

## Article

# Promoting Sustainability: Wastewater Treatment Plants as a Source of Biomethane in Regions Far from a High-Pressure Grid. A Real Portuguese Case Study

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**Abstract:** Wastewater treatment plants (WWTP) located in regions far from a high-pressure grid can produce renewable biomethane, which can partially substitute the natural gas locally consumed. However, the economic viability of implementing biomethane plants in WWTP has to be guaranteed. This paper uses the discount cash flow method to analyze the economic viability of producing biomethane in a WWTP located in Évora (Portugal). The results show that, under the current conditions, it is unprofitable to produce biomethane in this WWTP. Since selling the CO<sub>2</sub> separated from biogas may result in an additional income, this option was also considered. In this case, a price of 46 EUR/t CO<sub>2</sub> has to be paid to make the project viable. Finally, the impact of potential government incentives in the form of feed-in premia was investigated. Without selling CO<sub>2</sub>, the project would only be profitable for feed-in premia above 55.5 EUR/MWh. If all the CO<sub>2</sub> produced was sold at 30 EUR/t CO<sub>2</sub>, a premium price of 20 EUR/MWh would make the project profitable. This study shows that the economic attractiveness of producing biomethane in small WWTP is only secured through sufficient financial incentives, which are vital for developing the biomethane market with all its associated advantages.

**Keywords:** biomethane; natural gas grid; bioenergy; biogas; gas supply decarbonization; incentives



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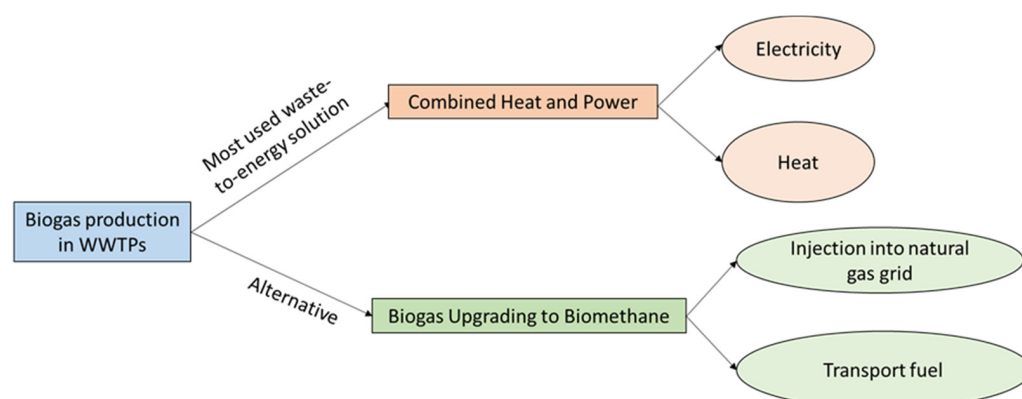


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## 1. Introduction

The search for alternative energy sources is a present challenge for societies [1]. The need to find a replacement for fossil fuels emerged both because of the scarcity of known non-renewable fuel reserves and because of the environmental problems caused by greenhouse gas (GHG) emissions [2,3]. In this context, renewable energies have become important in the last decades mainly because of the sources from where they come [4,5]. Indeed, the global total primary renewable energy supply in the world reached around 80 EJ in 2018, with an average annual growth rate of 2.0% since 1990 [6]. Renewable energies can also improve the relationship between sustainability and resilience, an important aim if we look at how COVID-19 quickly changed our lifestyle [7]. Among the available renewable energy sources, renewable waste has a double benefit to societies [8]. Waste-to-energy solutions reduce the amount of waste that needs to be treated or that is disposed of and at the same time produce energy that can replace conventional fossil fuels, hence promoting the evolution towards sustainable paths [9]. Clear examples of such solutions involve the sludge produced in wastewater treatment plants (WWTP), which has a huge potential to be converted into energy or fuels [10], but in many cases still ends up in landfills [11,12]. Nowadays, the most used waste-to-energy solution in WWTP is the conversion of the produced sludge into biogas in digesters [13] and then to electricity and heat in combined

heat and power (CHP) systems [14–16] (Figure 1). Biogas is mainly composed of  $\text{CH}_4$  (50–75%) and  $\text{CO}_2$  (25–45%) [17], and when it is burned with air, mainly  $\text{CO}_2$ , water vapor and nitrogen are released [18].  $\text{CO}_2$  is an important GHG; however, CHP systems are a better solution than emitting  $\text{CH}_4$  during the anaerobic decomposition of sludge [19]. Another alternative to the onsite conversion of biogas to electricity and heat (presented in Figure 1) is to upgrade it [20], thus removing  $\text{CO}_2$  and producing a high purity  $\text{CH}_4$  stream, which is called “biomethane” and can replace traditional natural gas [21]. Biomethane is very versatile. It can be injected into a natural gas grid, where it is mostly consumed for the production of heat [22]. Moreover, it can be used as a transport fuel [20]. Due to its benefits, biogas upgrading techniques for the production of biomethane are increasing in presence at industrial levels [23,24]. Indeed, many studies focused on making the process more affordable have recently been presented [25,26].



