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Decision support tool for the construction and seasonal operation of farm-scale anaerobic digestion plants

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ABSTRACT

Optimal plant design and management are critical components for the successful operation of farm-scale anaerobic digestion (AD) plants. However, this often proves challenging due to difficulties in designing and sizing the plant based on specific site conditions. The current investigation aims to address these difficulties by developing a universal decision support tool to assist in the optimal design and management of agriculture-based AD plants, accounting for site-specific practicalities and implications. The tool consists of various mathematical functions, which enable numerous simulations to be created and run. The developed tool was applied to a case study, located in Ireland, to test its usefulness, where the analysis showed the optimal, site-specific, plant design with key assessment indicators. For this case study, the feedstock availability assessment determined that the lignocellulose and non-lignocellulose biomass within a 10 km distance of the site. Based on the local energy demand of the area, the tool modelled an optimal AD plant design, including feedstock storage, digester volume, engine capacity, and digestate storage. The tool applied various technical, economic, and ecological assessment indicators to the plant to gauge its viability. Therefore, demonstrating the tool's usefulness in assisting stakeholders to make informed decisions and reducing costs by optimising plant design and performance.

1. Introduction

Farm-scale anaerobic digestion (AD) is an attractive technology for the mitigation of greenhouse gas emissions, and the production of renewable energy, especially in the agriculture and food sectors. However, considerable challenges exist in the widespread adoption of the technology, partially stemming from the design and seasonal operation of potential (or existing) AD plants. These difficulties can be exasperated in countries with immature and inexperienced bioenergy industries, where failures to adequately assess, design, and operate such plants can result in higher capital and operating costs. Moreover, operational difficulties are often exasperated by wide variations in operators' skill and ability; occasionally leading to feedstock overloading or the use of a conservative feeding strategy; resulting in a loss or significant reductions of potential methane yields [1].

A considerable amount of research has been undertaken to mitigate such issues, mainly through the development of methodologies and/or the use of computer-based tools, which increase the reliability and applicability of the information available to plant operators [2–4]. Such techniques have traditionally included the systematic analysis and planning of biomass resources, as well as the assessment of subsequent technical and economic implications at a regional level. Most of these tools apply geographical information systems (GIS) based approaches for mapping the distribution of biomass potential [5–7], assessing optimal plant locations [8], as well as evaluating various economic and environmental criteria [9,10]. However, a significant number of these studies only provide a partial site evaluation with limited attention paid to developing a full assessment framework.

This study contributes to the current literature through the development of a universal decision support tool for the design and seasonal management of farm-scale AD plants, accounting for site-specific practicalities and implications. The analysis applied builds on the assessment criteria performed in other studies such as feedstock supply [11], storage capacity [12], energy generation [13], economic viability [14], and environmental implications [11]. However, this study distinguishes itself from the related body of knowledge by developing a complete methodology for the assessment of AD plants that accounts for

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Nomenclature

A	Cross-sectional area through which heat loss occurs (m^2)
B	Biogas production (m^3/year)
C	Heat capacity of feedstock (kJ/kg.°C)
$CapEx_{BC}$	The capital expenditure for biogas cleaning (€/unit)
$CapEx_{CHP}$	$CapEx_{Dig}$ The capital expenditure for the CHP unit (€/unit)
CHP_{cap}	The capital expenditure for the anaerobic digester (€/digester)
Cpf	CHP capacity (kWel)
DMcs	Specific heat of fluid (kJ/kg.°C)
DMm	Dry matter of co-substrates (%)
Ds	Dry matter of animal manure and slurry (%)
E_{GE}	Design margin of safety (%)
EP_o	The size of gas engine (kW)
E_t	Electrical power output (kW_{el})
F_t	Net electricity production in year t(MWh)
M_{FD}	Biomass fuel expenditure in year t(€)
H_D	Total flow of digestate (tonnes/month)
h_l	Head space of digester (%)
HV_b	Heat loss (kW)
I_t	Lower calorific value for biogas (MJ/Nm^3)
LCOE	The total investment costs in year t(€)
MAC	Levelised unit cost of energy (€/MWh)
Mfst	Marginal abatement cost (€/tCO2)
mf	Total feedstock (tonnes/month)
M_t	Mass flow rate of feedstock (kg/s)
Mvs	Operation and maintenance costs in year t(€) Total volatile solids consumed in reactions
Mwt	(tonnes/month) Total water consumed in reactions (tonnes/month)
NCFt	Expected net cash flow at time t and r (€)
NPV	total revenues and total cost over the lifetime of the power plant (€) Project lifespan (years)
t	Difference between the present values of the
n	Energy required for heating feedstock (kW)
q	The volume to be added (m^3)
Q	Heat transfer capacity of pipe (kW)
QP	Total heat requirement for the process (kW)
Qr	Discounted rate
r	The average periodic rate at which the enterprise
rp	can borrow from time 0 to n Volumetric flow of substrate (m3/year)
S	Total biomass fed to digester (tonnes/year)
S_{cs}	Quantity of animal feedstock available
S_m	(tonnes/year)
TER	Total GHG emission reduction over the lifetime of the power plant (tCO_2)
tr	Retention time (days)
t_y	Operational full load (hours/year)
U	Overall heat transfer coefficient (W/m2.K)
v	Fluid velocity (m/s)
VD	Digester volume (m3)
ΔT	Inside/Outside Temperature difference (°C or K)
ΔT_w	Temperature difference across the surface area (°C ρf or K)
η_{el}	Fluid density (kg/m3)
η_{th}	Electrical Efficiency (%) Heat Efficiency (%)

site-specific practicalities and implications.

