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The importance of governmental incentives for small biomethane plants in South Spain.

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Abstract

A novel analysis addresses the economic viability of biomethane production from small biogas plants in South Spain, as a claim to promote the use of green energy and reduce the consumption of natural gas. To this end, the importance of governmental incentives to reach profitability in biomethane plants is illustrated through a case study. To date, no study addressing this problem specifically for South Spain can be found. The study considers the whole process from biogas production to biomethane feeding into the grid, for three different biomethane capacities (50, 100 and 150 m^3/h) and includes an exhaustive sensitivity analysis. For the three cases, implementing a biomethane plant is not viable and, therefore, not attractive for investors. Results considering biomethane governmental incentives as feed-in premia show significant improvements on the profitability of the largest plants. For example, supporting 150 m^3/h biomethane production capacity plants with a premium price of only 6 €/MWh (6.6 cents/m^3) results in 270 k€ NPV. Nevertheless, the smallest biomethane plants are hardly feasible. Concerning governmental support through investment subsidies, 150 m^3/h plants are profitable if 10% of the investment is subsidized, whereas the smallest plants do not reach profitability even if 50% of the investment is subsidized.

Keywords

Biomethane production; Biogas upgrading; Green energy; Governmental incentives; Waste valorization.

1. Introduction

The development of rural areas in terms of energy independence has been the focus of several works during the last years [1–4]. Renewable energy production plays a major role in the development of rural areas and their independence from large energy producers. Sustainable development policies recently announced by policy-makers need to close gaps between natural resource consumption and affordable green energy production [5–7]. The evolution towards green energy systems is limited for economic reasons since renewable energy projects have to overcome drawbacks associated with investment and operational costs [8,9]. Among renewable energy production in rural areas, biogas coming from the anaerobic digestion of biomass is a promising option to both green energy production and waste valorization [10]. Additionally, the production of biogas favors the circular economy in rural areas by reducing the quantity of waste sent to landfills and converting it into value-added products. Biogas can be obtained from several feedstocks such as for example agricultural residues, energy crops, wastewater and industrial organic waste [11]. Biogas is mainly composed of methane (CH_4), carbon dioxide (CO_2), and to a lesser extent, nitrogen (N_2), oxygen (O_2), hydrogen (H_2), hydrogen sulphide (H_2S), and siloxanes [12]. Biogas composition depends on the substrate and operating conditions [13], although the typical composition is around 60% CH_4 and 40% CO_2 [14]. For this reason, biogas needs to be upgraded to biomethane if its final use is to directly replace natural gas. To achieve this, many biogas upgrading technologies are available, namely: high-pressure water scrubbing, organic physical scrubbing, chemical absorption, membrane technology, adsorption systems and cryogenic upgrading [15–19].

Even though all biogas upgrading technologies have similar performances in terms of methane recovery (96-99.5%), membrane technology is compelling for this purpose. The reasons are many: it presents the lowest electricity consumption, good CH_4 selectivity, modular design, which minimizes investment costs, small space requirements, and availability for low capacities [17,20]. Another important fact is that membrane technology does not require heat, unlike organic physical scrubbing or chemical absorption. Moreover, maintenance requirements are low and it operates without hazardous chemicals [21]. Thus, membrane technology has been fully commercialized at industrial scale and it is expanding swiftly [22]. Regardless of the technology used, the emissions from biomethane production are considerably lower than that from fossil fuel production. For example, carbon intensity of crude oil production was determined to be 10.3 g CO_2 eq./MJ (average value in several countries) [23]. Regarding biomethane emissions, they were estimated on 3.7 g CO_2 eq./MJ (average value for various biomethane production technologies) [24].

Despite the multiple benefits of biomethane production and utilization, there are still technical barriers that need to be addressed. Currently, the hardest technical challenge for biogas upgrading is the removal of siloxanes. There are experimental evidences of the damage caused by siloxanes to equipment due to the production of silica via siloxanes combustion [12]. Furthermore, the impacts of siloxanes on human health are not clear at the moment [13]. Further research is needed to understand operational and safety consequences of siloxanes [13].

In Europe, the number of biogas production plants increased from 6227 in 2009 to 17432 in 2017 [25]. In Spain, the number of biogas plants (206 in 2017) is very low in comparison with the largest European biogas producers. For instance, the number of biogas plants in 2017 in Germany and Italy was 10971 and 1655, respectively. The main reason for these figures was the existence of economic incentives that favor the development of these technologies in the above-mentioned countries [26,27]. Currently in Germany, the electricity obtained from biogas is mainly supported by a market premium scheme, the market premium being determined though a tendering scheme. Typically, only small capacity biogas/biomethane plants are entitled to feed-in tariffs with values that depend on numerous factors. The latest reform of the Renewable Energy Sources Act (EEG 2017) resulted in a significant reduction of the feed-in tariffs, but the previous laws set out the conditions for the development of the biogas/biomethane sector in the country (From 2009 to 2014, the EEG contemplated a bonus for biogas upgrading) [28]. As a consequence of the policies, the number of biogas/biomethane production plants in Germany has continuously increased from the beginning of the century. It is estimated that 950 Mm^3 of biomethane were produced in Germany in 2017 [28]. In Italy, the development of biogas production was unlocked from 2008 to 2012 because of the appearance of the highest feed-in tariff in Europe (280 €/MWh for plants of up to 1 MW). This led to the increase in the number of biogas plant from 510 in 2010 to 1264 in 2012. After the establishment of biogas as a renewable energy source, policies favored small biogas plants of up to 600 kW [28]. Despite the large biogas production presented by Italy, only 8 biomethane plants were in operation in 2017 [28]. To fully develop the biomethane production in Italy, a new decree, which provides for 4.7 billion € incentives for the production of biomethane and advanced biofuels for transport, was published in March 2018. The new incentive scheme is based on a biofuel certificate system and aims to increase the number of biomethane production plants in the period between 2018 and 2022 [29]. Currently, in Spain there are no policies in place to promote the production of biogas and biomethane. As a consequence, the country has no biomethane plant in operation. The facts suggest that the growth of biogas production in Spain, and consequently of biomethane, requires new incentive policies that make this renewable energy affordable.

In the South of Spain, the agri-food industry is an important activity and generates wastes that can be valued through anaerobic digestion. However, as in many other regions of the World, the potential of biogas production of the Spanish food industry is still untapped and governmental efforts are needed to unlock it. With this in mind, this novel study focuses on the governmental incentives that are needed to make small biomethane production plants in the agri-food industry of South Spain economically feasible. As a real case study, the paper presents the results of the techno-economic analysis of producing biomethane from strawberry extrudate, a current residual stream from a strawberry processing plant (HUDISA S.A) located in Lepe, Andalusia (South-Spain). In a previous work, the methane production from strawberry waste was addressed from the technical point of view and promising results were achieved [30]. This work goes a step forward and aims to evaluate the profitability of the whole process from biogas production to biomethane feeding into the grid, for three different biomethane capacities (50, 100 and 150 m^3/h). Biomethane feed-in premia and investment subsidies, two typical governmental incentives that might be applied to a biomethane plant [21,22], are considered and their impacts analyzed. The novelties presented in our work are the following. To the best of our knowledge, this is the first work in which the profitability of small biomethane plants in South Spain is analyzed. Thus, our study aims to be a guide for policy-makers in our region. Furthermore, our work is based on experimental data of biogas production from real waste obtained from an industrial plant. Therefore, our approach contributes to wider economic realistic data for biomethane production plants.

