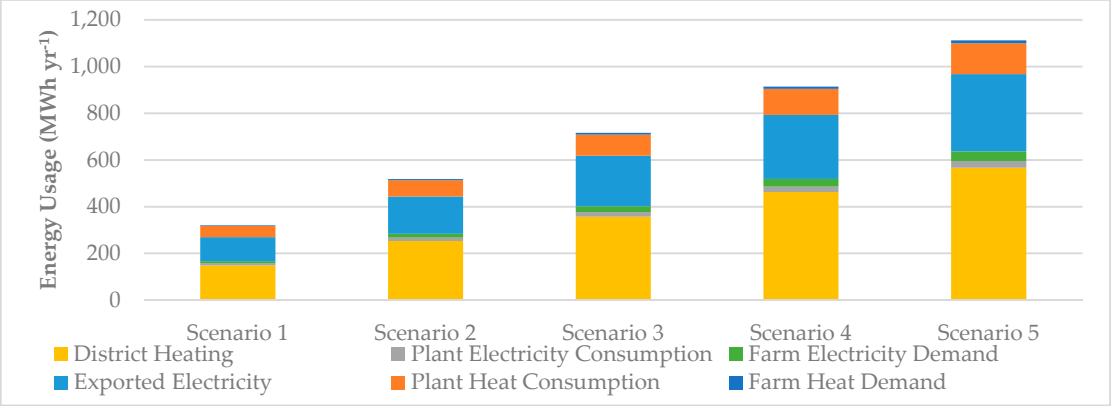

Figure 4. Final electrical and thermal energy usage via the combined heat and power (CHP) unit.

Table 5. Technical characteristics of scenarios under study.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Herd Characteristics					
Herd size (adult cows)	50	100	150	200	250
Cow manure yield (t FW yr^{-1})	505	1010	1515	2020	2,525
Crop Characteristics					
Land available for energy crops (ha)	21.19	24.10	27.00	29.90	32.81
Grass silage yield (t FW yr^{-1})	941	1070	1,199	1,328	1,457
CHP Specifications					
CHP engine power (kW_e)	17	26	39	46	55
Methane Yield					
Methane yield [a] (m^3 yr^{-1})	42,316	66,718	91,120	115,521	139,923
Energy Consumption of AD Plant					
Electricity consumption (kWh yr^{-1})	10,414	14,979	19,544	24,109	28,674
Heat consumption (kWh yr^{-1})	48,225	69,212	90,173	111,117	132,048
Farm Energy Demand					
Electricity demand (kWh yr^{-1})	8125	16,250	24,375	32,500	40,625

Heat demand (kWh yr^{-1})	2458	4915	7373	9830	12,288
Final Use of Excess Energy					
Exported electricity to grid (kWh yr^{-1})	102,697	159,917	217,137	274,357	331,577
Equivalent electricity consumption in residential homes (Irish homes year^{-1}) [a]	24.5	38.1	51.7	65.3	78.9
Exported heat to district heating system (kWh yr^{-1})	148,193	252,918	357,667	462,434	567,215
Equivalent heat consumption in residential homes (homes year^{-1}) [b]	13.5	23.0	32.5	42.0	51.6

[a] Methane yield utilised by the CHP unit annually; [b] Electricity consumption of an average residential house was assumed to be 4200 kWh yr^{-1} [79]; [c] Heat consumption of an average residential house was assumed to be 11,000 kWh yr^{-1} [79].

3.2. Environmental Results

A CO_2 balance that fully assesses the CO_2 inputs and outputs of the scenarios under investigation is presented in Table 6. The methodology undertaken was a "cradle-to-grave" approach to provide an accurate representation of the net CO_2- savings for each of the SSAD scenarios per year.

All scenarios investigated exhibited a net CO_2 reduction, ranging between 2,059–173,237 kg CO_2-eq yr^{-1}. Significant net CO_2 savings were shown for each of the scenarios under investigation, even in the smallest farm size investigated (Scenario 1), with savings of 41,180 kg CO_2-eq. over the lifespan of the plant (equivalent to taking 87 cars off the road). This shows that SSAD can have a meaningful contribution, even at relatively small sizes. The activity which resulted in the largest production of CO_2 emissions was the "Biogas Production Process", where the release of CO_2 in the combustion of biogas contributed approximately 90% to 95% of the total CO_2 emissions released per annum.