**Figure 1.** Process scheme of alternatives to valorize biogas.

The production of biomethane presents itself as a really interesting option for regions with no natural gas reserves and that are far from a high-pressure natural gas grid. The natural gas consumed in those regions needs to be brought by road tankers, hence increasing the overall costs and the environmental impacts caused by the transport. The consumption of locally produced biomethane instead of traditional natural gas would avoid these two issues. Moreover, this alternative prevents the consumption of natural gas, therefore extending the life span of the reserves of this kind of fossil fuel. On the other hand, the upgrading stage needed for removing  $\text{CO}_2$  from biogas and the transportation of the final biomethane to a delivery point would add an important cost to the operation of the WWTP. Therefore, economic feasibility studies are needed to assess the real benefits of upgrading the biogas produced in WWTP into biomethane and its potential profitability for regions far from high-pressure natural gas grids. There are studies that have already addressed the profitability of biogas/biomethane production plants sourced by various substrates in general [27,28] and by sewage sludge in particular [15,29–31]. For example, Venkatesh et al. compared several routes for energy recovery from sewage sludge [29]. Among the several options, they considered biogas upgrading to biomethane for transport. Other examples are the study of Mills et al., which compared producing biomethane for grid injection with other options [15], of Collet et al., which compared (among others) biogas upgrading with biomethane injection into the grid with and without  $\text{CO}_2$  conversion into methane via methanation [30], or of Michailos et al., who studied the techno-economic feasibility of coupling biomethanation with digestate gasification [31]. These studies show that the choice of the most financially and environmentally attractive option depends on several factors, such as the electricity grid carbon intensity, existence of nearby users for the surplus heat produced by CHP systems, fuel and energy vector prices, the weighting factors used to combine the environmental and economic results, incentives, region, etc. For the Portuguese scenario and for regions far from the high-pressure natural gas grid, no studies dealing with the profitability of biomethane production from WWTP have been

found. This work arises as a study for closing the gap herein explained. To the best of the authors' knowledge, no works have been presented to date dealing with profitability studies of the replacement of natural gas by biomethane as a solution for regions far from the high-pressure natural gas grid.

In this work, a real case study approach is used to analyze the economic feasibility of upgrading the biogas produced in the WWTP of Évora (Portugal). Évora was chosen as a real example of a city that is far from the high-pressure natural gas grid and to which the natural gas is supplied by road transportation. To meet the objective proposed, this work is organized as follows. First, the current status of biogas and biomethane production in Portugal is analyzed, followed by a description of the case study selected. The scenarios considered are also explained in this section. The economic model and the main assumptions of this work are explained in the method section. The results obtained are then presented and analyzed, followed by a discussion section. Finally, the conclusion section summarizes the main achievements of our work.

## 2. Biogas and Biomethane in Portugal

In 2020, biomethane from biogas was produced Europe-wide in 729 plants in 18 countries [32,33]. The production has been steadily growing, and so has the size of the biomethane plants [32]. The shift from CHP to upgrading biogas to biomethane that occurs in Europe has various reasons: developments in biogas upgrading technologies, low cost-effectiveness of electricity biogas plants and the new opportunities for biomethane use in the transport sector [34]. In 2017, a total of 1.94 billion cubic meters of biomethane were produced in Europe; with Denmark, Sweden and Germany having the greatest production per capita [32]. Water scrubbing and membrane separation are the most used upgrading techniques [32]. According to Terlouw et al. [35], the European biomethane potential is 95 billion cubic meters by 2050, so the current production is still far away from its potential. Most of the European biomethane is combusted in CHP systems, but its use as a transport fuel has been increasing [36]. In 10 of the EU (European Union) member states, biomethane is injected into the natural gas grid [34]. The European renewable energy directive imposes 14% of renewable energy in the transport sector by 2030, with a sub-target of 3.5% of advanced biofuels and biogas in this sector [37]. This is a political drive towards the implementation of biomethane plants, and it is expected that the sector will develop in Europe in the next decade [38].