2. Method

2.1 Economic model and selection of indicators

This paper presents the feasibility analysis of producing biomethane from residual strawberry extrudate and injecting it into the natural gas grid (see Figure 1 for a scheme of the process). The profitability analysis was carried out using the Discounted Cash Flow (DCF) method and the data needed was obtained both experimentally and through literature review. The indicators chosen to measure the economic feasibility were Net Present Value (NPV), Discounted Payback Time (DPBT), Internal Rate of Return (IRR) and Profitability Index (PI). Eq. (1)-(4) present the formulas used to calculate each indicator.

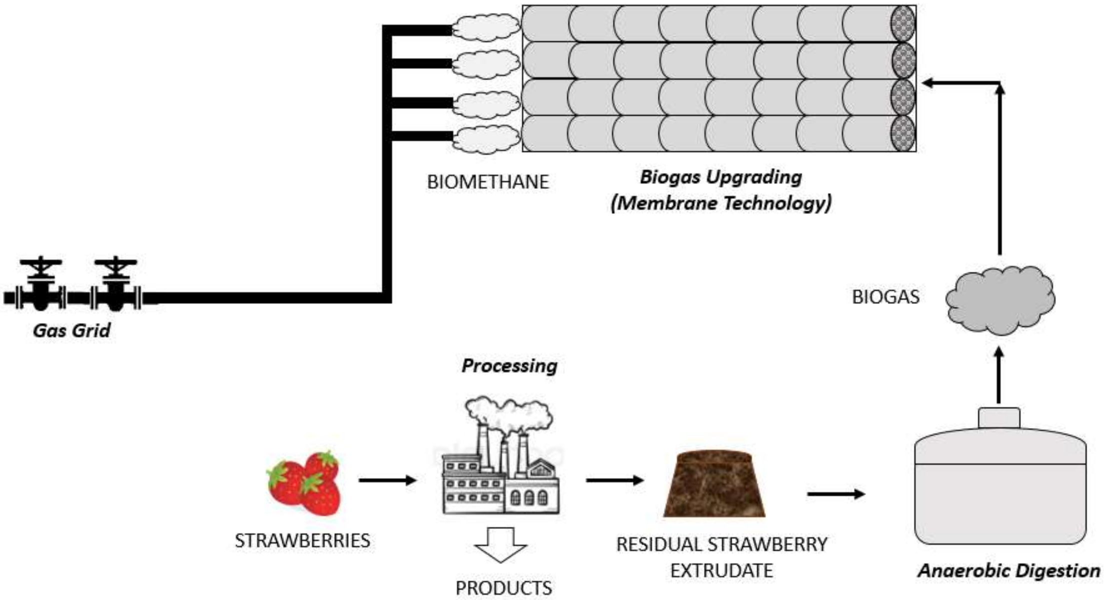

Figure 1. Biomethane production from residual strawberry extrudate.

$$\text{NPV} = \sum_{t=0}^{n} \frac{I_t - O_t}{(1+r_d)^t} \tag{1}$$

$$\sum_{t=0}^{\mathrm{DPBT}} \frac{I_t - O_t}{(1+r_d)^t} = 0 \quad (2)$$

$$\sum_{t=0}^{n} \frac{I_t - O_t}{(1+\mathrm{IR}\ \ )^t} = 0 \quad (3)$$

$$\mathrm{PI} = \frac{\sum_{t=0}^{n} \frac{I_t - O_t}{(1+r_d)^t}}{C_{\mathrm{inv}}} \quad (4)$$

Where *n* is the lifetime of the project, *t* the time, I_t the cash inflow at time *t*, O_{t} the cash outflow at time *t*, r_{d} the discount rate, and C_{inv} the investment cost. The determination of the cash inflows, cash outflows and investment cost is explained in detail in Appendix I. Some of the main assumptions and characteristics of the model are described in the next paragraphs.

All the calculations were done as a function of predefined biomethane plant sizes. Three different biomethane capacities (50, 100 and 150 m^3/h) were considered and the amount of wastes that needed to be fed into the bioreactor to obtain these biomethane capacities were calculated (see Appendix I for details). According to the results obtained, the amount of wastes needed for feeding the biogas plant are: 828 t/a for 50 m^3/h; 1656 t/a for 100 m^3/h; and 2485 t/a for 150 m^3/h. To put these values into context, in Andalucia, 21% of the strawberry crop is used for the production of secondary products, which leads to the generation of residual strawberry extrudate (around 7%, in wet weight, of the processed strawberry) [31]. Considering that the strawberry production in the Huelva region in the 2018-2019 season was 341556 t [32], the total amount of extrudate generated in the province would be around 5000 t. Therefore, the proposed plant sizes range from one sixth to half of the generated waste for the whole region of Huelva.

In this study, a 6% discount rate was assumed. This value was calculated summing the Spanish inflation rate in 2019 (0.8% [33]), the SME financing costs in Spain in the first semester of 2019 (median, 2.2% [34]) and a term accounting for the risk (3%). It was considered that the investment would be financed by resorting to a loan (loan period equal to 15 years). It was assumed that the distance from the upgrading plant to the natural gas grid, *d*, was 0.5 km, although this parameter will be analyzed in-depth due to its importance. Further assumptions of the model are explained in Appendix I and the inputs needed to conduct the feasibility analysis are reported in Table A.1 of this Appendix.

2.2 Baseline cases, governmental incentives and sensitivity analysis

Three different capacities for the biomethane plant (50, 100 and 150 m^3/h) were studied. Table 1 presents the different scenarios defined for the profitability evaluation for each capacity. Scenarios 1, 2 and 3 correspond to the baseline cases, which do not consider any kind of incentives. Biomethane governmental incentives as feed-in premia were analyzed in scenarios 4, 5 and 6. Premium prices from 2 to 30 €/MWh were considered for all capacities, hence allowing to compare their effect for each capacity. Governmental incentives in the form of subsidies worth a percentage of the capital expenditures (scenarios 7, 8 and 9) were varied in a different range for each capacity, since, as it will be seen later, the profitability reached for the largest capacities is significant at low and medium percentage values.

Sensitivity analysis was carried out to evaluate the impact of important parameters on profitability. The evaluation was performed by creating a tornado plot for each capacity. The selected parameters for this analysis were M&O costs (scenarios 10, 11 and 12), capital expenditure on the grid for biomethane transportation (scenarios 13, 14 and 15), electricity price (scenarios 16, 17 and 18), cost of disposing waste (scenarios 19, 20 and 21), and interest rate (scenarios 22, 23 and 24). The selection of these parameters for the sensitivity analysis is explained in section 3.1. The selected parameters were varied for the three capacities studied in this work in order to obtain a wide range of results, which allows an in-depth analysis of the feasibility of producing biomethane from strawberry extrudate. In the sensitivity analysis, no subsidies on investment were taken into account, but premium prices were always considered so that profitability can be reached.