Table 6. Annual CO_2 balance for scenarios under study.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Herd size (adult cows)	50	100	150	200	250
CO_2 Produced (kg CO_2-eq. yr^{-1})					
Crop Production					
Soil ploughing and crumbling	264	300	336	372	408
Sowing and maintenance	300	341	382	423	464
Sowing	90	102	114	126	139
Weed control (fuel)	13	15	17	19	21
Weed control (mineral production)	36	41	46	51	56
Fertiliser spreading (fuel)	381	434	486	538	591
Fertiliser (mineral production)	5013	5699	6386	7073	7760
Feedstock Collection and Transport					
Harvest	2665	3030	3395	3760	4125
Harvest transport	1439	1636	1,833	2030	2227
Silo compaction	497	565	633	701	769
Digester feeding (Crops)	1331	1513	1695	1878	2060
Collection and digester feeding (Manure)	92	185	277	370	462
Biogas Production Process					
CO_2 Content	133,652	210,722	287,722	364,863	441,933
Digestate Disposal					

Transport and spreading of digestate	2355	3387	4419	5451	6484
Total CO_2 produced	148,127	227,970	307,813	387,656	467,499
CO_2 reduction (kg CO_2-eq. yr^{-1})					
Do nothing scenario					
Manure storage	51,323	102,646	153,970	205,293	256,616
Manure land application	20,529	41,059	61,588	82,117	102,646
Farm Energy Demand					
On-farm electricity	2982	5964	8946	11,928	14,909
On-farm heating	614	1229	1843	2458	3072
Final Use of Excess Energy					
Electricity exported	37,690	58,689	79,689	100,689	121,689
Heat exported to district heating	37,048	63,229	89,417	115,609	141,804
Total CO_2 reduction	150,187	272,816	395,452	518,093	640,736
Net CO_2 savings (kg CO_2-eq. yr^{-1})	2059	44,846	87,639	130,437	173,237
Equivalent savings in cars displaced (cars per year)[a]	4.36	94.90	185.45	276.01	366.57

[a] Diesel consumption per car is reported to be 1259 litres $yr^{-1,}$ as reported in the literature [80].

3.3. Economic Results

A comprehensive economic analysis was carried out to investigate the revenues, expenditures, and financial indicators of each of the scenarios under investigation over a 20-year life span, as illustrated in Table 7. The results of this analysis showed SSAD plants to be economically feasible and profitable for commercial dairy farms with >100 dairy cows. However, the payback periods of farm sizes between 100 and 200 dairy cows were relatively long, which may dissuade potential investors.

The largest revenue generators were electricity sold to the national grid and thermal energy sold to a nearby district heating system (where available). These two applications should be key considerations in the planning process for any such development considered.

The capital expenditure required decreased significantly as the capacity of the plant increases, primarily due to the economies of scale that occur. In addition to the economic analysis of the scenarios under study, this work also explored the adoption of a capital grant subvention in an attempt to provide a possible political pathway to increase the adoption of SSAD in Ireland. Such subvention has proven successful in countries such as Sweden, France, Wales and England, where capital grants of up to 50% have been applied [5]. As shown in Figure 5 and 6, the addition of a 50% capital subvention grant had a significant impact on the scenarios payback periods, resulting in all scenarios having a discounted payback period of under 17 years, with herd sizes above 100 cows particularly attractive with a payback period of under eight years.

