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A combined stochastic NPV and game-theoretic framework for the evaluation of investment decisions in a biogas plant

Antonio Di Bari

antonio.dibari@unical.it

University of Calabria

Maria Romaniello

University of Campania "Luigi Vanvitelli"

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Abstract

Biogas plants constitute a viable alternative for achieving both environmental and economic objectives. On the one hand, they address the challenge of waste management within a circular economy framework; on the other, they provide opportunities to generate economic returns through electricity production. Moreover, such facilities offer a profitable option for livestock farmers, who can supply manure to the plant while reducing disposal costs. However, the limited capacity of the plant may give rise to competition among farmers, who may choose whether to supply manure depending on the stochastic evolution of manure flows over time. In this study, we develop a mathematical model grounded in game theory and a stochastic net present value (SNPV) framework, computed through Monte Carlo simulation techniques, to assess the economic benefits for the plant operator and two livestock farmers. We propose a sequential game with three players, in which the plant operator moves first, followed by the two farmers acting as the second and third players, respectively. The Monte Carlo approach is employed to simulate manure flow dynamics at each point in time over the entire project lifecycle.

Keywords: Biogas plant, Monte Carlo technique, Dynamic game, Stochastic Net Present Value

1 Introduction

Nowadays, waste reduction has become a key objective aligned with the principles of sustainability and the circular economy. Within a circular economy framework, anaerobic digestion represents a process capable of converting complex organic substrates,

such as manure, livestock slurry, agro-industrial residues, and the Organic Fraction of Municipal Solid Waste, into biogas ([1]).

A substantial body of literature emphasizes the prominent role that anaerobic digestion is expected to play in a circular economy model, owing to its ability to recover energy from organic materials, including manure and a wide range of agronomic residues ([2], [3]). Ellacuriaga et al. [4] focus on the digestion process by examining reactor operating conditions, treatment capacity optimization, and the reduction of operational costs that could foster bioenergy production.

Previous studies faced the evaluation of biogas plant through the discounted cash flows approaches. For instance, Havrysh et al. [5] adopt the Net Present Value (NPV) and the Profitability Index (PI) to assess the economic viability of a biogas plant. Furthermore, their study presents a sensitivity analysis indicating that the profitability of biogas plant projects is more strongly influenced by the plant load factor, while it is relatively less affected by increases in initial investment and substrate costs. Although biogas plants generate benefits for the community, their implementation may at times be unattractive due to high capital costs ([6]). Govender et al. [7] analyse the factors that have discouraged investment in biogas technology in South Africa. Specifically, the authors identify the sale of thermal energy with heat and power process as key drivers positively influencing project appraisal outcomes. Furthermore, the South African renewable energy programme highlights the potential for the development of biogas projects. For their analysis, Govender et al. [7] use the NPV.

In the evaluation of biogas plants, it is essential to account for the uncertainty and risks characterising these projects, as is generally the case for biomass-based investments. Uncertainties may relate to supply volumes, demand conditions, market prices, and technological change ([8]). Several methods are available to incorporate uncertainty into project evaluation. For example, the real options approach (ROA) allows uncertainty to be mitigated by explicitly incorporating managerial flexibility into the valuation process ([9]). In his value, Trigeorgis [9] shows that there are various types of operational flexibility that can be modelled, for example option to defer, option to abandon, option to switch, etc. In an energy context, De Blasis et al. [10] mitigate the uncertainty of photovoltaic energy production, demand, and electricity price through the valuation of an option to defer a photovoltaic project. D'Alpaos [11] shows the usefulness of the ROA for evaluating an anaerobic digestion facility for the production of electricity.

Another widely adopted approach in the literature are the Monte Carlo techniques

enable the management of uncertainty by simulating multiple NPV scenarios and creating a cumulative frequency distribution of NPV ([12]). Platon and Constantinescu [13] show that through the application of the Monte Carlo simulation methodology, the probability distribution of all potential event outcomes is derived via iterative evaluations of the model. Some studies combine Monte Carlo technique with NPV to evaluate oil and gas production sharing contract ([14]), to evaluate a plant for the simoultaneous generation of electrical and thermal energy ([15]), to analyze the uncertainty in the NPV of a project of cogeneration systems consisting of a gasifier powered by biomass coupled with a bottoming internal combustion engine powered by the gas produced through the gasification process ([16]), to evaluate the risk of a plant of anaerobic digestion of manipueira to generate clean electricity ([17]).