Table 1. Matrix of the scenarios analyzed.

Scenario	Biomethane capacity (m^3/h)	Feed-in premia (€/MWh)	Investment subsidies (%)	Sensitivity analysis	Parameter analyzed (value and units)
1	50	No	No	No	-
2	100	No	No	No	-
3	150	No	No	No	-
4	50	Yes (2-30)	No	No	-
5	100	Yes (2-30)	No	No	-
6	150	Yes (2-30)	No	No	-
7	50	No	Yes (2-50)	No	-
8	100	No	Yes (2-30)	No	-
9	150	No	Yes (2-16)	No	-
10	50	Yes (26-28)	No	Yes	M&O (±1 %)
11	100	Yes (10-12)	No	Yes	M&O (±1 %)
12	150	Yes (4-6)	No	Yes	M&O (±1 %)
13	50	Yes (26-28)	No	Yes	d (0-1 km)
14	100	Yes (10-12)	No	Yes	d (0-1 km)
15	150	Yes (4-6)	No	Yes	d (0-1 km))
16	50	Yes (26-28)	No	Yes	p_e (±20 %)
17	100	Yes (10-12)	No	Yes	p_e (±20 %)
18	150	Yes (4-6)	No	Yes	p_e (±20 %)
19	50	Yes (26-28)	No	Yes	p_{wastes} (±10 €/t)
20	100	Yes (10-12)	No	Yes	p_{wastes} (±10 €/t)
21	150	Yes (4-6)	No	Yes	p_{wastes} (±10 €/t)
22	50	Yes (26-28)	No	Yes	r_d (±3 %)
23	100	Yes (10-12)	No	Yes	r_d (±3 %)
24	150	Yes (4-6)	No	Yes	r_d (±3 %)

3. Results

3.1 Baseline case results

To evaluate the impact of different types of governmental incentives on the profitability of the investment in a biomethane plant, first, it is necessary to define the feasibility of the baseline case scenarios. As explained before, in this work, three cases were considered as the baseline (scenarios 1, 2 and 3 of Table 1). These scenarios differ in the biomethane capacity of the plant, which ranges from 50 m^3/h to 150 m^3/h. Profitability is not reached in any of the baseline cases as seen in Table 2, which could be anticipated from the inexistence of biomethane plants in Spain and is in line with this fact. Indeed, the results show that profitability is far from being obtained for all the capacities considered. Thus, without any kind of incentive, the investment in this type of renewable energy source for the substitution of natural gas is unlikely. DPBT is longer than 20 years in all cases and PI reports negative profitability in agreement with NPV. The investment in larger than 150 m^3/h capacity plants could be profitable without any incentive scheme since NPV and PI evolve towards profitable values as the biomethane capacity increases.

Table 2. Baseline cases results.

Biomethane capacity (m^3/h)	50	100	150
NPV (k€)	-1442	-1206	-651
DPBT (a)	>20	>20	>20
IRR (%)	n.d.	n.d.	n.d.
PI (-)	-1.20	-0.56	-0.22

The obvious reason for the negative results obtained in the baseline case scenarios is the relation between the high costs incurred and the lower revenues obtained by the biomethane plant. To evaluate the relative importance of the different types of costs and compare them, Figure 2 presents the share of the yearly costs of the biomethane plants. Additionally, the distribution of costs will be useful for the sensibility analysis in section 3.3. M&O corresponds to the highest cost for the three capacities (around 30% of the total costs), which is in agreement with previous studies for this kind of industrial plants [35,36]. Investment also imposes remarkable costs for biomethane plants (between 21 and 24% of the total costs). The relative importance of labor costs decreases with an increase in the biomethane capacity of the plants because of the boost in the other costs. Electricity consumption also plays an important role. In the anaerobic digestion stage, electricity is mainly consumed by pumps, as well as to keep the temperature needed in the digester. Depending on the raw material, electricity may also be consumed to grind it [37] (in the present case grinding is not needed). Regarding the electricity consumed in the upgrading stage, it is mainly employed for compression purposes [21].

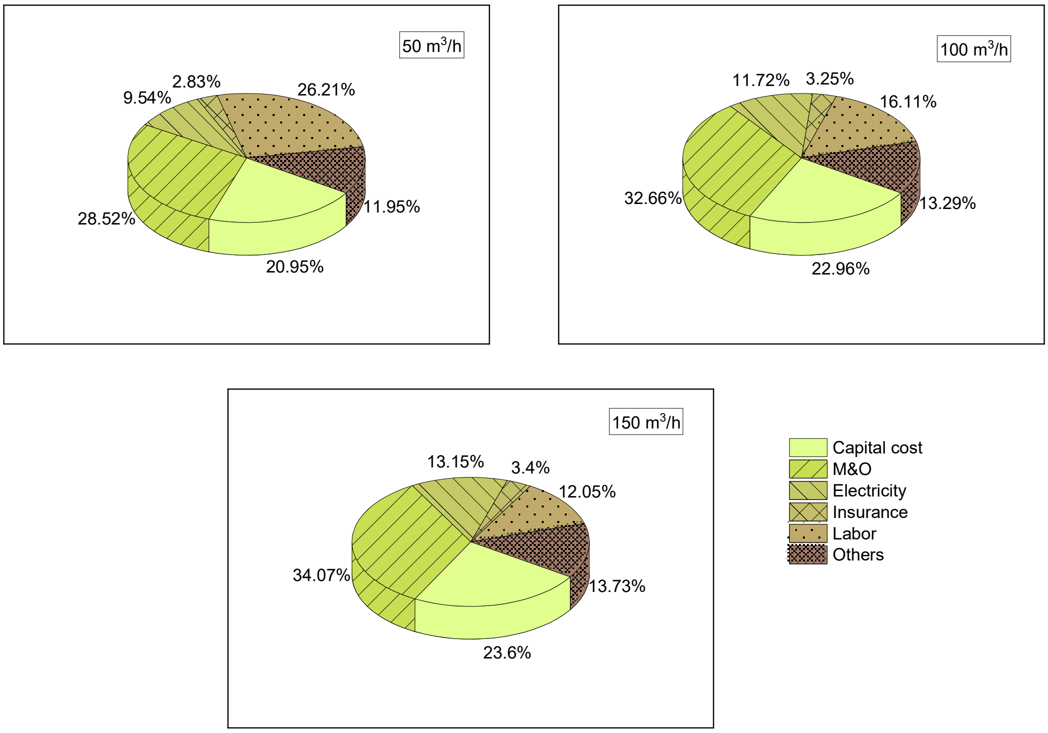

Figure 2. Cost distribution for different plant sizes.

3.2 Influence of governmental incentives

Once the baseline case results were obtained, the influence of governmental incentives on the profitability of producing biomethane from strawberry extrudate was studied. Two political instruments typically used to increase the uptake of green energy were analyzed: feed-in premia (section 3.2.1) and investment subsidies (section 3.2.2). To this end, the selected indicators (NPV, PI, DPBT and IRR) were evaluated for a wide range of government incentive values.