Table 7. Economic results of small-scale anaerobic digestion plants over a 20-year lifespan.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Herd size (adult cows)	50	100	150	200	250
Project Revenues (€)					
On-site electricity savings	€32,338	€64,675	€73,613	€98,150	€122,688
On-site heating savings	€3,932	€7,864	€11,796	€15,728	€19,660
Sale of exported electricity	€323,727	€504,099	€684,472	€864,844	€1,045,216
Sale of exported heat to district heating	€88,916	€151,751	€214,600	€277,461	€340,329
Support Scheme for Renewable Heat	€66,663	€114,091	€161,530	€208,977	€256,430
Total Revenues	€515,576	€842,480	€1,146,000	€1,465,159	€1,784,322
Project Expenditures (€)					

Investment Costs					
Capital Costs Inc. CHP	€290,099	€345,479	€400,860	€456,241	€511,622
Operating Costs					
Maintenance and Repair Costs incl. CHP	€145,049	€172,740	€200,430	€228,121	€255,811
Insurance	€87,030	€103,644	€120,258	€136,872	€153,487
Labour	€42,625	€67,204	€91,784	€116,363	€140,943
Total Operating Costs	€274,704	€343,588	€412,472	€481,356	€550,241
Financial Indicators					
Profit before tax (€)	€240,872	€498,892	€733,538	€983,803	€1,234,082
NPV at 5% (€)	-€135,418	-€26,758	€67,339	€171,168	€275,006
IRR (%)	-2%	4%	7%	9%	11%
Payback period (Years)	25.65	12.87	10.18	8.66	7.75
Discounted payback period (Years)	N/A	24.02	14.56	11.64	10.05
Payback period Incl. capital grant (Years)	11.03	6.43	5.09	4.33	3.88
Discounted payback period Incl. capital grant (Years)	16.34	7.96	6.02	5.00	4.42

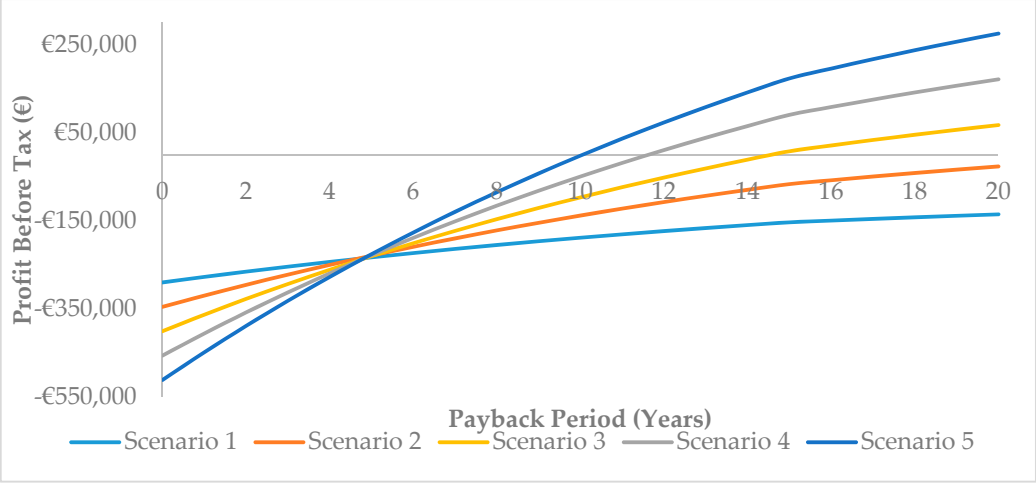

Figure 5. Comparison of discounted payback periods of scenarios.