To identify the tool's applicability, it was applied to a case study in Sligo, Ireland, which has the added benefit of potentially addressing regional issues resulting from limited experience and knowledge of AD [15]. To provide this comprehensive assessment, the following were considered: feedstock seasonal availability; storage capacity requirements; plant sizing and energy generation capacity; economic feasibility; and environmental implications. The successful application of this decision support tool, as put forward in this paper, would allow inexperienced decision-makers to evaluate the viability of AD for a specific site. This would result in several benefits, such as (i) an initial appraisal of technology and land requirements associated with the operation of AD systems, (ii) safeguarding a reliable biomass supply chain while minimising the quantity of biomass feedstock required, (iii) reducing often-costly storage capacity by minimising the lag between supply and demand.

2. Materials and methods

2.1. Case study

The output of this work consists of an open-sourced decision support tool that includes all the parameters discussed in the methodology section. This tool is available for download from the attached appendix. In order to demonstrate that the tool is useful and functions it was applied to a case study with the results highlighted in the remainder of this paper. The selected case study was the IDA Oakfield Park development, situated in Sligo, Ireland. The site is located in a mostly rural agricultural setting with an existing energy demand from a nearby industrial park under development.

In order to evaluate the spatial distribution and seasonal availability of the biomass, a combination of statistical and spatial methods was utilised. To determine the spatial distribution of lignocellulosic biomass, a geographic information system (GIS) based analysis was carried out using ArcGIS Pro Patch 2 (2.7.2). This software was used with a georeferenced database whose layers indicated agriculture land use across Ireland by crop type; sourced by request from the Irish Department of Agriculture. The biomass collection boundary of the site was based on the maximum transport distance in which anaerobic feedstock can be economically moved. This can vary significantly as it is heavily dependent on the energy density of the biomass. Typically, it's economically viable to transport liquid manures 10 km, while feedstock's with a greater DM can be moved up to 40 km [16,17]. Since the proposed decision support tool is simulating a CSTR digester operating primarily on liquid manures, a biomass collection radius of 10 km was used. Once the plant location and collection boundary was identified, a GIS model was developed to identify the cropland available within the collection area. Since data detailing the location, number and farm types within the collection boundary of the site were not available, these assumptions were instead based upon the livestock herd within the county of Sligo, Ireland.

A key aspect of the model was to enable the user to run scenarios that were specific and practical to their proposed plant conditions. The following estimates and assumptions were made to ensure the simulation was realistic for the site selected:

- The plant's digester and CHP unit were sized to meet the local thermal energy demand of a nearby industry park, estimated to be 7611 MWh_{th}/year. The revenue received for this energy was estimated to be 2.0 c€ kWh^{-1}, which is in line with similar case studies [14].
- The heat losses received while transferring the heat to a local user were estimated using Crane's methodology [18], with the heat transfer capacity of the pipework presented in Equation (1).
- It was assumed that all surplus electricity generated was exported to the national grid, receiving a feed-in tariff of 15.8 c€ kWh^{-1} [14].

$$Q = \pi r^2 \text{ v } \Delta T \text{ C} \quad (1)$$

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}).

One of the user inputs for the tool is the type and quantity of cropland (hectares) that can be devoted to energy crop production. In order to achieve this a georeferenced map was generated of the spatial distribution of crop biomass within the catchment area. In this GIS analysis, fifteen of the most common crop types were considered. These classifications included the following: spring oats, spring wheat, sugar beet, triticale, winter barley, winter oats, winter wheat, bog, fallow, grass, linseed, maize, potatoes, spring barley and others. The results found the following crop types in the study area: grass (22,532 ha), potatoes (11.43 ha), barley (3.58 ha), bog (10.56 ha) and unclassified other crops (13.8 ha). This clearly shows grass to be the dominant crop in terms of land cover within the catchment area. Based on these figures, it was assumed that grass silage would be the only lignocellulosic biomass the plant would operate on, due to its abundance.

After an extensive search, it was found that data detailing farm locations and equivalent livestock numbers were not freely available. Therefore, the quantity of livestock within the catchment area was estimated using a percentage of the total livestock within the county. This percentage was determined by comparing the land cover of the catchment area (314 km^2) to the total land cover within the county (1838 km^2) [19].

2.2. Description of the decision support tool

The tool uses a model to evaluate the plant's operational practicalities, as well as both environmental and economic implications. All simulations were created and run using the software package Microsoft Office Excel (Microsoft Office 2016, Microsoft Corporation, Redmond, WA, USA).

The tool comprises of mathematical functions that enable the creation and execution of numerous biogas plant simulations. These simulations can be used to assess biogas projects using various indicators *e.g.*, net present value (NPV), levelised unit cost of energy (LCOE), and marginal abatement cost (MAC). Fig. 1 presents the tool's system boundary, encompassing the data inputs, analysis, and data outputs. The system boundaries covered are divided into four main elements: (i) feedstock availability and capture, (ii) biogas production, (iii) energy production, and (iv) digestate handling. The main user inputs for the tool include the livestock herd (number of animals), type and quantity of cropland available (hectares), and expected revenue (or savings) achieved per unit of electricity and heat sold (or utilised).

2.3. Feedstock availability & capture

The proposed decision support tool evaluates the seasonal availability of the feedstocks to be transformed into energy and the subsequent monthly storage requirements. The lignocellulose and non-lignocellulose biomass considered in the tool represent the location where the authors deemed the tool to be most applicable. The Republic of Ireland was selected as it has an immature bioenergy industry [20]. The typical crops in the region and equivalent cultivation times are illustrated in Fig. 2, with the corresponding crop yields and purchase costs presented in Supplementary Material Table 1. Crop residues represent the materials remaining on cultivated land after the crop has been harvested.