In Portugal, most of the biogas comes from landfills and is used in the production of electricity [32]. In 2017, the number of biogas plants in the country was 64 [32], a number that was lower than the one of 1998, 103 [36]. However, this decrease is not reflected in primary biogas production, as shown in Figure 2.

From 1997 to 2018, there was a shift in the main source of biogas from pig slurry residues [39] (included in "other" in Figure 2) to municipal solid wastes [12]. Till 2007, the Portuguese electricity feed-in-tariff favored landfill gas to the detriment of biogas from other sources, which lead to investments in landfill gas systems [40]. Decree-Law 225/2007 of 31 May matched the electricity feed-in-tariff for all biogas sources but did not produce a large impact. One reason for this may be the economic crisis that immediately followed the change in the legislation, and that hindered the investments in the renewable energy sector.

The Portuguese biogas market is not mature in terms of biogas plants installed [41]. There is still untapped potential for the production of biogas in Portugal that needs to be uncovered [40], and new investments are needed to implement biogas systems for the recycling of organic effluents. More than half of this potential comes from municipal wastes, mostly from the organic fraction of municipal solid wastes. The potential of sewage sludge for the production of biogas in the country was estimated as 1.42 PJ/year (considering it is used for CHP) [40]. Less than 20% of this potential was realized in 2018, despite the fact that most of the big WWTP in the country already produce biogas and sell electricity to the grid [36].

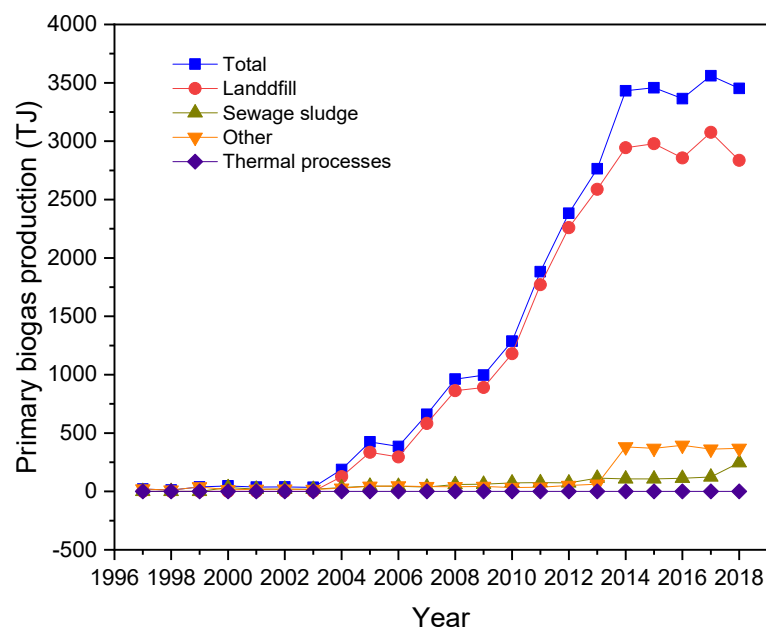


Figure 2. Primary biogas production in Portugal from 1997 to 2018 (Data source: [12]).

To date, there is no biogas upgrading plant in the country, even though the potential exists [36]. The injection of biomethane into the Portuguese natural gas grid would be an interesting option since it could be a partial replacement for the natural gas consumed in the country, which is all imported. Furthermore, it would use the current infrastructure and take advantage of the investments already made in the Portuguese natural gas grid. In line with what has been said, the recent National Energy and Climate Plan [42] lists several actions to be taken for promoting biomethane in Portugal. One of these is the creation of specific regulations for the injection of biomethane into the natural gas grid. Additionally, the plan states that targets for the incorporation of renewable gases will be set. Other than the creation of technical regulations and targets, incentive mechanisms, such as the ones implemented in Sweden, the United Kingdom, Italy, the Netherlands or Germany, can be established so that biomethane is attractive for uses other than power production [36].

### 3. Case Study

#### 3.1. Évora

Évora (38°34'0" N, 7°54'0" W) is a Portuguese city located in a rural region in South-western Iberia. The municipality of Évora occupies an area of 1307 km<sup>2</sup> and hosts circa 57,000 inhabitants. It was selected as a case study on the profitability of upgrading biogas produced in WWTP and injecting it into a local natural gas grid since it is representative of a town in the interior of the country that is not connected to the high-pressure grid. Many other cities are in this situation, and the natural gas that they consume is supplied by road tankers. The consumption of natural gas in Évora in 2018 was  $5.048 \times 10^6$  Nm<sup>3</sup> [43] (services: 37%; industry: 37%; households: 26%), 67% more than ten years before.