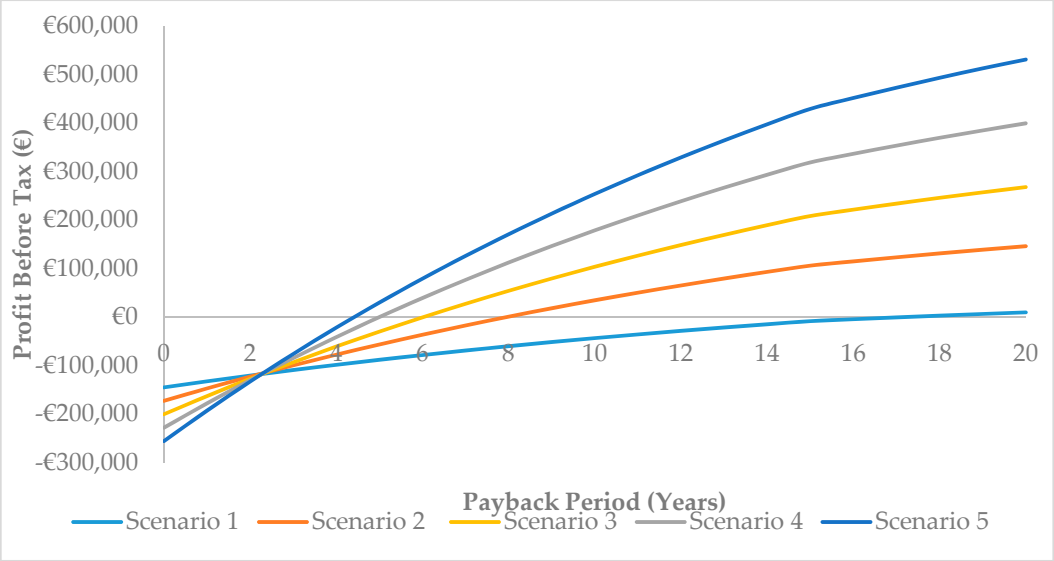

Figure 6. Comparison of discounted payback periods of scenarios (including 50% capital subvention grant).

4. Discussion

4.1. Financial Significance

The scenarios explored in this work showed SSAD plants to be economically feasible and profitable for dairy farms with >100 dairy cows. However, due to the study's boundaries, some costs were not considered, such as grid connection, civil works, etc. Such considerations are deemed important for the overall viability and future implementation of SSADs in practice and should be further investigated.

The need for further government supports and financial incentives is still apparent, where the relatively long payback periods projected may dissuade investors. Incentives available in Ireland, such as the REFIT scheme, have had a significant economic influence in reducing payback periods. Although the scheme provided only two tariffs, at a rate of 15.8 c€ kWh^{-1} for plants with a CHP capacity up to 500 kW and 13.7 c€ kWh^{-1} for plants exceeding this capacity [72]. Consequently, this puts smaller capacity plants at a disadvantage, as they have higher costs due to economies of scale. Comparing Irish rates to other EU countries, Germany provides a rate of 23.73 c€ kWh^{-1} to plants with a total installed capacity of less than 75 kW_e. Likewise, the United Kingdom provides a tariff of 4.50 p£ kWh^{-1} to plants with a capacity of less than 250 kW. The issue reappears with the recently introduced *Support Scheme for Renewable Heat*, which provides a single tariff of 2.95 c€ kWh^{-1} to all plants generating less than 1000 MWh yr^{-1} [75]. To maximise the potential deployment of SSAD plants, government support schemes need to recognise the additional costs associated with smaller capacity plants and, therefore, implement policy that counteracts such expenditures.

Based on the literature and the findings of this study, the cost of finance has been the overriding barrier in the deployment of SSAD plants across Europe [11,63,81]. Issues cited include investors being uneasy with the technology due to limited case studies, the relative newness of the technology, and a lack of expertise within financial institutions to assess such plants. A potential government support explored in this study was the adoption of a capital grant subvention. Such legislation has proven successful in countries such as Sweden, France, Wales and England, where capital grants of up to 50% have been applied [68]. As shown in Table 7, the addition of a 50% capital grant subvention reduced the payback period by 3.88 years to 14.62 years, providing a possible pathway for the Irish government to support the deployment of SSAD.

Over the next few years, it is anticipated that the capital and operational costs of such plants will reduce dramatically. This is based on the most recent technological advancements, where a growing

emphasis on smaller capacity plants has led to cost reductions, primarily through the development of modular systems and plug and play design. Several companies are in the testing phase or have fully commercialised such systems in the European market place, with a wide variety of technologies at various sizes now in development [82–87].

4.2. Environmental Outlook

From an environmental perspective, all scenarios examined exhibited a net CO_2 reduction ranging between 2 and 173 tonnes CO_2-eq. per year (Table 6). If the widespread deployment of SSAD were to occur in Ireland, a CO_2 reduction of at least 211,349 tonnes could be achieved if 20% of all farms with >250 dairy cows (61 farm holdings) were to implement the technology [27]. Ireland's expected failure to meet its EU 2020 commitments will put further pressure on the state to undertake a climate action policy, due to the compensation (in the form of carbon credits) it will be forced to pay [88]. In addition, the state has also committed itself to at least a 40% reduction in GHG emissions by 2030, resulting in a need for long-term climate action policy [89].