The non-lignoclellulosic biomass considered in the proposed tool was selected based upon their predominance in the considered region and its accessibility, namely animal products (cattle manure, pig manure, and poultry manure). The quantity of biomass available as anaerobic feedstock from livestock sources was based upon the total manure theoretically produced and the potential capture rates during the grazing and non-grazing period (Supplementary Material Table 1). The grazing period was used to gauge the seasonal availability of the manure sources considered. All manure produced outside of the grazing period was deemed to be accessible as an anaerobic feedstock. A capture rate of 20% was assumed for manure produced during the grazing period [14]. It was assumed that no fee was charged for the use of manure feedstock, as the farmer would receive in return nutrient-rich digestate. The seasonal storage requirements for lignocellulose and non-lignocellulose biomass were determined using the AD feedstock consumed by the plant's digester and the individual biomass volume derived from its density.

2.4. AD plant sizing & design

The proposed decision support tool uses user inputs and assumed constants to simulate the operation of an AD plant. The resulting outputs include information on plant size, biogas production, parasitic energy demand, energy generation, and digestate output. The plant modelled comprised of a continuous stirred-tank reactor (CSTR) and used a combined heat and power (CHP) unit for the combustion of all biogas. As

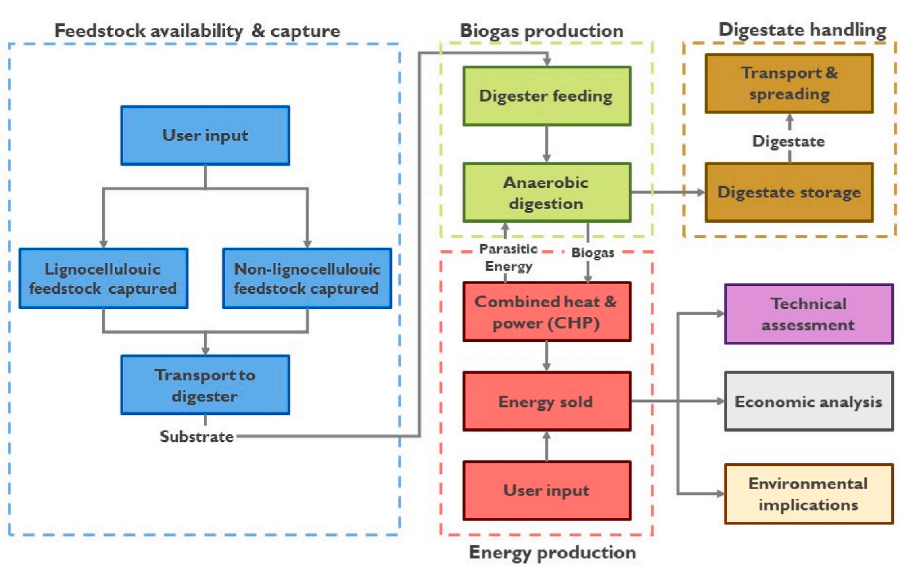

Fig. 1. System boundary of the decision support tool.

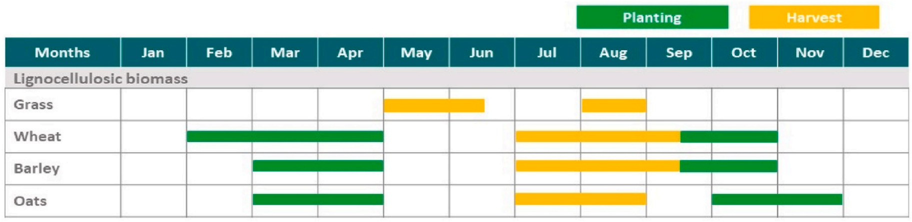

Fig. 2. Seasonal sowing and harvest of crops in Ireland [21].

lignocellulose biomass substrate typically has a significantly higher DM content, the tool limited the amount added to the digester to a band of 7% and 12% [22]. Equation (2) was used to determine the total amount of biomass that can be fed to the digester annually [17]. It was assumed that the plant operated under upper mesophilic conditions at 40 °C with a 30-day hydraulic retention time and an annual operating time of 7000 h (80% of the year) [23–25]. Based on these set parameters, it was possible to determine the plant's optimum size using Equation (3) [26].

$$\sum S_{cs} = \frac{0.15 \times S_m - DM_m \times S_m}{\sum DM_{cs} - 0.15} \tag{2}$$

where S_{cs} is the total biomass fed to digester (tonnes/year); S_m is the quantity of animal feedstock available (tonnes year^{-1}); DM_m is the fraction of dry matter of animal manure (%); S_m is the quantity of animal feedstock average (tonnes year^{-1}); DM_{cs} is dry matter of co-substrates (%).

$$V_D = S \times \frac{t_r}{365 \times H_D \times D_s} \tag{3}$$

where S is volumetric flow of substrate (m^3 year^{-1}); tr is retention time (days); H_D is head space of digester (%); D_s is design margin of safety (%).

Feedstock characteristics and standard methane yields were sourced from the literature and incorporated into the model (as shown in Table 1). This more conservative approach was used to widen the practicality of the tool.

The parasitic energy demand of farm-scale AD plants can vary significantly, as they are dependent on a range of factors including site ambient temperature, plant size, hydraulic retention time, and substrate temperature. The tool estimates the electrical consumption of the plant to be 7.2 kWh t^{-1} [40], which assumes electricity consumption to be driven primarily by the pumping and stirring of the feedstock. The total

Table 1
Physical and chemical properties of biomass under study.