3.2.1 Biomethane governmental incentives through feed-in premia

In this work, biomethane governmental incentives through feed-in tariffs with a premium price policy structure were considered (scenarios 4, 5 and 6). It was assumed that the premium price in top of the market price of natural gas was constant, and guaranteed over 20 years. The range established for premium prices, 2 €/MWh to 30 €/MWh, was selected to provide a wide collection of data. Figures 3 and 4 reveal the dependence of the NPV and PI results on the value of the premium price, whereas Table 3 and 4 provide the results obtained for DPBT and IRR at each premium price value considered.

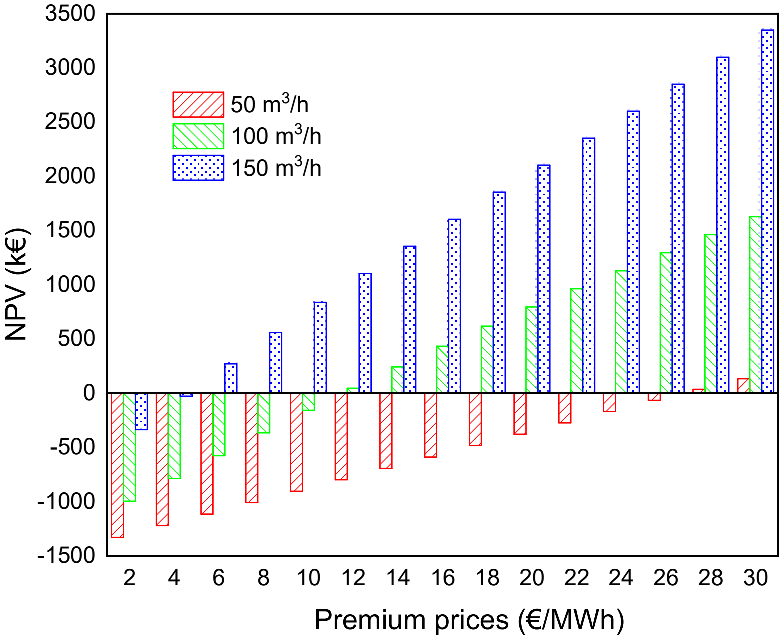

Figure 3. NPV for several premium price values and biomethane plant sizes.

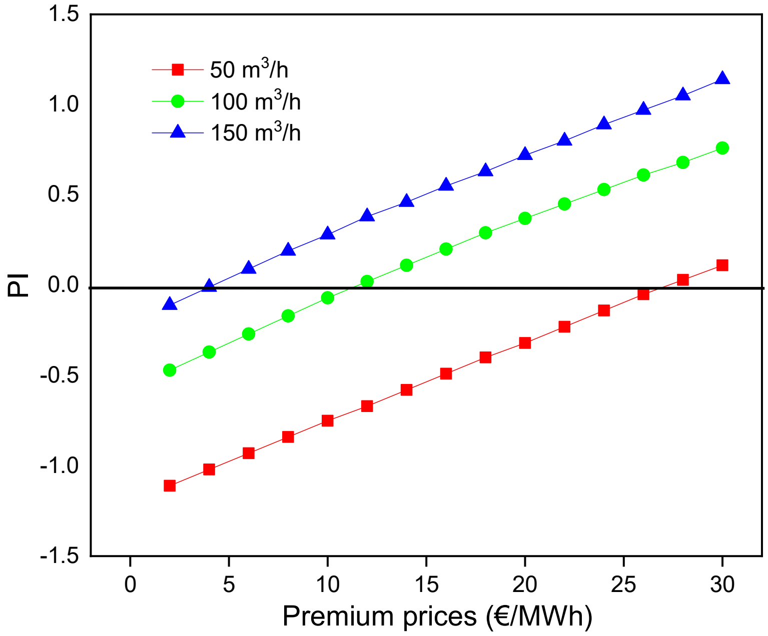

Figure 4. PI value for several premium price values and biomethane plant sizes.

Analyzing the results, one can conclude that the smallest biomethane plants studied in this work (50 m^3/h) are only profitable for the highest premium prices considered, which makes them not competitive with other renewable energy options. Nevertheless, the smallest biomethane plants may be the key for reducing the consumption of fossil natural gas in rural areas and hence may justify higher political and economic efforts. The support of small plants is occurring in some European countries (e.g., manure or biowaste based small scale plants in Germany [28]). For 50 m^3/h plants, the first positive NPV value (35 k€) is achieved for a premium price of 28 €/MWh; in this case the PI value obtained is 0.03 and the DPBT is still very high (19 years). Therefore, deviations in the values considered for the input parameter may result in an economical unviable project. Additionally, such a long payback time is not attractive for investors. The IRR obtained for the 28 €/MWh premium price was 6.3%, which may not be competitive in terms of capital budgeting comparing with other potential renewable energy investments, such as hydropower or onshore [38]. Having this considerations in mind, it would probably be more appropriate to set a 30 €/MWh premium price for the smallest plants to avoid economic breakage in case of cost fluctuations (e.g., electricity costs). Even though, at this value most investors would not invest since the payback period is still high, 17 years.

Table 3. DPBT (years) for several premium price values and biomethane plant sizes.

Plant size (m^3/h)	**Premium price (€/MWh)**														
	2	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**
50	>20	>20	>20	>20	>20	>20	>20	>20	>20	>20	>20	>20	>20	19	17
100	>20	>20	>20	>20	>20	20	17	15	9	4	<1	<1	<1	<1	<1
150	>20	>20	17	15	10	4	<1	<1	<1	<1	<1	<1	<1	<1	<1

Table 4. IRR (%) for several premium price values and biomethane plant sizes.

Plant size	**Premium price (€/MWh)**														
(m^3/h)	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**
50	-	-	-	-	-	-	-	-	-	-	-	-	-	6.3	10.8
100	-	-	-	-	-	6.1	10.7	17.4	29.3	77.2	>100	>100	>100	>100	>100
150	-	-	9.4	16.1	28.0	79.5	>100	>100	>100	>100	>100	>100	>100	>100	>100