4.3. Comparison to Other Studies

Although this study reports on a specific case study, the results are relevant worldwide, especially those with significant livestock and agricultural productivities. In the literature, some studies have investigated the economics of implementing AD plants on small- to medium-sized farms in various countries and regions [68,90,91,92,93]. The overriding theme has been that the financial viability of a plant often needs to be assessed on a case-by-case bases as it is often highly dependent on local conditions, such as cost of energy, feedstock type and availability, and government incentives. Therefore, careful consideration of such variables needs to be taken at the project planning stages.

SSAD has increasingly become a topic of interest for researchers, mainly driven by the growing emphasis to reduce the negative environmental impact of agriculture waste streams and increasing investment in renewable energy production. Research trends in the topic have included the optimisation of plant design and operations [94–96], feedstock pre-treatments [96–98], the impact of trace compounds [99–101], and biogas cleaning technologies, and its integration to afford further energy generation [102–104]. Further research could expand the potential integration of these technologies with small-scale AD systems, and make its implementation more likely.

4.3. Irelands Future Outlook

Irelands national herd size has grown significantly in the past five years from 1,082,500 dairy cows in 2013 to 1,369,100 in 2018 (+21%) [20,105]. Much of the recent growth has stemmed from the removal of the European-wide milk production quotas in 2015, which saw milk output increase by 8% and 9% in 2016 and 2017, respectively [106]. Growing herd sizes allows SSAD plants to become more feasible because of economies of scale, as shown in Table 7.

The sector is projected to grow further due to Teagasc (the government's semi-state advisory authority) targeting a national herd increase of 19% by 2025 in comparison to 2018 [20,107]. When considering these targets, it is anticipated that the average national farm herd will exceed 100 dairy cows by 2025. The argument for the applicability of SSAD continues to deepen not only for the potential economic benefits but also for its capacity to mitigate GHG emissions.

5. Conclusions

Over the coming years, it is anticipated that the Irish government will come under increased pressure to enact measures to mitigate the negative environmental impact of the agricultural sector. This will be further heightened by the targeted growth of the dairy sector, increasing to 1.7 million dairy cows by 2025, with the average herd size growing to over 100 cows [107]. Of the renewable energy technologies available, SSAD is particularly promising for both the reduction of GHG emissions and the economic value in the form of on-site energy generation. This study uses a non-

linear model to determine the technical, environmental, and economic viability of SSAD on Irish dairy farms ranging from 50 to 250 dairy cows. The study found the technology to be profitable within the lifespan of the plant on farms with dairy herds exceeding 100 cows (payback periods of 12.87 to 7.75 years). In addition, all scenarios with dairy herds sizes >100 cows showed a net CO_2 reduction ranging between 2059 and 173,237 kg CO_2-eq. yr^{-1}.

Although SSAD plants were shown to be viable, significant government supports are still needed to achieve financial returns that are attractive to investors. One support explored in this study was the inclusion of a capital subvention grant at rates similar to schemes in other EU countries. Incorporating the result had a significant economic impact, reducing payback periods by 3.88 years to 14.62 years. Furthermore, there is a need for the reintroduction of an electricity feed-in tariff applicable to SSAD plants. Without such a mechanism, the size of plants is limited to the electrical demand of local applications, significantly limiting expansion and financial returns. Both measures provide potential pathways for the government to support and accelerate a domestic biogas industry.

For future research, we suggest the analysis of the seasonal feedstock supply, parasitic energy consumption and net energy production variabilities experienced by farm-scale AD plants. Such seasonal variabilities can negatively affect the sustained operability and economic viability of plants as they often have contractual obligations to provide a consistent energy output year-round with minimum variations in the quantities and quality of energy produced. In addition, a greater understanding of Irish farmer's perception of AD is needed. Key information essential to the long-term success of AD in Ireland is still lacking in the literature, such as characteristics of potential adaptors, uptake rates, and perceived barriers.

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