Investments in biogas plants are characterized by the involvement of multiple agents in the decision-making and operational process, each seeking to maximize their own objective function. In the case of manure fed biogas plants, the primary stakeholders typically include livestock farmers, who supply manure, and plant operators, who manage the anaerobic digestion facility. For livestock farmers, supplying manure to a biogas plant represents an economically advantageous practice, as it allows them to reduce manure disposal and treatment costs. Accordingly, it is essential to analyze the strategic interactions between farmers and biogas producers. Yazan et al. [18] employ an agent-based modeling framework to investigate the conditions that may foster mutually sustainable cooperation between livestock farmers and biogas plant operators. Other contributions have examined strategic behavior in the biogas production sector through the lens of game theory. Skovsgaard and Jensen [19] integrate game-theoretic analysis with a mixed-integer programming model to optimize the biogas value chain and to explore the economic drivers underlying the widespread upgrading of biogas plants.

This paper aims to develop a mathematical model to assess the economic benefits of a biogas plant for both the plant operator and the participating livestock farmers. As discussed above, such projects are characterized by substantial uncertainty and by the presence of strategic interactions among stakeholders. To explicitly incorporate these two dimensions into the evaluation framework, we combine a stochastic Net Present Value (SNPV), computed through Monte Carlo simulation techniques, with a game-theoretic approach designed to capture the strategic interplay among the agents involved. The model is formulated as a dynamic game with three players, namely the plant operator and two livestock farmers, who adjust their strategies in response to variations in manure supply. The quantity of manure is treated as an exogenous and

stochastic variable within the model, thereby introducing uncertainty into the strategic environment and influencing equilibrium outcomes over time.
The paper is organized as follows. Section 2 develops the mathematical valuation model. Section 3 provides an hypothetical case study. Section 4 provides the main findings and conclusive remarks of the paper.

2 Model

Our model aims to develop a methodological tool for the assessment of biogas production plants from the perspective of both the plant operator and the livestock farmers who supply bovine manure.
For farmers, the development of a biogas plant in proximity to their agricultural holdings represents a significant economic benefit. By depositing manure at the biogas facility, farmers would save on the disposal costs they would otherwise incur in the absence of the plant. Proper manure disposal is particularly important for protecting water resources from pollution caused by nitrates originating from agricultural sources. The challenge, however, is that the plant has a limited capacity, which may lead farmers to compete for the opportunity to deposit manure and secure the associated economic benefits.
In this section, we develop a model based on a stochastic Net Present Value (SNPV) framework that accounts for the uncertainty in manure inflows, which can vary over time, as well as the strategic interactions between the plant operator and two farmers competing sequentially.

2.1 Manure flows simulation

In this section, we model the temporal evolution of manure using the Monte Carlo simulation method. It is assumed that manure at time 0 (M_0) evolves over time $t \in [0, T]$ according to the following geometric Brownian motion:

$$\frac{dM(t)}{M(t)} = \mu dt + \sigma dW(t) \tag{1}$$

where μ represents the drift parameter, σ is the volatility and W is a standard Brownian motion.[1] We aim to simulate the daily manure flows considering $i = 1, 2, ..., m$ simulations; therefore, the day-by-day ($t = 0, 1, ..., n$) discretized solution is given by:

[1] We let evolve the manure, that is a kind of biomass, following the Geometric Brownian motion considering that previous studies explained that the stochastic models, such as the geometric Brownian motion, can be used to predict the biomass ([20]).

$$M_t^i = M_{t-1}^i \exp\left[\left(\mu - \frac{\sigma^2}{2}\right)T + \sigma\sqrt{T}Z_t^i\right] \tag{2}$$

where Z is the standard normal variable. Table 1 shows the structure of simulations.