In agreement with our analysis, increasing the capacity of biomethane plants leads to a reduction of the premium price needed to reach profitability. In accordance to this fact, 100 m^3/h and 150 m^3/h plants present the first positive NPV value for lower premium prices than 50 m^3/h. Indeed, for 150 m^3/h a positive NPV is achieved with a premium price of 6 €/MWh, which makes this plant capacity the most prone to be feasible with little effort. Furthermore, the NPV obtained is quite noticeable (270 k€). An important drawback of this capacity plants is the high amount of wastes needed, whose volume could not be constantly produced throughout the entire year due to the seasonal production of determined crops. Nevertheless, agricultural ecosystems in Andalucia presents different crops and activities that generate different waste the entire year, such as animal manures, sewage sludge or other agricultural waste from the same area as orange peels or other seasonal berries. Therefore, the co-digestion of strawberry extrudate with other wastes will also be an interesting option to study in future works as other authors have already proposed [27,30,35,39]. 100 m^3/h could be a compromise option between biomethane governmental incentives and waste quantity needed. The first NPV positive value for this capacity was found at 12 €/MWh, which is a relatively easy-value to be achieved by public funds in the form of governmental incentives. Furthermore, remarkable profitability can be achieved at relatively medium values of biomethane governmental incentives. For example, NPV was 242 k€ and PI was 0.11 for a premium price of 14 €/MWh, which is also a reasonable value to be provided by Spanish government. For this value, DPBT was 17 years and IRR was 10.7%, which are much more attractive for third party funds than the obtained for 50 m^3/h with higher governmental incentives. Even if these results are more attractive, a payback of 17 years is still considered high for investors. In view of this discussion and under the hypotheses adopted in this work, it seems that reasonable values for biomethane governmental incentives as premium prices would be as follows: 30 €/MWh for 50 m^3/h; 16 €/MWh for 100 m^3/h; and 8 €/MWh for 150 m^3/h. In comparison with the natural gas price assumed in this work (50 €/MWh), the feed-in premia needed for 150 m^3/h and 100 m^3/h seem reasonable. For 50 m^3/h, the necessary feed-in premium may be too ambitious. If one compares the proposed feed-in premia with the one that is offered by the 2018 scheme for promoting biomethane production in Italy (61 €/MWh [28]), the premia for the three biomethane plant capacities studied are below the Italian incentive. Those results suggest that incentives for biomethane production are affordable for the Spanish government.

3.2.2 Biomethane governmental incentives through investment subsidies

Governmental incentives can also be offered through investment subsidies, which may be granted by the government as a percentage of the initial investment costs. This option is very helpful to fund investors in those cases where the initial investment is much higher than operational costs [40]. Herein, depending on the capacity of the plants, we selected subsidies that amount to different percentages of the investment costs as follow: 2-50% for 50 m^3/h; 2-30% for 100 m^3/h; and 2-16% for 150 m^3/h. For 50 m^3/h capacity plants, the percentage of investment costs supported was increased until half of the investment is covered. For both 100 m^3/h and 150 m^3/h, the maximum percentages of investment costs covered that were analyzed were lower since the results for the chosen indicators were considerably better and it was not worthy to analyze subsidies that cover higher percentages of investment costs. Figures 5 and 6 show the results obtained for NPV and PI.

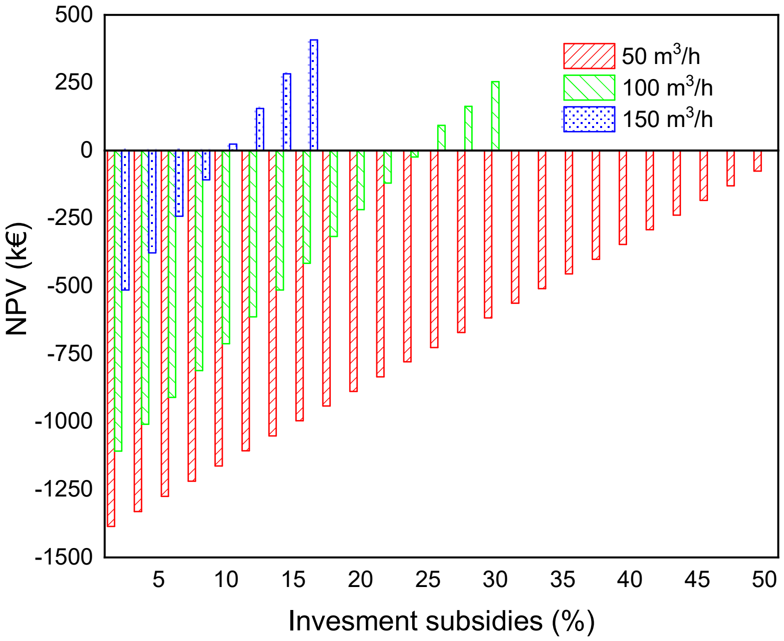

Figure 5. NPV for several percentages of investment costs covered by a subsidy and for various biomethane plant sizes.

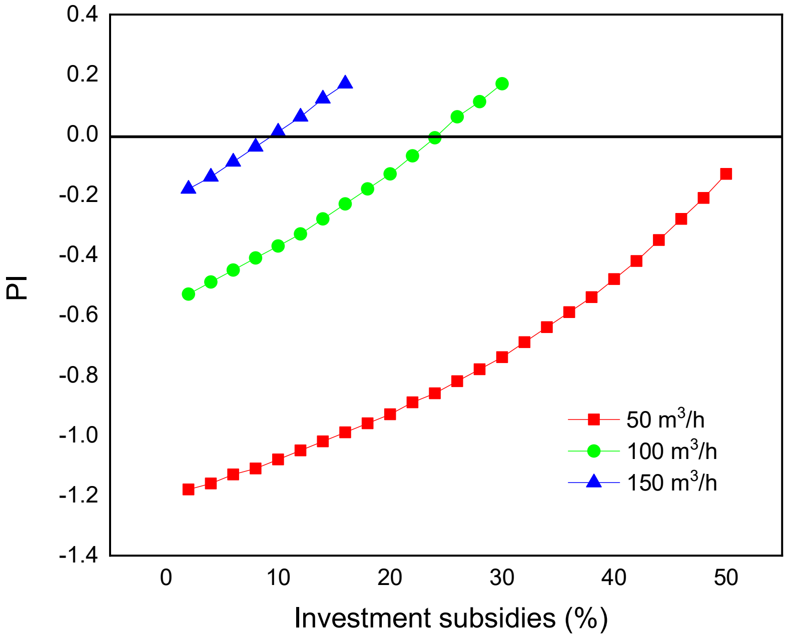

Figure 6. PI for several percentages of investment costs covered by a subsidy and for various biomethane plant sizes.

Similarly to the previous cases, in these scenarios (7, 8 and 9), a higher percentage of the investment needs to be subsidized for the smaller capacity plants to be profitable. Indeed, even if 50% of the investment is covered by subsidies, 50 m^3/h capacity plants do not achieve profitability (NPV -76 k€). 54% of the investment should be covered by subsidies to obtain profitable results (NPV 29 k€). In this hypothetical situation, small cost fluctuations could result in a negative effect on NPV and lead to a non-viable project. DPBT and IRR obtained in this case were 18 years and 7.5%, respectively. Better results were obtained for 100 m^3/h capacity plants. For this scenario, the biomethane plant would be profitable if subsidies amount to 26% of the investment costs. Remarkable indicators results were obtained for 28% of investment (i.e., 163 k€ NPV and 0.11 PI), which is a reasonable value that could be provided by public funds. If subsidies covered 12% of the investment costs, acceptable economic results would be obtained for 150 m^3/h plants. In this scenario, the values of the indicators were: 155 k€ NPV; 0.06 PI; 18

years DPBT; and 7.78% IRR. 150 m^3/h plants would be profitable only with 10% of investment subsidies (24 k€ NPV; 0.02 PI; 20 years DPBT; and 6.1% IRR). The large differences between the profitability of different capacity plants is due to the value of operational costs in comparison with the required investment costs (see Figure 2). If the subsidy covers a small percentage of the investment in higher capacity plants (with a higher share of investment costs in the total costs), the impact is higher than covering a large percentage of subsidies for lower capacity plants.