#### 3.2. The Évora Wastewater Treatment Plant

The Évora WWTP has an anaerobic biodigester, which receives the primary and secondary sludge that results from the wastewater treatment and produces biogas. Currently, this biogas is burned in a spark-ignition engine that produces electricity and heat. This energy is used internally in the plant; with the heat being used to maintain the digestion process temperature under mesophilic conditions, and the electricity being utilized in the operation of the WWTP. Even though the onsite energy valorization of the biogas produced in the biodigester lowers the electricity consumed in the treatment of the wastewater and helps to reduce the energy consumption from the grid, the main energy vector substituted

is electricity supplied by the national grid, which has an already high incorporation of renewable energies. In 2018, in Portugal, the share of energy from renewable energy sources in electricity, heating and cooling and transport was, respectively, 52%, 41% and 9% [12]. In this context, it is interesting to look for sustainable alternatives for the valorization of the biogas produced in the WWTP.

The WWTP of Évora serves a population equivalent of 47,702 inhabitants and had in 2009 an average volumetric flow rate of effluents of 9987 m<sup>3</sup>/day and of sludge to digest of 87 m<sup>3</sup>/day (74 and 13 m<sup>3</sup>/day of primary and secondary sludge, respectively) [44]. The average BOD5 (biochemical oxygen demand) was 357 mg/L, and its load in the effluent was 104,079 kg/month [44]. The Évora WWTP also receives the scum, oil and fat from other WWTP of the region [44]. The bioreactor produces on average 24,917 m<sup>3</sup> of biogas per month [44]. The Évora WWTP CHP system started operating in 2007 and has 180 kW capacity [44]. It produces an average of 38,564 kWh/month, which represents 26% of the energy consumed in the WWTP [44]. The electricity consumption of the WWTP places it in the consumer band-IC, which corresponded to an electricity price with all taxes and levies included of 0.1440 EUR/kWh in 2018 [12].

### 3.3. The Évora Regasification Unit

Évora is a region that does not have access to the high-pressure natural gas network [45]. Therefore, the natural gas distributed within the city comes from an autonomous regasification unit that receives liquefied natural gas (LNG) arriving in road tankers coming from the LNG terminal of Sines, typically three per week [46]. The tankers transport 19 to 20.5 t of LNG at average thermodynamic conditions of −162 °C and 1 bar [46]. The gasification unit is located in the South of the city (such as the WWTP), 1.2 km away from the WWTP. It contains a reservoir with a capacity of 120 m<sup>3</sup> of LNG (53.4 t of LNG at a temperature of −155 °C and a pressure of 4 bar) [46].

### 3.4. Scenarios Considered

The main motivation to define the scenarios analyzed in this work is considering the shift from producing electricity and heat from the biogas currently generated in the WWTP of Évora to upgrading biogas to biomethane, which enables the replacement of fossil fuels by a renewable gas in applications where other renewable sources are scarcer. The biomethane injected in the natural gas grid would mainly be used for heating purposes (services, industry and households). To fulfill the aforementioned purpose, three scenarios were defined. All of them consider the replacement of the CHP system that is currently working in the WWTP by a biomethane upgrading unit and the construction of a piping system that transports the biomethane to the Évora regasification unit. The main points that differentiate the scenarios are the existence of government incentives for biomethane grid injection and the sale of the CO<sub>2</sub> separated in the upgrading stage.

- Scenario 1: this case was selected as the baseline scenario for the proper comparison with the two actions expressed above. Therefore, in this scenario, no CO<sub>2</sub> is sold, and no incentives for producing biomethane were considered. The different revenues and costs necessary to install and run the biogas upgrading unit are herein analyzed.
- Scenario 2: this case examines the dependence of the economic viability indicators on the prices for selling CO<sub>2</sub>. A discussion on the CO<sub>2</sub> price needed to make the project profitable in comparison with the realistic CO<sub>2</sub> selling price is also included.
- Scenario 3: the last scenario considered in this work includes both the effect of biomethane incentives offered by the government and the sale of CO<sub>2</sub>. Furthermore, a comparison between the biomethane incentives needed to make the project profitable with and without selling the CO<sub>2</sub> was carried out.