$\downarrow i/t \rightarrow$	**0**	**1**	**2**	**...**	**n**
1	M_0	M_1^1	M_2^1	...	M_n^1
2	M_0	M_1^2	M_2^2	...	M_n^2
...	...	...	...	...	...
m	M_0	M_1^m	M_2^m	...	M_n^m

Table 1: Manure simulation framework

2.2 Strategic interactions

Our model considers a three-player game consisting of the plant operator and two farmers who are potential suppliers of manure. The three players may undertake different strategic actions depending on how the quantity of manure evolves over time. The players move sequentially in the following order. The plant operator (X) moves first and must decide whether to accept (a) or not accept (n) the supply. Farmer 1 (Y) makes the second move by deciding whether to feed (a') or not feed (n') the manure produced on their farm to the biogas plant. Farmer 2 acts as the third player, deciding whether to feed (a'') or not feed (n'') the manure. We denote as ξ_h the final nodes of the game where $h = 1, 2, 3, 4, 5$. Thus, the set of strategies of plant operator (first player) is $X = \{a, n\}$; the set of strategies of farmer Y (second player) is $Y = \{(a', n')\}$; the set of strategies of farmer Z (third player) is $Z = \{(a'', a''),\ (a'', n''),\ (n'', a''),\ (n'', n'')\}$. The plant operator X chooses an action x from his strategy set X; farmer Y chooses an action y from her strategy set Y; and farmer Z chooses an action z from his strategy set Z. In the case where X accepts the manure supply, and both Y and Z decide to supply the biogas plant with manure, the payoffs for the three players are given by $\pi_X(\xi_1)$, $\pi_Y(\xi_1)$, and $\pi_Z(\xi_1)$, respectively. In the case where X accepts the manure supply, Y decides to supply the plant, and Z decides not to supply the plant, the payoffs for the three players are given by $\pi_X(\xi_2)$, $\pi_Y(\xi_2)$, and $\pi_Z(\xi_2)$, respectively. In the case where X accepts the manure supply, Y decides not to supply the plant, and Z decides to supply the plant, the payoffs for the three players are given by $\pi_X(\xi_3)$, $\pi_Y(\xi_3)$, and $\pi_Z(\xi_3)$, respectively. In the case where X accepts the manure supply, and both Y and Z decide not to supply the plant, the payoffs for the three

players are given by $\pi_X(\xi_4)$, $\pi_Y(\xi_4)$, and $\pi_Z(\xi_4)$, respectively. In the case where X does not accept the manure supply, the game terminates and all three players receive $\pi_X(\xi_5)$, $\pi_Y(\xi_5)$, and $\pi_Z(\xi_5)$. The solution of the game is obtained through the backward induction method, where the preceding player, by anticipating the moves of the subsequent player, chooses the action that maximizes their payoffs. The solution of the game proceeds by backward induction starting from the third stage, which corresponds to the decision of player Z. Player Z chooses between a'' and n'' conditional on player Y's previous action: if player Y decides to supply manure to the biogas plant (a'), then Z selects between a'' and n''; similarly, if player Y decides not to supply manure (n'), player Z again chooses between a'' and n''. Player Y obtains the payoff associated with player Z's choice. Anticipating Z's optimal response, player Y selects the action between a' and n' that maximizes their own payoff. Finally, player X chooses between a and n. Player X knows that if a is chosen, the resulting payoff depends on the subsequent actions of players Y and Z, whereas if n is chosen, the game terminates immediately. Therefore, player X selects the action that yields the higher payoff. This choice determines the subgame perfect Nash equilibrium outcome derived via backward induction. We denote the payoffs associated with the Nash equilibrium obtained via backward induction by $\pi_X(x^*, y^*, z^*)$, $\pi_Y(x^*, y^*, z^*)$, and $\pi_Z(x^*, y^*, z^*)$, respectively for the three players, where (x^*, y^*, z^*) represent the optimal choices of the players taking into account the actions of the others. Figure 1 shows a graphical representation of the sequential game.