3.3 Sensitivity analysis

In order to evaluate the impact of the uncertainty in the different parameters assumed in section 3.2, a sensitivity analysis on the profitability of the different biomethane capacity plants was carried out. Most of the parameters varied in the sensitivity analysis were selected based on the results presented in Figure 2 and were related to the costs with the largest shares in the total costs: M&O costs, electricity price, and costs of investing in the biomethane distribution grid, namely by varying the distance of the plant to the grid. Inasmuch as revenues may play a key role for small biomethane plants, the effect of avoided costs for waste treatment on the profitability was also studied. Moreover, the impact of varying the discount rate was also analyzed. Figures 7, 8, and 9 summarize the NPV results obtained in the sensitivity analysis for each plant size studied. In order to study the effect of the uncertainty in the selected parameters, the scenarios with the first positive NPV value for a specific feed-in premium was considered.

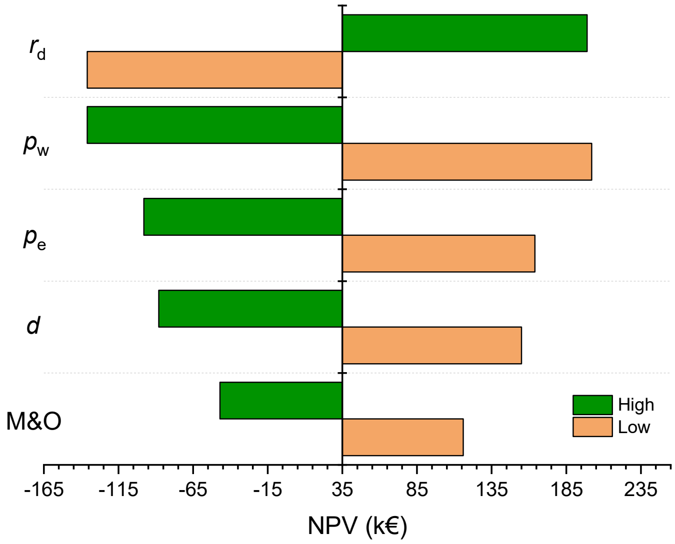

Figure 7. Effect of parameter variation on NPV for 50 m^3/h biomethane plants and a feed-in premium of 28 €/MWh.

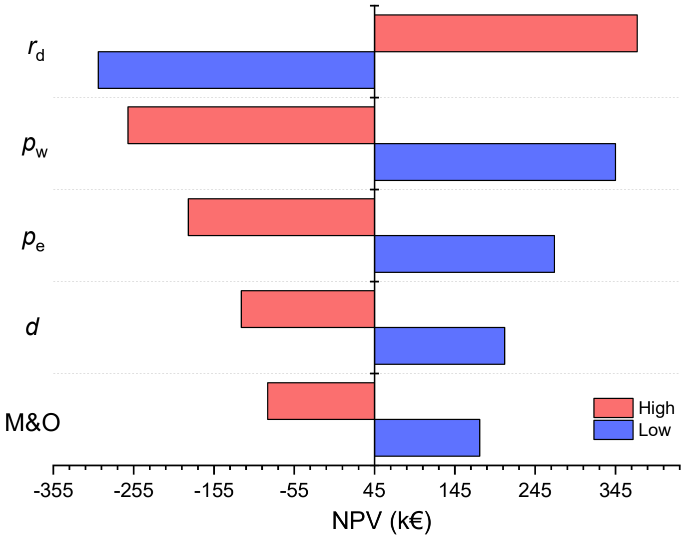

Figure 8. Effect of parameter variation on NPV for 100 m^3/h biomethane plants and a feed-in premium of 12 €/MWh.

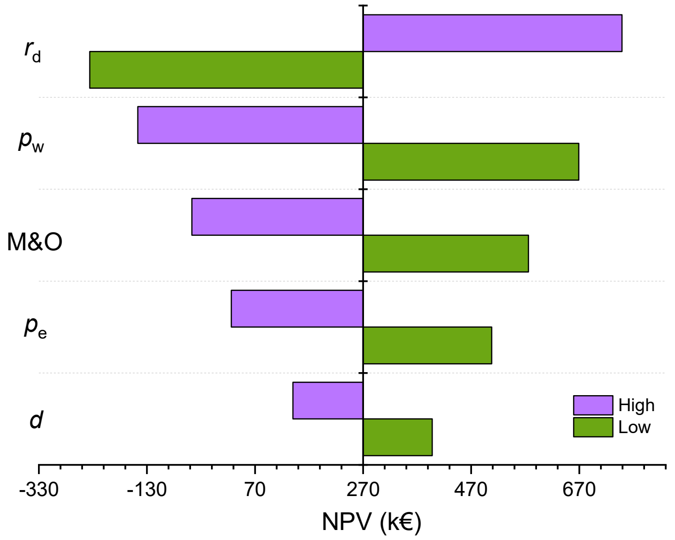

Figure 9. Effect of parameter variation on NPV for 150 m^3/h biomethane plants and a feed-in premium of 6 €/MWh.

Starting with the analysis of the impact of the uncertainty in M&O costs, this parameter was varied by ±1% of its standard value (scenarios 10 to 12). As it can be seen in Figure 7, the effect of M&O costs is significant for the lowest capacity plant, and a little variation of their value could lead to a high difference in NPV result. Furthermore, this effect is even higher in the larger capacity plants studied (Figures 8 and 9). Thus, M&O costs can be considered a critical parameter and efforts to reduce them as much as possible should be undertaken. Focusing on the different scenarios, the intensity of the results varies among them. Indeed, an increase by 1% of M&O costs makes NPV to be negative for all capacities. For example, a decrease of -82 k€ of NPV value is observed for 50 m^3/h. On the other hand, a decrease of 1% in the M&O costs in scenarios 10, 11 and 12 makes NPV much profitable (i.e. 81 k€ increase for 50 m^3/h). These results highlight the importance of selecting reliable parameters for the economic analysis and the interest of performing a sensitivity analysis.

Even though the variation of M&O costs causes substantial changes in the economic performance of the project, for the smaller plant capacity, the highest impact corresponds to the variation of the discount rate, r_d. This parameter was varied by ±3% and Figures 7 to 9 present the results obtained (scenarios 22, 23 and 24). A 3% increase in r_d resulted in a -171, -344 and -506 k€ decrease in the NPV value for 50, 100 and 150 m^3/h, respectively.

For the largest capacities, the parameter that has more impact on the results is the price of wastes. The impact of the avoided costs of waste treatment is analyzed in scenarios 19, 20 and 21. The impact of the price of wastes on the annual revenues is considerably important and its reduction from 15 €/t to 5 €/t leads to a negative NPV for all the scenarios herein studied. For the same reason, an increment in this price from 15 €/t to 25 €/t would result in extra-avoided costs for treatment, which would make small biomethane production plants more profitable. These results suggest that local authorities responsible for waste management issues should promote the increase of the collection taxes for waste disposal and management. This way, the industrial activities which generate these kinds of wastes would be more prone to look for an alternative disposal for them. Therefore, and as a consequence of this measure, more biogas plants could be set up as a valuable valorization of wastes, and hence renewable synthetic natural gas could be produced or renewable electricity production could be increased.