## 4. Methods

The discount cash flow method was chosen to assess the profitability of upgrading biomethane in the Évora WWTP under the conditions specified in the aforementioned

scenarios. This method is widely used for the profitability analysis of engineering projects, and it mainly evaluates the difference between revenues and costs (in terms of cash inflows and cash outflows). Furthermore, in this method, the effect of time is taken into account by the discount rate parameter ( $r_d$ ). The indicators usually used to conclude if a project is profitable (enough) or not are the net present value (NPV), discounted payback time (DPBT), internal rate of return (IRR) and profitability index (PI). These indicators are calculated by means of Equation (1) to Equation (4). NPV establishes the difference between the present value of cash inflows and cash outflows over a period of time. DPBT refers to the years needed to recover the initial expenditure considering the time value of money. IRR is the discount rate that makes the NPV of all cash flows of a project equal to zero. Finally, PI indicates the amount of value created per money unit invested.

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

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

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

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

In the above equations,  $I_t$  and  $O_t$  are, respectively, the cash inflow and outflow in the period of time  $t$ ,  $C_{\text{inv}}$  the investment cost and  $n$  the project lifetime.

Cash inflows are calculated by Equation (5).

$$I_t = R_{\text{biomethane}} + R_{\text{CO}_2} + R_{\text{CHP avoided cost}} \quad (5)$$

The yearly revenues obtained by selling biomethane to the grid are calculated by Equation (6) and are based on the average quantity of biomethane produced ( $Q_{\text{biomethane}}$ ) and its unit selling price ( $p_{\text{NG}}$ ) plus the potential incentives that may be provided by the Portuguese government ( $p_{\text{premium}}$ ). The quantity of biomethane was calculated assuming a complete separation of  $\text{CH}_4$  from the average yearly biogas produced in the WWTP and considering that 60% of the biogas is methane [47,48]. It was considered that the biomethane could be sold to the operator of the regasification unit at 0.0263 EUR/kWh, which was, in the second semester of 2018, the price excluding taxes and levies of the natural gas to a consumer in band I5 (consumption between  $1 \times 10^6$  and  $4 \times 10^6$  GJ) [12].

$$R_{\text{biomethane}} = Q_{\text{biomethane}} \times (p_{\text{NG}} + p_{\text{premium}}) \quad (6)$$

The revenues obtained by selling  $\text{CO}_2$  to other industries (Equation (7)) are obtained by the multiplication of the amount of  $\text{CO}_2$  produced yearly ( $Q_{\text{CO}_2}$ ) and the unitary  $\text{CO}_2$  selling price ( $p_{\text{CO}_2}$ ). It was considered that 40% of the biogas is  $\text{CO}_2$  and that this gas can be completely separated from the biogas.

$$R_{\text{CO}_2} = Q_{\text{CO}_2} \times p_{\text{CO}_2} \quad (7)$$

The money currently spent for the operation of the CHP unit would be saved if it would be replaced by a biomethane plant. This is included in the model as a revenue that corresponds to the yearly avoided costs for not using the CHP unit for cogeneration purposes. It is calculated by multiplying the unitary cost for maintaining and operating the CHP unit ( $C_{\text{u,CHP}}$ ) by the average electricity produced by the CHP system monthly ( $Q_{\text{e,CHP}}$ ) and by the number of months in a year (Equation (8)). According to Monte [44], the WWTP would spend between 0.0075 and 0.015 EUR/kWh for the operation and management of

the cogeneration system. An average value of 0.01125 EUR/kWh was chosen to perform the analysis.

$$R_{\text{CHP avoided cost}} = C_{u,\text{CHP}} \times Q_{e,\text{CHP}} \times 12 \quad (8)$$

Cash outflows are calculated by Equation (9). This equation includes a set of costs that are computed in Equation (10) to Equation (16) and that relate to two different stages: biogas upgrading stage (noted by the subscript 1) and biomethane transport to the regasification tank (noted by the subscript 2).

$$O_t = (C_{\text{loan},1} + C_{\text{il},1} + C_{\text{om},1} + C_{\text{df},1} + C_{\text{ins},1}) + (C_{\text{loan},2} + C_{\text{il},2} + C_{\text{om},2}) + C_e + C_{\text{lab}} \quad (9)$$

The costs considered for biogas upgrading were chosen in agreement with previous studies [27,49]. These costs refer to: loan needed to cover the investment to construct the upgrading unit ( $C_{\text{loan},1}$ ), the interests on this loan ( $C_{\text{il},1}$ ), yearly operation and maintenance (O&M) of the upgrading stage ( $C_{\text{om},1}$ ), depreciation ( $C_{\text{df},1}$ ) and insurance ( $C_{\text{ins},1}$ ). The costs of transporting biomethane to the regasification tank are related to: the loan needed to cover the investment in the transport infrastructure ( $C_{\text{loan},2}$ ), the interests on this loan ( $C_{\text{il},2}$ ) and operation and maintenance of the infrastructure ( $C_{\text{om},2}$ ). Moreover, labor costs ( $C_{\text{lab}}$ ) are considered, as is the electricity needed to run the upgrading unit and the electricity to be bought from the grid because the CHP system is replaced by the biomethane upgrading unit ( $C_e$ ).