2.2.1 Payoffs description

Assuming that the two farmers produce the same quantity of manure M_t^i, we model the payoffs for each i simulation at each time instant t as follows. When the plant operator decides to accept manure, and both farmers decide to supply the plant, the plant operator obtains:

$$[\pi_X(\xi_1)]_t^i = EG_t^i(pe - co) - cf \tag{3}$$

where EG_t^i represents the electricity generated by the biogas plant, pe is the electricity selling price in the presence of incentive mechanism, co represents the operating costs including the procurement cost of manure coinciding with the transportation cost, cf is the fixed cost of feedstock acceptance. The fixed cost of manure acceptance cf refers to the amount required to handle the manure even though the farmer decides not to supply manure to the biogas plant (for example, biology monitoring costs, administrative costs, various costs, etc).

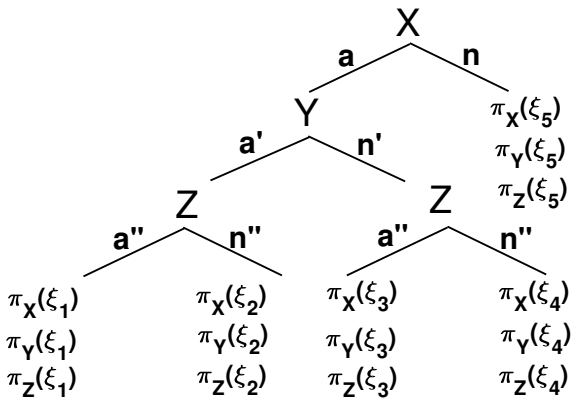


Fig. 1: Sequential game between the biogas plant (X) operator and two farmers (Y and Z)

The electricity generated EG is equal to the product among the energy content of biogas ,EB, expressed in $\frac{kWh}{m^3}$, the biogas volume, BV, expressed in m^3, and the efficiency rate of the plant in terms of electricity generated, ef, expressed in % ([7]). In our model the biogas volume is uncertain since it depends on the manure volume that can change during the time. Thus, we have:

$$EG_i^t = EB \cdot BV_t^i \cdot ef \tag{4}$$

In turn, BV_t^i is given by:

$$BV_t^i = \min(2M_t^i, TR) \cdot \gamma + MS \cdot \omega \tag{5}$$

where γ is a biogas yield factor from manure expressed in m^3/ton, ω is a biogas yield factor from energy crops (for example, maize silage) expressed in m^3/ton, MS is a fixed quantity of energy crops needed to produce biogas, TR is the plant's maximum capacity threshold expressed in ton, . Thus, the Eq. 3 can be rewritten as:

$$[\pi_X(\xi_1)]_t^i = EB \cdot [\min(2M_t^i, TR) \cdot \gamma + MS \cdot \omega] \cdot ef \cdot (pe - co) - cf \tag{6}$$

Considering the same actions, the farmer that acts as second player Y obtains:

$$[\pi_Y(\xi_1)]_t^i = \begin{cases} pd \cdot M_t^i & \text{if} \quad M_t^i \leq TR \\ pd \cdot TR - ca \cdot \max(M_t^i - TR, 0) & \text{if} \quad M_t^i > TR \end{cases} \tag{7}$$

where pd represents the cost savings associated with avoiding manure disposal, and ca is an additional burden that the farmer must bear if attempting to dispose of a quantity exceeding the plant's capacity. This may be interpreted, for instance, as a penalty arising from the additional transport of excess manure that must be returned to the farmer. The Eq. 7 can be expressed in the following compact form:

$$\pi_Y(\xi_1)_t^i = \min[pd \cdot M_t^i \ , \ pd \cdot TR - ca \cdot \max(M_t^i - TR, 0)] \tag{8}$$

The third-moving farmer Z obtains:

$$[\pi_Z(\xi_1)]_t^i = \begin{cases} pd \cdot M_t^i & \text{if} \quad 2M_t^i \leq TR \\ pd \cdot (T - M_t^i) - ca \cdot \max(2M_t^i - TR, 0) & \text{if} \quad 2M_t^i > TR \end{cases} \tag{9}$$