The aforementioned figures also show the effect of electricity price variation (scenarios 16, 17 and 18). For 50 m^3/h plants, NPV could be altered from 35 k€ to -47 k€ by a 20% increase in the electricity price. Thus, developing strategies for obtaining a stable electricity price could be an interesting option for tackling this problem. To ensure a moderate electricity price, renewable policies could evolve towards negotiations with electricity producers, which would allow keeping a stable price during the first years of operation of this kind of industrial plants. This way, concerns about electricity price variations would be solved and investors would feel more attracted towards these renewable energy investments.

The results of varying the distance from the biogas upgrading plant to the grid are also discussed. The results were obtained for a variation in the distance of ±0.5 km. As can be seen in Figures 7 to 9 (scenarios 13, 14 and 15), and as expected, an increase in the distance to the grid worsens the NPV results. Thus, the existence of natural gas grids in the proximity of the biomethane upgrading plants is another essential factor to consider when analyzing the implementation of such a facility, since NPV can be considerably affected by the distance to the grid. Indeed, for 150 m^3/h capacity plants (Figure 9), the existence of a natural gas grid collection point within the biomethane installation would mean that a feed-in premium of only 4 €/MWh would be required. Another interesting option to promote biomethane as a natural gas substitute would be the total payment by the government of the investment costs of implementing distribution grids, which could be even considered as a new kind of governmental incentives. Figure 7 shows that this is particularly important for the smaller biomethane plants.

4. Conclusions

In this work, the profitability of small capacity waste-based biomethane plants in Spain under several scenarios was addressed. As the investment in the three plants studied, with sizes varying from 50 to 150 m^3/h, is not economically feasible and, therefore, lacks attractiveness for investors, biomethane governmental incentives via feed-in premia and investment subsidies were investigated. Results from biomethane governmental incentives as premium prices show remarkable outcomes for biggest capacity plants. For example, 150 m^3/h biomethane production capacity plants supported with a premium price of only 6 €/MWh lead to a significant NPV (270 k€). Furthermore, an NPV of 242 k€ and a PI of 0.11 for a 14 €/MWh premium were obtained for 100 m^3/h. The smallest biomethane capacity plants are more difficult to support. The first positive NPV value (35 k€) for 50 m^3/h plants was achieved for a feed-in premium of 28 €/MWh. Regarding governmental investment subsidies to cover a certain percentage of the initial investment, similar results were obtained in terms of which biomethane capacity plant is easier to support. Again the best results were obtained for 150 m^3/h capacity plants, where a subsidy that covers only 10% of investment is needed to ensure their profitability. As a matter of fact, if the subsidy amounted to 12% of the initial investment, the outcomes for investors would be significant (NPV of 155 k€). Reasonable investment subsidies should be granted to 100 m^3/h capacity plants (28% of investment subsidies would produce 163 k€ NPV). Smallest biomethane capacity plants would not reach profitability even if 50% of investment was subsidized.

Overall, our study affirms the necessity of granting governmental incentives to small biomethane production plants in Spain in order to promote renewable and sustainable alternatives to natural gas. Furthermore, the governmental incentives would boost the production low-carbon energy sources. For both types of governmental incentives, the same conclusion can be drawn. Bigger efforts are needed for the smallest biomethane capacity plants or new technological solutions should be adopted. An interesting option for the smallest biomethane plants would be to mix various wastes in order to obtain a mixed substrate in higher quantities. Thus, in future works economic analysis and/or profitability studies will be carried out to evaluate several mixes of wastes based on previous references. Furthermore, further economic evaluation could be carried out in more realistic scenarios based on data from already existing biomethane plants, which would help to define a governmental incentives scenario more accurately.

Appendix I. Details on the model used for the feasibility analysis

Cash inflow (I_t) is composed by three revenues which are related to: biomethane sale ($R_{biomethane}$), governmental incentives for biomethane injection into the grid ($R_{subsidies}$), if they exist, and the avoided cost for the treatment of the wastes (R_{wastes}) (Eq. (A.1)). The latter exists in some Spanish regions like, for example in Madrid or Andalusia, and it would be avoided if the wastes are used for biogas production.

$$I_{\mathrm{t}} = R_{\mathrm{biomethan}} + R_{\mathrm{subsidies}} + R_{\mathrm{wastes}} \tag{A.1}$$

The revenues obtained by selling biomethane to the natural gas grid are described by Eq. (A.2) and are proportional to the energy content of the biomethane produced ($Q_{biomethane}$) and the specific price of the biomethane (p_{NG}).

$$R_{\mathrm{biomethan}} = Q_{\mathrm{biomethane}} * p_{\mathrm{NG}} \tag{A.2}$$

In this work, all the calculations were done as a function of predefined capacities of the biomethane plant, and therefore of predefined values of $Q_{biomethane}$. Governmental incentives in the form of feed-in premia payed to the biomethane injected into the grid are considered in Eq. (A.3), where $p_{\mathrm{subsidies}}$ is the premium price payed for each unit of biomethane produced.

$$R_{\mathrm{subsidies}} = Q_{\mathrm{biomethane}} * p_{\mathrm{subsidies}} \tag{A.3}$$

On the other hand, the revenues obtained as avoided costs for the treatment of wastes are accounted by Eq. (A.4). Both the amount of wastes avoided (Q_{wastes}) and the unitary price of disposing those wastes (p_{wastes}) are part of this equation.

$$R_{\mathrm{wastes}} = Q_{\mathrm{wastes}} * p_{\mathrm{wastes}} \tag{A.4}$$

The amount of wastes that are needed to reach the production of the predefined quantities of biomethane was obtained through Eq. (A.5) in terms of the biogas capacity

(Q_{biogas}), the production rate (PR), the percentage of volatile solids (vs) in the total solids (ts) in the waste ($\frac{\%vs}{ts}$) and the operating hours of the biomethane plant (n_{wh}).

$$Q_{wastes} = \frac{Q_{biogas}}{PR * \frac{\%vs}{ts}} * n_{wh} \tag{A.5}$$

Biogas capacity was calculated assuming a biogas composition of 60% CH_4 – 40% CO_2 (Eq. A.6). Regarding biogas plant sizes, they were selected in order to maximize the saturation of the upgrading phase in agreement with previous studies [27,36].

$$Q_{biogas} = \frac{Q_{biomethane}}{0.6} \tag{A.6}$$

The discounted cash outflow term (O_{t}) expressed by Eq. (A.7), is composed by four groups of costs, which correspond to biogas production (identified by the subscript 1), biogas upgrading to biomethane (identified by the subscript 2), biomethane distribution to an existing natural gas grid (identified by the subscript 3), and labor.

$$O_{\mathrm{t}} = (C_{\mathrm{loan1}} + C_{\mathrm{il1}} + C_{\mathrm{mo1}} + C_{\mathrm{df1}} + C_{\mathrm{ins1}} + C_{\mathrm{e1}}) + (C_{\mathrm{loan2}} + C_{\mathrm{il2}} + C_{\mathrm{mo2}} + C_{\mathrm{df2}} + C_{\mathrm{ins2}} + C_{\mathrm{e2}}) + (C_{\mathrm{loan3}} + C_{\mathrm{il3}} + C_{\mathrm{mo}}\ ) + C_{\mathrm{lab}} \tag{A.7}$$