	Dry Solids (g kg^{-1})[aa]	Volatile Solids (g kg^{-1})[b]	VS DS^{-1} (%)[a b]	Methane Yield (m^3 kg VS)	Density (kg/m^3)
Cow Manure	87.5 ± 2.1 [27]	66.9 ± 1.8 [27]	76.5 [27]	0.350 [28]	1027.68
Pig manure	48.6 [29]	62.90 [30]	73.9 [30]	0.320 [28]	1040 [31]
Poultry manure	850 [32]	60.0 [30]	90.9 [30]	0.345 [33]	450 [34]
Grass Silage	292.7 [27]	87.5 [27]	91.7 [27]	0.319 [35]	750
Barley	919 [36]	743 [36]	80.8 [36]	0.337 [35]	630
Wheat	950 [37]	790 [37]	83.2 [38]	0.304 [35]	820
Oats	908 [36]	807 [36]	88.8 [36]	0.271 [35]	580
Potato waste	123 [39]	106 [39]	86.5 [39]	0.344 [35]	675

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

parasitic thermal energy demand is presented in Equation (4); comprising of heat losses to the atmosphere Equation (5) and the heat demand to maintain the digester at the desired temperature Equation (6). The parasitic heat losses were tailored to match Irish weather conditions. The average temperature of the feedstock fed to the digester was assumed to be 10 °C with the ambient temperature adjusted by month, as shown in Supplementary Material Table 2 [41]. In order to estimate the plant's heat transfer coefficients, the specifications of the construction material used were assumed. These characteristics included the following: 300 mm concrete floor in contact with the earth at 1.7 W m$^{2\circ}$C; 6 mm steel plate "sandwich" with 100 mm insulation at 0.35 W m$^{2\circ}$C; floating cover at 1.0 W m$^{2\circ}$C [42].

$$Q_r = h_l + q \tag{4}$$

where Qr is the total heat requirement for the process (kW); h_l is heat loss (kW); q is the energy required for heating feedstock (kW).

$$h_l = U \times A \times \Delta T_w \tag{5}$$

where h_l is heat loss (kW); U is the overall heat transfer coefficient (W/m^2.K); A is the cross-sectional area through which heat loss occurs (m^2); ΔT_W is the temperature difference across the surface area (°C or K).

$$q = C\, Q\, \Delta T \tag{6}$$

where q is energy required for heating feedstock (kW); C is heat capacity of feedstock (kJ/kg.°C); Q is the volume to be added (m^3); ΔT is the temperature drop across the surface area (°C).

Digestate production within the decision support tool was determined using the theoretical evaluation in Equation (7). As the digestate produced is partly derived from manure, it cannot be applied to land during the winter months, in accordance with the EU Nitrates Directive. In Ireland, slurry cannot be applied to fields from the 15th of October to the 12th/15th/31st of January (depending on the farm's location within the country) [43]. The tool was adjusted to match these country-specific restrictions. Based on these conditions, the tool estimated the digestate storage requirements for the plant.

$$M_{FD} = M_{fst} - M_{VS} - M_{Wt} \tag{7}$$

where M_{FD} is the total flow of digestate (tonnes/month); M_{fst} is the total feedstock (tonnes/month); M_{vs} is the total volatile solids consumed in reactions (tonnes/month); M_{wt} is the total volatile solids consumed in reactions (tonnes/month).

Selecting an appropriate biogas utilisation method can often be challenging for AD plant operators, as it typically depends on local circumstances and the country's/region's political and economic framework. The technology chosen often determines the economic viability of the plant making it a key decision. Of the technologies available, a CHP unit was selected to be incorporated into the tool, as it could be considered the most appropriate option for energy generation in farm-scale AD plants [44]. The tool used Equation (8) to estimate the appropriate size of the CHP unit [26], with its corresponding efficiencies determined through the use of Equation (9) and Equation (10) [17]. In the tool, the energy produced is first used to satisfy the plant's parasitic energy demand with all surplus energy available for export at the developer's discretion. The tool allows the user to input the amount of energy eventually utilised and the revenue gained per unit of electricity and heat exported.

$$CHP_{cap} = \frac{B \times \left(\frac{HV_b}{3.6}\right)}{t_y} \times \eta_{el} \tag{8}$$

where CHP_{cap} is CHP capacity (kW_{el}); B is biogas production (m^3/year); HV_b is lower calorific value for biogas (MJ/Nm^3); t_y is operational full load (hours/year); η_{el} is electrical efficiency (%).

$$\eta_{el} = 19,02 \times (EP_o)^{0,10} \tag{9}$$

where η_{el} is electrical efficiency (%) and EP_o is electrical power output (kW_{el}).

$$\eta_{th} = 50,998 \times \exp(0,0002 \times EP_o) \tag{10}$$

where η_{th} is heat efficiency (%) and EP_o is electrical power output (kW_{el}).

2.5. Economic analysis

The decision support tool was also developed to provide insights into the economic viability of the AD plant being examined by the user; covering establishment costs, operating expenditures, potential revenue, and analysis through economic indicators. This provides a comprehensive overview of the economic practicalities of establishing and operating the plant. Estimating the capital costs of an AD plant can be challenging, as expenditures are often dependent on multiple factors, resulting in significant variations. To overcome this difficulty, the tool estimated the capital expenditure of the plant's digester, CHP unit, and biogas scrubbing system using power regression of best-fit data, which were derived from the literature [17,45]. The mathematical equations used for these specific investment costs are described in Equations (11, 12 and 13). Costs associated with engineering and planning costs for the installation were estimated to be 15% of the total capital costs, as reported in the literature [26]. The construction costs incurred due to feedstock storage were also accounted for in the model, at €10/m^2 for lignocellulosic biomass (height of storage assumed to be 3.0 m) and €40/m^3 for non-lignocellulosic biomass [46].

$$CapEx_{Dig} = \left[14239 \times \left(\frac{B}{7000}\right)^{-0,2209}\right] \times \left(\frac{B}{7000}\right) \tag{11}$$

where $CapEx_{Dig}$ is the capital expenditure for the anaerobic digester (€/digester) and B is biogas production (m^3/year).

$$CapEx_{CHP} = \left[3814,8 \times (E_{GE})^{-0,2916}\right] \times EP_o \tag{12}$$

where CHP_{cap} is CHP capacity (kW_{el}); E_{GE} is the size of the gas engine; EP_o is electrical power output (kW_{el}).

$$CapEx_{BC} = \left[56297 \times \ln\left(\frac{B}{7000}\right)\right] - 197310 \tag{13}$$

where $CapEx_{BC}$ is the capital expenditure for biogas cleaning (€/unit) and B is biogas production (m^3/year).