The Eq. 9 can be expressed in the following compact form:

$$[\pi_Z(\xi_1)]_t^i = \min\{pd \cdot M_t^i \ , \ pd \cdot \max(TR - M_t^i, 0) - ca \cdot \max[M_t^i - \max(TR - M_t^i, 0) \ , \ 0]\} \tag{10}$$

When the plant operator decides to accept manure, and farmer Y decide to supply the plant, farmer Z decide not to supply the plant operator obtains:

$$\pi_X(\xi_2)_t^i = EB \cdot [\min(M_t^i, TR) \cdot \gamma + MS \cdot \omega] \cdot ef \cdot (pe - co) - cf \tag{11}$$

the second-mover farmer obtains $[\pi_Y(\xi_2)]_t^i = \pi_Y(\xi_1)]_t^i$ and the third-mover farmer should pay the cost for manure disposal $[\pi_Z(\xi_2)]_t^i = -pd \cdot M_t^i$. When the plant operator decides to accept manure, and farmer Y decide not to supply the plant, farmer Z decide to supply the plant operator obtains $[\pi_X(\xi_3)]_t^i = [\pi_X(\xi_2)]_t^i$ since we assume the same manure quantities for the farmers. In this scenario, player Y would obtain $[\pi_X(\xi_3)]_t^i] = -pd \cdot M_t^i$ and player Z would obtain:

$$[\pi_Z(\xi_3)]_t^i = \min[pd \cdot M_t^i \ , \ pd \cdot TR - ca \cdot \max(M_t^i - TR \ , \ 0)] \tag{12}$$

Note that, in this case, the payoff of the third-mover farmer coincides with Eq. 8. This is because the second-mover farmer would always have access to the plant's full capacity, even if the third-mover farmer were to withdraw manure. Therefore, if the second-mover farmer decides not to supply manure to the plant, the third-mover farmer would have access to the entire capacity of the biogas plant. When the plant operator decides to accept manure, and both farmers decide not to supply the plant, the plant operator obtains $[\pi_X(\xi_4)]_t^i = -cf$ and the two farmers obtains $[\pi_Y(\xi_4)]_t^i = -pd \cdot M_t^i$ and $[\pi_Z(\xi_4)]_t^i = -pd \cdot M_t^i$. When the plant operator decides not to accept manure, the payoffs are: $[\pi_X(\xi_5)]_t^i = 0$, $[\pi_Y(\xi_5)]_t^i = -pd \cdot M_t^i$ and $[\pi_Z(\xi_5)]_t^i = -pd \cdot M_t^i$. Unlike the scenario of $[\pi_X(a, n', n'')]_t^i$, in the scenario of $[\pi_X(n)]_t^i = 0$ the plant operator could decide a priori not to accept manure, and would therefore avoid incurring the plant's fixed operating costs.

2.3 Stochastic NPV

The solution of each game via backward induction for each simulation at every point in time represents the economic benefit for each player. Discounting these economic benefits allows us to calculate m stochastic present value scenarios (SPV_0^i) of the project for the three players. The average across the simulations calculated at time 0 provides an estimate of the stochastic net present value at time 0. The final project valuation for biogas plant operator is:

$$SNPV_0^X = \frac{\sum_{i=1}^{m} \sum_{t=0}^{n} \frac{[\pi_X(x^*, y^*, z^*)]_t^i}{(1+r)^t}}{m} - I_0 \tag{13}$$

where r is the discount rate, and I_0 represent the initial investment to pursue the project. The final project valuation for farmer Y and Z are:

$$SNPV_0^P = \frac{\sum_{i=1}^{m} \sum_{t=0}^{n} \frac{[\pi_P(x^*, y^*, z^*)]_t^i}{(1+r)^t}}{m} \tag{14}$$

where $P = Y, Z$. This methodology allows for an evaluation of the biogas project both for the plant operator and for the farmers who can supply manure. The proposed model takes into account the uncertainty of the manure flow, which may vary over time, as well as the strategic interactions between the plant operator and the farmers.