The biogas production and biogas upgrading costs considered in this work correspond to: investment in the form of a loan (C_{loan1} and C_{loan2}), interest on the loan (C_{il1} and C_{il2}) maintenance and operation (M&O) (C_{mo1} and C_{mo2}), depreciation (C_{df1} and C_{df2}), insurance (C_{ins1} and C_{ins2}) and electricity (C_{e1} and C_{e2}). The costs related to biomethane distribution to the grid correspond to the investment in the form of a loan (C_{loan3}), interest on the loan (C_{il3}) and M&O (C_{mo3}). Depreciation and insurance were not included in the cost for biomethane distribution, in agreement with the Spanish normative to consider these items. Furthermore, according to previous references [36,41], additional compression is not needed if the natural gas grid operates at a similar pressure to the pressure of the biomethane produced. Thus avoiding the electricity cost for biomethane distribution to the grid [41]. Additionally, it was assumed that the biogas plant was built inside the facilities where the wastes are being generated to avoid waste transport costs.

Investment costs cover all the equipment required for the normal operation of each stage (e.g., compressors in upgrading stage), as well as engineering works and installation costs. It was considered that all the investment costs would be entirely covered by a loan provided by a third party. In Eq. (A.8), (A.14) and (A.20), the yearly investment costs are related to the total investment costs, which in turn are related to the specific costs. The latter costs for biogas production, biogas upgrading and biogas distribution were estimated in agreement with previous works [42–44]. To keep the investment cost of the biogas upgrading stage as low as possible, membrane technology was chosen in agreement with previous references [41,45,46]. Eq. (A.9), (A.15) and (A.21) make reference to the specific loan cost which needs to be paid each year of the investment period. It depends on the time (*t*) of the investment, which was considered yearly, and on the interest rate (r_{int}). M&O costs were estimated as a percentage of the investment cost for each stage (Eq. (A.10), (A.16) and (A.22). The same principle was followed for depreciation (Eq. (A.11) and (A.17)) and insurance (Eq. (A.12) and (A.18)). The cost of electricity was obtained through Eq. (A.13) and (A.19), in terms of the biogas capacity, unitary electricity consumption for each stage (C_{ue1}) and electricity price (p_{e}).

$$C_{\mathrm{loan1}} = \frac{C_{\mathrm{inv1}}}{n_{\mathrm{l}}} \tag{A.8}$$

$$C_{\mathrm{il1}} = [C_{\mathrm{inv1}} - C_{\mathrm{loan1}} * (t+1)] * r_{\mathrm{int}} \tag{A.9}$$

$$C_{\mathrm{mo}} \;\; = \;\; C_{\mathrm{inv1}} * p_{\mathrm{mo}} \tag{A.10}$$

$$C_{\mathrm{df1}} = C_{\mathrm{loan1}} * p_{\mathrm{df}} \tag{A.11}$$

$$C_{\mathrm{ins1}} = C_{\mathrm{inv1}} * p_{\mathrm{ins}} \tag{A.12}$$

$$C_{\mathrm{e1}} = Q_{\mathrm{biogas}} * C_{\mathrm{ue1}} * p_{\mathrm{e}} \tag{A.13}$$

$$C_{\mathrm{loan2}} = \frac{C_{\mathrm{inv2}}}{n_{\mathrm{l}}} \tag{A.14}$$

$$C_{\mathrm{il2}} = [C_{\mathrm{inv}} \;\; - C_{\mathrm{loan2}} * (t+1)] * r_{\mathrm{int}} \tag{A.15}$$

$$C_{\mathrm{mo2}} = \; C_{\mathrm{inv2}} * p_{\mathrm{mo}} \tag{A.16}$$

$$C_{\mathrm{df2}} = C_{\mathrm{loan2}} * p_{\mathrm{df}} \tag{A.17}$$

$$C_{\mathrm{ins2}} = C_{\mathrm{inv2}} * p_{\mathrm{ins}} \tag{A.18}$$

$$C_{\mathrm{e2}} = Q_{\mathrm{biogas}} * C_{\mathrm{ue2}} * p_{\mathrm{e}} \tag{A.19}$$

$$C_{\mathrm{loan3}} = \frac{C_{\mathrm{inv3}}}{n_{\mathrm{l}}} \tag{A.20}$$

$$C_{\mathrm{il3}} = [C_{\mathrm{inv3}} - C_{\mathrm{loan3}} * (t+1)] * r_{\mathrm{int}} \tag{A.21}$$

$$C_{\mathrm{mo3}} = \; C_{\mathrm{inv3}} * p_{\mathrm{mo}} \tag{A.22}$$

Labor cost (C_{lab}) is also contemplated in the model and is calculated by multiplying the unitary labor cost of each operator (C_{labu}) by the number of operators needed to run the biomethane plant (n_{op}).

$$C_{\mathrm{lab}} = C_{\mathrm{labu}} * n_{\mathrm{op}} \tag{A.23}$$

The economic inputs required for the feasibility study are collected in Table A.1.

Table A.1. Inputs used for the economic feasibility study.

Variable	**Symbol (unit)**	**Value**	**Reference**
Natural gas price	p_{NG} (€/MWh)	50	[47]
Unitary cost for waste disposal and management	p_{wastes} (€/t)	15	[48]
Unitary investment costs for stage 1	C_{inv1u} (€/kW)	50 m^3/h – 5100 100 m^3/h – 4800 150 m^3/h – 4500	[36,41,45]
Unitary investment costs for stage 2	C_{inv2u} (€/m^3/h)	50 m^3/h – 6300 100 m^3/h – 5800 150 m^3/h – 4500	[36,41,49]
Unitary investment costs for stage 3	C_{inv3u} (€/km)	237500	[35]
Biogas plant size	S_{biogas} (kW)	50 m^3/h – 150 100 m^3/h – 300	[27,36]

		150 m^3/h – 450	
Corporate taxes	C_{taxes} (%)	25	[50]
Period of loan	n_l (a)	15	[39]
Percentage of M&O	p_{mo} (%)	10	[35]
Discount rate	r_d (%)	6	-
Percentage of depreciation fund	p_{df} (%)	20	[35]
Percentage of insurance cost	p_{ins} (%)	1	[36]
Unitary electricity consumption for stage 1	C_{ue1} (kWh/m^3)	0.13	[45]
Unitary electricity consumption for stage 2	C_{ue2} (kWh/m^3)	0.29	[45]
Electricity price	p_e (€/kWh)	0.13	[51]
Labor cost per worker	C_{labu} (€/y/worker)	25000	[41]
Number of operators	n_{op} (worker)	4	[36]
Interest rate	r_{int} (%)	5	[36]
Operating hours	n_{wh} (h/a)	8000	-
Biomethane energy density	ρ_b (MWh/m^3)	0.011	[52]
Distance of biomethane plant to grid	d (km)	0.5	-
Production rate of biogas	PR (m^3/t vs)	838	[30]
Percentage of volatile solids to total solids ratio	%vs/ts (%)	0.9605	[30]

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