Obtaining information on operating expenditures of farm-scale AD plants proved challenging, due to the limited published case studies and the likely reluctance of developers/operators to disclose such costs [47]. However, after a comprehensive literature review, relevant data was gathered and integrated into the decision support tool, comprising all the major operating expenditures. The study has put forward the following expenditure estimates based on the literature findings:

- Maintenance and replacement expenditures were assumed to be 2.5% of the total capital cost per annum, as reported in relevant studies [48].
- The labour costs involved were estimated based on (i) the time required to operate the plant, which was assumed to be 8.5 working hours (net) per kW_{el} capacity installed, and (ii) an average salary of €25 h^{-1} for a staff member holding that position [49].
- Insurances costs were accounted for in the tool and were assumed to be 1% of the total capital expenditure [50].
- The estimated energy input to transfer the feedstock to the AD plant was estimated to be 1.1MJ/tonne km for lignocellulosic biomass and 1.6 MJ/tonne km for non-lignocellulosic biomass [40]. The energy required to transfer digestate for application was estimated to be 1.1MJ/tonne km [40]. Finally, the fuel cost during harvest and feedstock/digestate transportation is based on the purchase of white diesel at €1.31/litre [51].

Revenue received from the sale of energy (electricity and heat) can be easily adjusted by the user, allowing the tool to be tailored to individual circumstances. Several economic indicators were integrated into the tool to allow the user to adequately assess the economic viability of the proposed plant. These included the simple payback period, discounted payback period, internal rate of return (IRR), and NPV described in Equation (14). Taxes and interest were excluded from the tool's economic analysis as they are heavily dependent on the specific region/country. Moreover, the plant was further evaluated through the use of LCOE (Equation (15)). This economic indicator was used to gain an understanding of the viability of supplying electricity to the national grid.

$$NPV = \sum_{t=0}^{n} \frac{NCF_t}{(1+r)^t} \tag{14}$$

where NPV is the difference between the present values of the total revenues and total cost over the lifetime of the power plant (€) and NCF_t is the expected net cash flow at time t and r (€).

$$LCOE = \frac{\sum_{i=0}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{i=0}^{n} \frac{E_t}{(1+r)^t}} \tag{15}$$

where I_t is the total investment costs in year t(€); M_t is the operation and maintenance costs in year t(€); F_t is the biomass fuel expenditure in year t(€); E_t is the net electricity production in year t(MWh); r is the discounted rate; and n is the project lifetime (year).

2.6. GHG balance

The tool not only simulates the technical and economic practicalities but also considers the environmental implications. In order to achieve this, the tool considers the energy inputs and subsequent CO_2-eq outputs in operating an AD plant, including the cultivation process, transportation, digester feeding, and digestate disposal. All digestate produced was applied to agricultural land as fertiliser. The tool did not assess the processes related to the construction and disposal of the simulated AD plant, as the manufacturing methods were unclear. Additionally, methane leakage from the biogas plant was also considered, where 1.7% methane losses relative to methane production was assumed [52].

In terms of lignocellulosic biomass, energy inputs were accounted for in the cultivation, harvesting, recovery, and digester feeding processes, as presented in Table 2 and Supplementary Material Table 3. Energy inputs in terms of fuel were accounted for during the collection and transportation of feedstock/digestate. The tool also considers the greenhouse gas (GHG) emission savings in comparison to a "do nothing scenario", thus accounting for the emissions released during manure

Table 2
Energy consumption in farm activities.

Operation	Diesel Fuel Consumption ($l\ ha^{-1}\ y^{-1}$)			
	Grass Silage	Barley	Wheat	Oats
Crop production				
Soil ploughing	4.67 [55]	4.82 [55]	4.82 [55]	4.82 [55]
Seeding	5.31 [55]	18.65 [56]	9.78 [56]	27.8 [57]
Sowing	1.59 [55]	8.4 [58]	8.4 [58]	8.4 [58]
Weed control	0.24 [55]	1.6 [56]	0.2 [56]	3.27 [57]
Transport and spreading of fertiliser	18 [55]	18 [56]	18 [56]	18 [56]
Crop collection and transport				
Harvest	47.20 [55]	35.44 [56]	23.30 [56]	19.62 [57]
Harvest transport	25.49 [55]	9.44 [56]	3.24 [56]	3.24 [56]
Silo compaction	8.80 [55]	N/A	N/A	N/A
Digester feeding (Crops)	23.57 [55]	23.57 [55]	23.57 [55]	23.57 [55]

storage and application to land. Estimates for the release of GHG emissions during the storage of manure were assumed to be equivalent to the release of 20% of potential biogas over a two-month period, as reported in the literature [53]. Similarly, the emissions released when applying manure to land were estimated based on 10% of the remaining biogas potential [53]. The emission factor of biogas was calculated based on the global warming potential of methane, which was equivalent to 11.9 kg CO_2 [54].

The decision support tool assumed that no emissions were produced to meet the parasitic energy demand of the AD plant, as all energy needs were met internally via the CHP engine. The release of CO_2 from the combustion of biogas was accounted for within the simulation, at a rate of 83.6 kg GJ^{-1} [59]. As previously discussed, all electricity generated that exceeded the parasitic energy demand of the plant was exported to the national grid, where the emission savings were based on the energy mix at a rate of 0.367 t CO_2 MWh^{-1} [60]. It was assumed that the excess heat produced was used to displace kerosene. The energy and CO_2 outputs of kerosene were estimated to be 36.4 MJ l^{-1} and 0.25 tCO_2 MWh^{-1} [61,62]. The tool also included the marginal abatement cost (MAC) to measure the cost involved in reducing GHG emissions in the simulation as shown in Equation (16) [2].

$$MAC = \frac{(-1)NPV}{TER} \tag{16}$$

where MAC is marginal abatement cost (€ tCO_2^{-1}); NPV is the difference between the present values of the total revenues and total cost over the lifetime of the power plant (€); TER is the total GHG emission reduction over the lifetime of the power plant (tCO_2).