3 Case study

In this section we provide a numerical example to implement the model. Specifically, we consider a biogas plant whose economic benefits mainly derive from the sale of electricity to the grid. In particular, we consider a plant with an installed capacity of 199 KWe operating 8,000 hours per year and producing 1 592 000 kWh_e/year.[2]

3.1 Data description

In this work we assume that the flow of cattle manure at time 0 for each farmer is $M_0 = 11.51$ tons and evolves stochastically according to a Brownian motion with drift $\mu = 0$ and volatility $\sigma = 0.1$. The maximum daily capacity of the plant is 23 tons of cattle manure and 5 tons of maize silage ($TR = 23$ tons and $MS = 5$ tons), with biogas yields equal to $\gamma = 281$ m^3/ton ([21]) and $\omega = 600$ m^3/ton, respectively. The energy content of biogas is $EB = 1.43$ ([22]) and the efficiency of the plant is equal to $ef = 0.33$ ([7]).
Regarding the economic parameters, we assume that the electricity selling price obtained through an incentive scheme is equal to $pe = 0.233$ €/kWh ([11]), while operating costs are equal to $co = 0.075$ €/kWh ([11]). Operating costs include input procurement costs, digestate disposal costs, labor costs, maintenance costs, and insurance costs. The fixed cost of manure acceptance is represented by the 10% of initial investment I_0 divided by 365 days and so $cf = 232.88$ €. The initial investment cost of the plant is $I_0 = 850\,000$ € ([11]). The analysis is conducted on a daily basis and therefore $n = 5\,475$ days (15 years). Data are summarized in Table 2.

3.1.1 Results and discussion

To implement the model, we first applied Eq. 2 to simulate the daily manure flows. The simulated paths are reported in Figure 2. Subsequently, for each simulated manure flow we solved the sequential game with three players, where each player anticipates the actions of the subsequent player. The payoffs obtained from the backward induction solution of the game for each simulated level of manure allowed us to compute the daily cash flows for the three players, taking into account their strategic interactions. By applying Eqs. 13 and 14 we obtained: $SNPV_0^X = 897\,930$ €, $SNPV_0^Y = 736\,220$ €, $SNPV_0^Z = 448\,460$ €. These results suggest that, once strategic interactions among the players are considered, the valuation is positive for all three agents. Therefore,

[2] To provide a realistic numerical example we consider the plant proposed in the study by [11].

Parameter	Description	Value
M_0	Initial value of manure	11.51 ton
μ	Manure drift	0
σ	Manure volatility	0.1
TR	Maximum capacity threshold of manure for the plant	23 tons
MS	Maximum capacity threshold of maize silage for the plant	5 tons
γ	Biogas yield factor from manure	281 m^3/ton
ω	Biogas yield factor from energy crops	600 m^3/ton
EB	Energy content of biogas	1.43 kWh/m^3
ef	Efficiency rate of the plant in terms of electricity	0.33
p_e	Electricity selling price	0.233 €/kWh
co	Operating costs	0.075 €/kWh
cf	Fixed cost of manure acceptance	$cf = 232.88$ €
I_0	Initial investment cost	850 000 €
n	Days	5 475

Table 2: Parameters for the numerical example

participation in the game is economically convenient for each of them. More specifically, our model allows the evaluation to incorporate the possibility that the plant operator may decide not to accept manure flows if they are too low to cover the fixed operational costs required to keep the plant ready to receive manure. It can also be immediately observed that the valuation for farmer X is higher than that for farmer Y because, unlike the latter, farmer X has access to the entire plant capacity.
The results suggest that the valuation of these projects is positive considering the uncertainty in the evolution of manure flows and the strategic interaction between the biogas plant operator and two farmers who may choose to deliver manure to the plant, thereby avoiding disposal costs. Therefore, the economic attractiveness of such plants should encourage governments to promote investments in this type of infrastructure, which is consistent with the United Nations Sustainable Development Goals. Previous studies have indeed highlighted the relevance of biogas plants for several United Nations Sustainable Development Goals, including Goals 6, 11, 12, 13, and 15 ([23]). In fact, [24] shows that biogas production allows to manage the waste in a very sustainable way, reduce the energy deficit, produce renewable energy, create new job position and reduce the negative impact on the environment.