Loans generate a yearly cash outflow calculated by dividing the amount of money needed for the investment ( $C_{\text{inv},i}$ ) by the number of years to repay the investment ( $n_1$ ) (Equation (10)).

$$C_{\text{loan},i} = \frac{C_{\text{inv},i}}{n_1} \quad (10)$$

where the subscript  $i$  refers to one of the two stages needed to deliver biomethane to the local grid (it takes a value of 1 for the investment in the biogas upgrading stage and 2 for the investment in the infrastructure needed to transport the biomethane to the regasification unit). The investment costs were calculated based on typical unitary costs  $C_{u,\text{inv},i}$  taken from the literature and reported in Table 1. It was considered that the loan would be repaid in 15 years [49].

The interests on the loans were expressed as previously done by other authors [49] (Equation (11)).

$$C_{\text{il},i} = [C_{\text{inv},i} - C_{\text{loan},i} \times (t + 1)] \times r_{\text{int}} \quad (11)$$

where time ( $t$ ) and interest rate ( $r_{\text{int}}$ ) play a key role. A 3% interest rate was considered, based on the SME financing costs in Portugal (average of the median reported in the period between 2014 and the 1st semester of 2019 [50]).

O&M and insurance costs were calculated as a percentage of the investment costs ( $p_{\text{mo},i}$  and  $p_{\text{ins}}$ , respectively, for O&M and insurance). Similarly, the depreciation costs were calculated as a percentage of the loan ( $p_{\text{df}}$ ) (Equations (12)–(14)).

$$C_{\text{om},i} = C_{\text{inv},i} \times p_{\text{om},i} \quad (12)$$

$$C_{\text{df},1} = C_{\text{loan},1} \times p_{\text{df}} \quad (13)$$

$$C_{\text{ins},1} = C_{\text{inv},1} \times p_{\text{ins}} \quad (14)$$

The cost of the electricity is the sum of two terms: (i) the cost of electricity spent to upgrade the biogas produced, calculated from the amount of biogas that is produced by the biodigester monthly ( $Q_{\text{biogas}}$ ), the consumption of electricity per unit of biogas upgraded ( $C_{u,e}$ ), and the electricity price ( $p_e$ ); and (ii) the electricity that would not be produced by

the CHP system and, therefore, would need to be purchased. The latter depends on the electricity produced by the CHP system ( $Q_{e,CHP}$ ) and the electricity unit price.

$$C_e = 12 \times Q_{\text{biogas}} \times C_{u,e} \times p_e + 12 \times Q_{e, \text{CHP}} \times p_e \quad (15)$$

Additionally, the labor cost ( $C_{\text{lab}}$ ) was calculated by multiplying the number of extra operators needed to run the upgrading unit ( $n_{\text{op}}$ ) by the annual cost of an operator ( $C_{\text{lab,u}}$ ). The latter was based on the Portuguese yearly national minimum wage (8400 EUR/year [12]), plus the mandatory social security contributions (1995 EUR/year [51], and 1154 EUR/year [45]).

$$C_{\text{lab}} = C_{\text{lab,u}} \times n_{\text{op}} \quad (16)$$

It is worth mentioning that an additional compression stage following biogas upgrading is not needed since it was assumed that the natural gas tank operates at a similar pressure to that of the biomethane produced [52]. It was considered that the lifetime of the project is 20 years [53] and that the discount rate ( $r_d$ ) is 6%. This value was calculated by summing the Portuguese inflation rate in 2019 (0.3% [12]), the SME financing costs in Portugal in the first semester of 2019 (median, 1.85% [50]) and a term accounting for the risk (3.85%). A list of the model inputs is presented in Table 1.