3. Results

3.1. Seasonal feedstock availability

The spatial and seasonal availability of the lignocellulosic and non-lignocellulosic biomass were estimated for the collection area under study. Supplementary Material Table 4 describes the seasonal availability of biomass in accordance with the methodology put forward in the previous sections. These findings show that all feedstock availability scenarios have sufficient lignocellulosic and non-lignocellulosic biomass to meet the plant's operational needs. As can be seen in Supplementary Material Table 4, the feedstock supply is highly seasonal, especially for lignocellulosic biomass, where it occurs only during three months of the year, owing to dependence on the harvesting period. Production of non-lignocellulosic biomass is more consistent, as it is generated throughout the year; although in greater quantities over the winter period. Therefore, there is an apparent need for an extensive biomass storage provision, to ensure the gap between supply and demand is fulfilled.

3.2. Design and operation of AD plant

As previously discussed, the feedstock required was calculated based on (i) the local energy demand and (ii) an acceptable ratio between lignocellulosic and non-lignocellulosic biomass. Based on the feedstock analysis, grass silage and manure were selected to be the sole feedstocks used in the plant, as they were by far the most abundant. The required feedstock to meet the energy outputs requirements of the plant consisted of an annual consumption of 26,964 tonnes of manure and 11,810 tonnes of grass silage as described in Table 3. The characteristics of this feedstock are presented in Table 1 and Supplementary Material Table 1. It is clear after comparing biomass availability and the biomass required, the catchment area could adequately accommodate this need.

Unlike many other studies, where biomass availability is assessed on an annual basis only, this decision support tool provides detailed information with regards to seasonal storage requirements, therefore, enabling the user to potentially benefit from additional cost savings by optimising storage capacity. As shown in Table 4, differences can be seen between the feedstock storage requirements throughout the year, with the maximum lignocellulosic biomass storage required peaking in August (3499 m^3) and non-lignocellulosic biomass topping out in January (10,039 m^3).

To provide practical information to the user, the tool recommends design specifications for the plant in terms of sizing and capacity requirements, as shown in Table 3. This allows the user to understand the real-world implications of the plant under consideration. To provide additional flexibility, the set of operating parameters of the case study can be adjusted, thereby, allowing the user to explore a wider range of plant operational configurations. As can be seen in Table 4, the parasitic electrical demand remains relatively consistent throughout the year, while the thermal energy demand varies depending on the outside ambient temperature. These findings concur with similar studies

Table 3
Proposed AD plant configuration.

Anaerobic feedstock required	
Manure (tonnes yr^{-1})	26,964
Grass silage (tonnes yr^{-1})	11,810
Pre-storage requirements	
Manure storage	
Total manure storage (m^3)	10,039
Crop storage	
Grass silage (m^3)	10,498
Anaerobic digester	
Operating parameters	
Digester operating temp (°C)	40.00
Hydraulic retention time (days)	30.00
Head space of digester (%)	25.0%
Digester margin of safety (%)	20.0%
Digester dimensions	
Digester volume (m^3)	4780
Diameter of digester (m)	12.66
Radius of digester (m)	6.33
Height of digester (m)	37.98
Area of digester floor (m^2)	125.85
CHP unit	
CHP electricity capacity (kW_{el})	789
Electrical efficiency (%)	36%
Thermal efficiency (%)	57%
Post-storage requirements	
Digestate storage (m^3)	6091

Table 4
Technical operation of the plant case study under investigation.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Feedstock Demand and storage													
Required supply of biomass (t FW/month)	3231	3231	3231	3231	3231	3231	3231	3231	3231	3231	3231	3231	38,774
Lignocellulose biomass in storage (m^3/month)	1312	875	437	0	1312	2624	2187	3499	3062	2624	2187	1750	–
Non-lignocellulose biomass in storage (m^3/month)	10,039	8799	7499	6259	4989	3749	2479	1240	0	2548	4943	7491	–
Gas Output													
Methane output (m3/month)	136,723	136,723	136,723	136,723	136,723	136,723	136,723	136,723	136,723	136,723	136,723	136,723	1,640,673
Parasitic energy demand													
Parasitic electrical demand (kWh)	23,264	23,264	23,264	23,264	23,264	23,264	23,264	23,264	23,264	23,264	23,264	23,264	279,170
Parasitic thermal demand (kWh)	106,594	106,519	106,557	106,471	106,424	106,326	106,314	106,339	106,376	106,448	106,512	106,567	1,277,447
Utilisation of energy													
CHP net electrical energy output (kWh/month)	445,880	445,880	445,880	445,880	445,880	445,880	445,880	445,880	445,880	445,880	445,880	445,880	5,350,566
CHP net thermal energy output (kWh/month)	634,513	634,587	634,550	634,634	634,682	634,778	634,791	634,766	634,728	634,657	634,594	634,539	7,615,819
Digestate													
Digestate output (m^3 FW/month)	1523	1523	1523	1523	1523	1523	1523	1523	1523	1523	1523	1523	18,274
Digestate storage requirement (m^3 FW/month)	6091	0	0	0	0	0	0	0	0	1523	3046	4568	–

conducted internationally [63]. In this case study, the plant configuration has been altered to provide a consistent thermal and electrical energy output. There is an opportunity for the tool to be expanded in an attempt to match electrical output with appliances with an energy demand that varies throughout the year. As anticipated, the digestate storage requirements were primarily driven by the regulatory restrictions brought about by the EU Nitrates Directive, with the maximum capacity needed emerging at the end of the restricted period, peaking at 6091 m^3 in January.