3.2 Sensitivity analysis

We perform a sensitivity analysis to examine how the valuations of the three players vary with respect to relevant parameters of the model. Specifically, we analyze how $SNPV_0^X$, $SNPV_0^Y$, and $SNPV_0^Z$ change as a function of the electricity energy efficiency parameter ef, the plant capacity TR, the volatility affecting manure flows

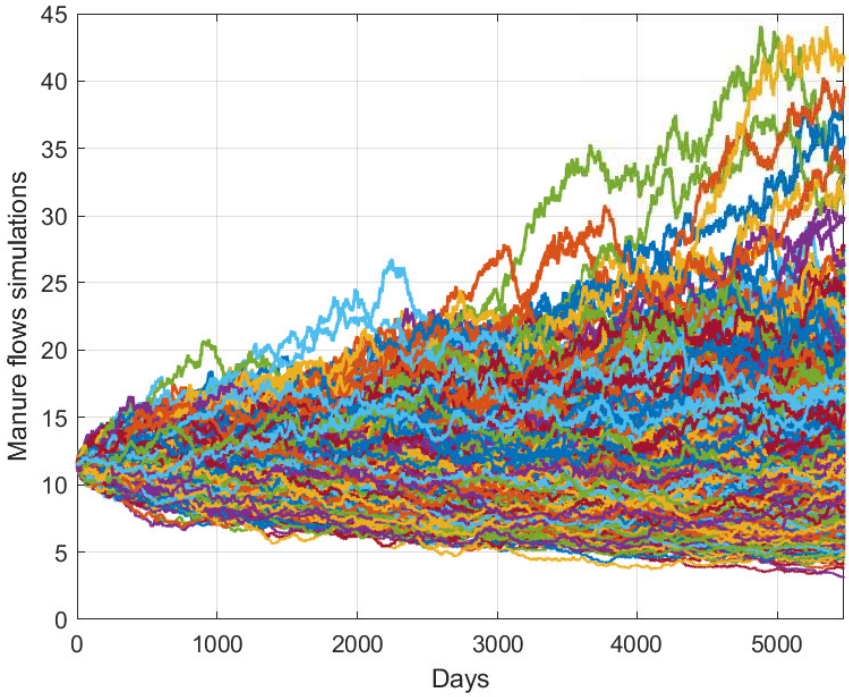


Fig. 2: Monte Carlo simulations of manure

σ, and the fixed costs cf. Figure 3 shows that the valuation for farmer Y is always higher than the valuation for player Z. This occurs because player Y, by acting before player Z, has access to the entire plant capacity and therefore has greater opportunities to capture the economic benefits associated with the avoided manure disposal cost. Figure 3 also shows that, as the energy efficiency of the plant increases, the valuation for the plant operator, $SNPV_0^X$, tends to increase. By contrast, for the farmers the project value increases only up to a certain point and then remains constant. This occurs because, when efficiency is very low, the plant operator may find it unprofitable to accept manure flows, forcing farmers to dispose of their manure by paying the disposal fee. Once the biogas plant becomes economically profitable for the operator, the economic benefits for the farmers remain constant, since beyond that point the efficiency parameter no longer affects the farmers payoffs. The analysis also shows that the valuations for all three players decrease as σ increases. A higher value of σ increases the volatility of manure flows, leading to more frequent realizations of very low or very high manure quantities. However, when manure volumes exceed the plant capacity, the excess must be disposed of externally, generating additional disposal

costs and thereby reducing the overall economic benefits relative to a scenario with less volatile manure flows. Finally, the last two panels show that the valuations for all three players increase as the plant capacity TR increases, whereas the valuation for the plant operator decreases as the fixed cost parameter cf increases.