**Table 1.** Economic variables used as input for the profitability study.

Variable	Value	Reference
$p_{\text{NG}}$ (EUR/MWh)	27.3	[12]
$C_{u,\text{inv},1}$ (EUR/m <sup>3</sup> )	6000	[27,49,54]
$C_{u,\text{inv},2}$ (EUR/km)	237,500	[28]
$n_1$ (y)	15	[55]
$r_{\text{int}}$ (%)	3	[50]
$p_{\text{om},1}$ (%)	10	[28]
$p_{\text{om},2}$ (%)	10	[56]
$p_{\text{df}}$ (%)	20	[28]
$p_{\text{ins}}$ (%)	1	[49]
$C_{u,e}$ (kWh/m <sup>3</sup> )	0.29	[54]
$p_e$ (EUR/kWh)	0.144	[57]
$C_{\text{lab,u}}$ (EUR/year/worker)	11,549	[27]
$n_{\text{op}}$ (worker)	1	[49]
$n_{\text{wh}}$ (h/year)	8000	[58]
$r_d$ (%)	6	-
$Q_{\text{biogas}}$ (m <sup>3</sup> /month)	24,917	[44]
$Q_{e,\text{CHP}}$ (kWh/month)	38,564	[44]
$Q_{u,\text{CHP}}$ (EUR/KWh)	0.01125	[44]

## 5. Results

### 5.1. Baseline Scenario Results

Table 2 shows the results obtained for the baseline scenario. As it can be seen, the project herein proposed is not feasible under the conditions imposed, revealing the great challenge ahead in the path towards more sustainable societies with improved resilience. From the profitability analysis, a negative NPV of EUR −1325 k was obtained. Other parameters to highlight are the long DPBT obtained (more than 20 years, in agreement with the negative value obtained for NPV) and a PI of −2.23. These results would be very hard to overcome by optimizing plant parameters and increasing the number of years to recover the investment. Indeed, as it can be seen in Figure 3A, the poor economic performance is a consequence of the project presenting much higher total yearly costs than total yearly revenues. The relationship between yearly cash inflows (revenues, in green) and outflows (cost, in red) is not constant throughout the lifetime of the project, but, for example, in the first year, the costs are EUR 183 k and the revenues EUR 51 k. In these circumstances, if the

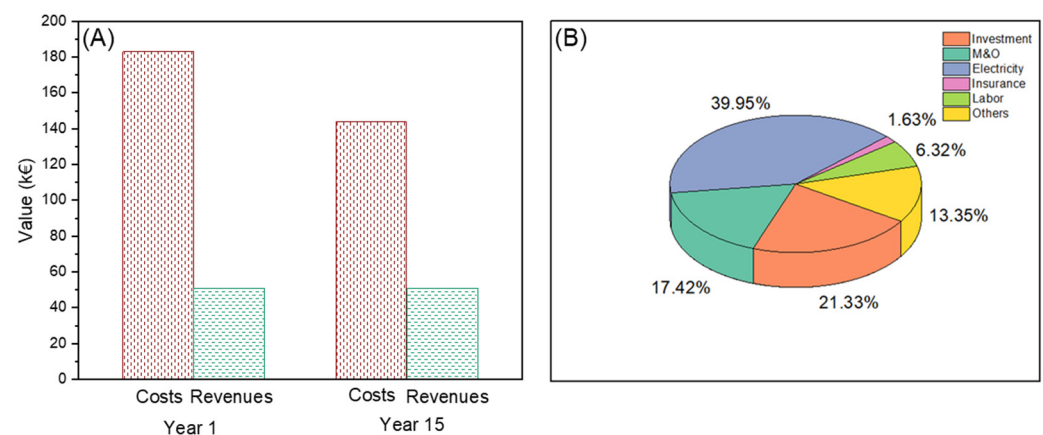


project lifetime was increased, the NPV would only evolve towards higher negative values over time.

**Table 2.** Results obtained for the baseline case.

Indicator (Units)	Value
NPV (k EUR)	−1325
DPBT (years)	>20
IRR (%)	n.d.
PI (-)	−2.23

To have a complete picture of the cash outflows and to find a profitable proposal that may be attractive for investors, costs were disaggregated and analyzed (Figure 3B).



**Figure 3.** Analysis of results obtained for the baseline scenario. (A) Annual costs and revenues for the baseline scenario. (B) Total cost disaggregation.