3.3. Economic analysis

The proposed tool was developed with the capacity to carry out a comprehensive economic analysis of the case study under investigation by the user over a period of 20 years (life span of the plant). This analysis can be customised, where plant revenues, expenditures, and economic indicators are assessed, as illustrated in Table 5. The results showed that the case study under investigation was economically feasible with a simple payback period of 9.50 years and a discounted payback period of 13.19 years (see Fig. 3). The largest revenue source was gained from exporting electricity, which was the primary driver in reducing the plant's payback period and enabling a steady return on revenue. There is a potential to reduce this payback period even further through the collection and use of various organic wastes (i.e. food waste, industrial waste) from nearby facilities, which could generate additional revenue through a gate fee. The largest expenditure proved to be the purchasing of lignocellulosic biomass, amounting to €7,085,822 over the plant's simulated lifespan.

The resulting analysis showed the LCOE of the case study to be €156.76/MWh, which is marginally less than the current feed-in tariff. It must be noted that this economic assessment parameter only assesses the feasibility of electricity generation while omitting other potential

Table 5
Economic results of small-scale anaerobic digestion plants over a 20-year lifespan.

Project Revenues (€)	
Sale of exported electricity	€16,866,374
Sale of thermal energy	€3,046,328
Total Revenues	€19,912,702
Project Expenditures (€)	
Investment Costs	
Cap. Ex. of digester (€)	€1,488,434
Cap. Ex. of CHP (€)	€430,347
Cap. Ex. of biogas cleaning (€)	€138,658
Storage of lignocellulosic (€)	€69,983
Storage of non-lignocellulosic (€)	€401,557
Engineering & planning (€)	€308,616
Total Investment Costs (€)	€2,837,596
Operating Costs	
Maintenance and repair	€1,418,798
Cost of feedstock	€1,228,099
Fuel costs (transportation of feedstock & digestate)	€7,085,822
Insurance	€851,279
Labour	€3,353,882
Total Operating Costs	€13,937,879
Economic Indicators	
Profit before tax (€)	€5,974,823
NPV at 5% (€)	€885,379
IRR (%)	8.45%
Payback period (Years)	9.50
Discounted payback period (Years)	13.19
LCOE (€/MWh)	€156.76

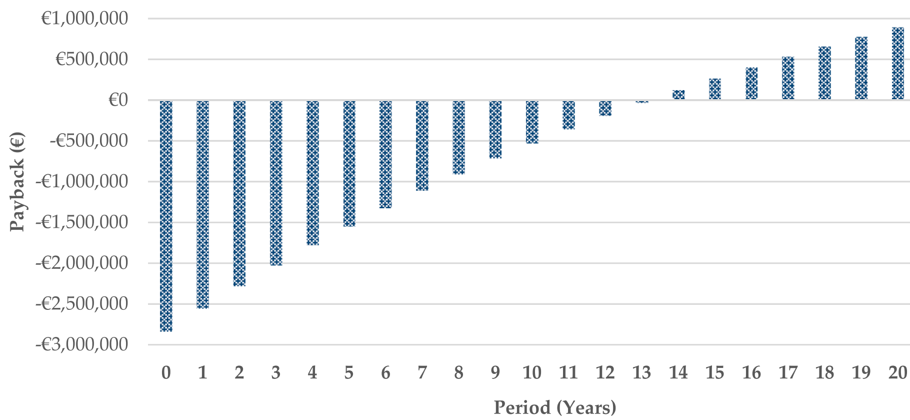

Fig. 3. Discounted payback period of the case study's biogas plant.

benefits such as the sale of thermal energy, anaerobic treatment of biomass, and generation of nutrient-rich digestate.

3.4. Environmental assessment

The tool developed provided a GHG balance of the proposed AD plant designed by the user, as illustrated in Table 6. This analysis consisted of an assessment of the emission inputs and outputs over the plant's operational lifetime. The findings showed that significant net CO2-eq savings could be achieved through the implementation of the case study, with a net CO_2-eq reduction of 7163 t CO_2-eq yr^{-1} and savings of 143,264 t CO_2-eq. over the lifespan of the plant (equivalent to taking 15,157 cars off the road per year). The activity which resulted in the greatest reduction in CO_2 emissions was the capture of gas otherwise released during "Manure Storage", with a contribution of 6510 t CO_2-eq per annum. A meaningful emission reduction contribution can also be seen from the displacement of fossil fuel-derived energy from the generation of thermal energy and electricity at 1904 and 1964 t CO_2-eq yr^{-1} respectively. The MAC was used to provide an indication of the cost-effectiveness of the technology in reducing GHG emissions, where the positive value (€12.08/tCO_2) showed the case study to be an attractive solution to mitigating GHG emissions. The investigation did not consider the emission inputs for the construction and disposal of the facility, as it was deemed outside the scope of the analysis.

Table 6
Annual CO_2 balance for the case study under investigation.

CO_2 Produced (kg CO_2-eq. yr$-^1$)	
Crop Production	
Soil ploughing and crumbling	3585
Sowing and maintenance	4078
Sowing	1217
Weed control (fuel)	181
Fertiliser spreading (fuel)	13,813
Fertiliser (mineral production)	181,515
Feedstock Collection and Transport	
Harvest	36,222
Harvest transport	19,558
Silo compaction	6753
Digester feeding (Crops)	18,089
Collection and digester feeding (Manure)	4934
Leakage	
Methane leakage	307,371
Biogas Production Process	
CO_2 Content	5,181,914
Digestate Disposal	
Transport and spreading of digestate	39,320
Total CO_2 produced	5,818,550
CO_2 reduction (kg CO_2-eq. yr^{-1})	
Do nothing scenario	
Manure storage	6,510,093
Manure land application	2,604,037
Final Use of Excess Energy	
Electricity exported	1,963,658
Heat exported	1,903,955
Total CO2 displacement	12,981,743
Net CO2 savings (kg CO2-eq. yr-1)	7,163,193
Equivalent savings in diesel (litres yr-1)	19,083,247
Equivalent savings in cars displaced (cars yr-1)	15,157
Marginal abatement cost (MAC) (€ tCO2-1)	12.08

a Diesel consumption per car is reported to be 1259 L yr^{-1}, as reported in the literature [64].