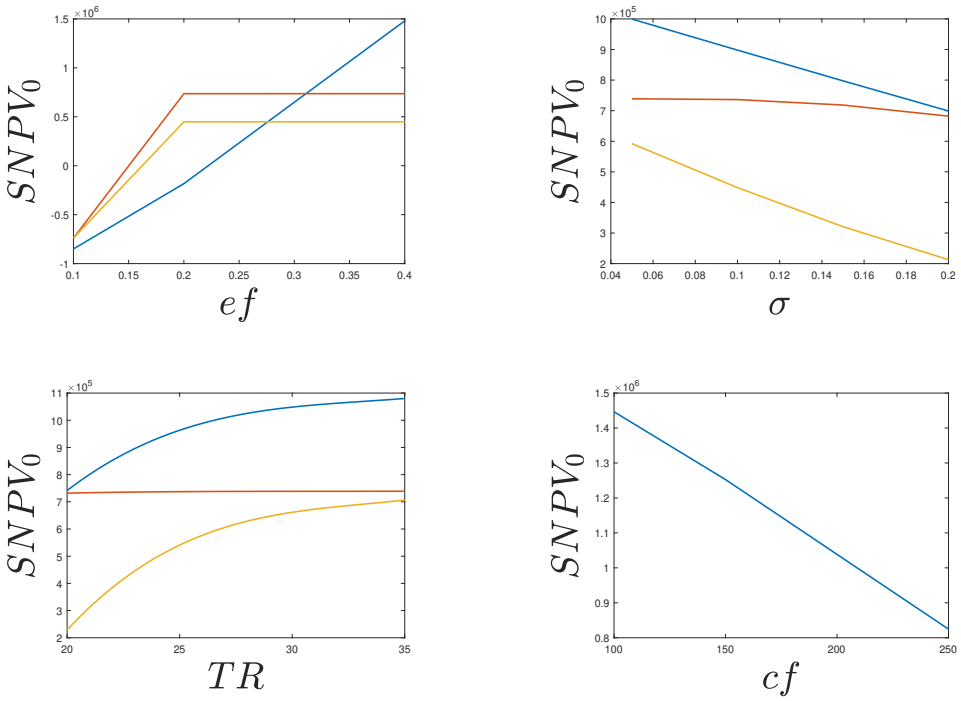


Fig. 3: Sensitivity analysis illustrating how the final valuation for each player varies with respect to selected parameters. The blue line corresponds to player X, the orange line to player Y, and the yellow line to player Z.

4 Conclusions

This paper presents a mathematical model to evaluate investments in the circular economy sector, with a specific focus on biogas plants. We consider a facility that produces biogas, subsequently converted into electricity, through the anaerobic digestion of manure and energy crops such as maize silage.

These investments are characterized by uncertainty regarding the evolution of manure supply over time, as well as by strategic interactions among the relevant market players, which in our model are assumed to be the plant operator and two farmers. Farmers

have a strong incentive to supply manure to the biogas plant, as this allows them to reduce disposal costs. However, since the plant has limited capacity, competition may arise between the two farmers. Furthermore, the plant operator must decide whether to accept manure depending on whether its quantity, unknown at the initial stage, is sufficiently high to cover the fixed activation costs.

The proposed model combines game theory with a stochastic net present value (SNPV) framework computed via Monte Carlo simulation techniques. Game theory is employed to capture the strategic interactions between the plant operator and the two farmers, who compete sequentially within a dynamic game setting. Monte Carlo methods are used to simulate manure flows, which may vary over time.

The paper also presents a case study illustrating the resulting valuations for the three players, taking into account both the uncertainty in manure flows, simulated through Monte Carlo techniques, and the strategic interactions. The results show that the valuations are positive for all three players, highlighting the attractiveness of such investments in terms of both economic and environmental benefits. Indeed, biogas plants represent a viable option for advancing the United Nations Sustainable Development Goals, as they are embedded within a circular economy framework that reduces environmental impacts, enables the production of renewable energy, and supports job creation.

Declarations

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Authorship contribution: Authors whose names appear on the submission have contributed sufficiently to the scientific work and therefore share collective responsibility and accountability for the results.

Compliance with Ethical Standards: This article does not contain any studies with human participants or animals performed by any of the authors. The authors declare that they have no conflict of interest.

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