4. Discussion

The feedstock analysis showed the importance of completing an integrated seasonal and spatial distribution assessment, where the results showed that there was a sufficient year-round supply of biomass locally. This enables decision-makers to comprehensively gauge the plant's feasibility and potential implications by improving the accuracy of the information available. While similar assessments have been previously conducted, many only provide a regional assessment without an evaluation of the seasonal feedstock availability and operational practicalities for specific sites. Not considering the seasonality of biomass production, can result in the need for often-costly storage capacity, which is required to meet the lag between supply and demand. Therefore, the process developed adds value to decision-makers by enabling them to safeguard a reliable biomass supply chain while minimising the quantity of biomass feedstock required. As for future research, the decision support tool could be expanded to consider more feedstock types such as industrial by-products and residues.

The complexity in the planning and design of AD plants is highlighted in the analysis of this paper's case study, where numerous approaches can be undertaken with associated issues needing to be overcome. To mitigate these difficulties, the proposed decision support tool recommends an optimal AD plant design and size based on the user inputs. Furthermore, the tool simulates the corresponding technical, economic, and environmental outputs of the plant. While economic and environmental assessments have been carried out extensively in other studies [50,65,66], there has been limited attention paid to developing a universal methodology that enables the user to carry out such an analysis on AD plants that meets their specific needs. Moreover, the modelling platform provided can be extended to other regions and energy utilisation methods such as district heating networks and drying processes (*e.g.* wood chips).

Although the tool developed yields useful insights into the assessment and design of AD plants, they have some limitations. Firstly, while many AD plants operate under the tools assumed plant conditions (*i.e.* mesophilic temperature range, single digester), there are a considerable portion of plants that use alternative operating conditions. While the consideration of such configurations was outside the scope of this study, there is room to further expand and improve the usefulness of the decision support tool by incorporating such considerations *e.g.* thermophilic. The insights generated from such information would be particularly beneficial for medium to large-scale plants as they are more likely to operate using alternative conditions.

Secondly, while the capital and operational cost functions incorporated into the tool are based heavily on the literature, significant variations may still be present between the estimated and real-world expenditures for several reasons. These variations may result from regional differences, existing local support schemes, the rise of inflation, or differences between manufacturers.

In comparison to other studies, much attention has been given to the planning of biomass resources and assessing the subsequent technical and economic impacts at the regional level [11–13]. GIS-based approaches have been employed to map biomass potential, evaluate plant locations, and consider various economic and environmental criteria [5–7]. However, many studies only partially evaluate biogas plant sites, with little attention paid to developing a comprehensive assessment framework. This study distinguishes itself by not only accessing criteria such as feedstock supply, storage capacity, energy generation, economic viability, and environmental implications, but also developing a complete methodology that accounts for site-specific factors. This is crucial since the success of AD plants is contingent on both the technical aspects of the process and the local context, including available feedstocks, climate, and regulatory requirements [14]. While this study reports on a specific case, the findings have global relevance, particularly in areas with significant livestock and agricultural productivity. Future research could expand the tool's capabilities to include other feedstock types, reactor types, and energy utilisation applications.

Over the coming years, it is anticipated that, as the consequences of climate change become increasingly apparent, there is growing pressure on the Irish government to mitigate the country's negative environmental impact. Of the technologies and measures available, AD holds significant promise particularly in the agriculture sector, for its capacity to generate economic value through the production of renewable energy, while reducing GHG emissions and promoting a circular economy. It is hoped that the decision support tool developed from this study positively influences the adoption of AD plants in immature markets such as Ireland, by increasing the understanding and information of the assessment, design, and planning of AD plants for stakeholders.

5. Conclusions

The purpose of this study was to develop a universal decision support tool to assist in the optimal design and seasonal management of agriculture-based AD plants, accounting for site-specific practicalities and implications. To demonstrate the effectiveness of the tool, it was applied to a case study located in Sligo, Ireland. The feedstock availability assessment of the site determined that the biomass resources within a 10 km distance of the proposed plant; consisting of an annual output of 1,000,418 t FW of grass, 177,224 t FW of cattle manure, and 31 t FW of barley. Based on the local energy demand of the area, the decision support tool modelled an optimal AD plant design, including feedstock storage (10,317 m^3 and 3499 m^2), digester volume (4780 m^3), and CHP unit capacity (789 kW_{el}), and digestate storage (3686 m^3). The economic and ecological assessments carried out by the tool identified the plants discounted payback period (9.50 years), net present value (€885,379), the levelised unit cost of energy (€156.76/MWh), and marginal abatement cost (€12.08t CO_2^{-1}). Therefore, demonstrating the tool's usefulness in (i) assisting stakeholders to make better decisions through an increased understanding of the plant's seasonal operation and (ii) reducing capital and operating costs by optimising plant design and performance. Looking forward, it is hoped that the insights generated will assist in accelerating the adoption of AD plants, by providing an increased understanding of the assessment, design, and planning implications of such plants for stakeholders.

Declarations

The authors confirm that this article, has not been previously published and is not under consideration for publication in another journal.

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Code availability

Not applicable.

Ethics approval

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Consent to participate

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Author contributions

Conceptualisation, S.O'C., E.E., and J.B.; validation, S.O'C., E.E., S. C. P, G.L., C.J., M.W., and J.B.; writing—original draft preparation, S. O'C.; writing—review and editing, S.O'C., E.E., S. C. P., C.J., M.W., G.L., and J.B.; supervision, E.E., S. C. P., and J.B. All authors have read and agreed to the published version of the manuscript.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rineng.2023.101097.

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