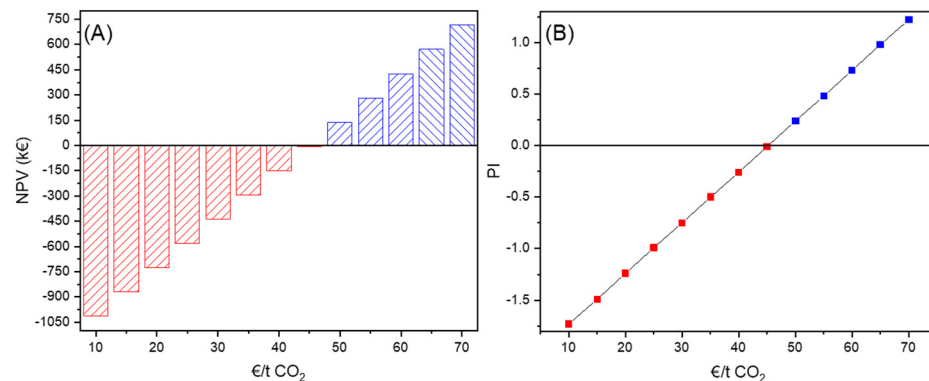
Electricity has the highest share of the costs. Most of the electricity costs (approximately 85% of the electricity share) refer to the electricity that needs to be bought to the national grid because the CHP system stops working. The rest of the electricity costs (approximately 15% of the electricity share) refer to the electricity consumption for biogas upgrading. One can see that the fact that the WWTP stops the production of electricity from biogas in the CHP unit to start upgrading biogas is strongly impacting the profitability of the project. This result was expected because electricity is much more expensive than natural gas. Other relevant costs are related to total investment, labor and O&M and should be considered further. The former could be partially covered by incentives in the form, for example, of investment subsidies, which could be granted by the Portuguese government as a percentage of the initial investment costs. The other two costs mentioned are not easy to reduce since it could directly affect the day-to-day operation of the biomethane plant.

It seems clear that, under the impositions introduced by the baseline scenario, there is not a chance to obtain profitability. To improve the baseline scenario, two extra revenues can be considered to balance the economic performance of the project: the CO<sub>2</sub> separated from the biogas stream could be sold, and government incentives for the production of biomethane could be granted. The impact of these two options will be analyzed below.

### 5.2. Impact of Selling CO<sub>2</sub> on the Profitability of the Biomethane Unit Proposed

In this section, the economic feasibility of replacing the CHP system currently in use in the Évora WWTP by a biomethane upgrading unit and by the transport infrastructure to inject biomethane into the local natural gas grid was analyzed assuming that all the CO<sub>2</sub> produced is sold. In order to properly examine the dependence of the project feasibility on the CO<sub>2</sub> selling price, a wide range of prices was considered in the analysis (from 10 to 70 EUR/t CO<sub>2</sub>). The commercial price of CO<sub>2</sub> depends greatly on the region and industry

and ranges from 3 to 360 EUR/t [59]. The lowest prices correspond to long-term contracts for CO<sub>2</sub> from ammonia producers, the highest to small amounts of CO<sub>2</sub> for lab purposes with a high degree of purity. Considering the capacities treated in this study, a price in the range of 10–70 EUR/t of CO<sub>2</sub> was assumed. Figure 4 shows the results obtained for the NPV (Figure 4A) and PI (Figure 4B) as a function of the CO<sub>2</sub> price considered.



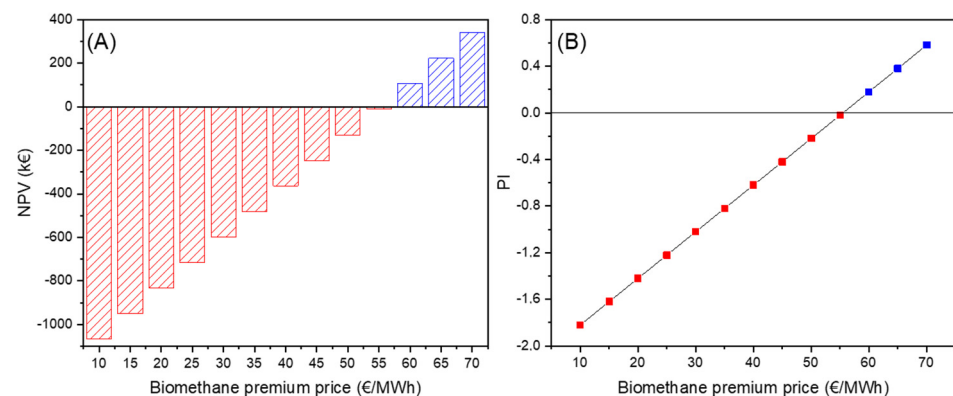
**Figure 4.** Economic results as a function of the CO<sub>2</sub> selling price. (A) NPV; (B) PI.

At 30 EUR/t CO<sub>2</sub>, the price considered as the reference price for CO<sub>2</sub> in this study (see Section 5.3), an NPV value of EUR −437 k was obtained, which is still not attractive for investors. In agreement with Figure 4A, a zero NPV would be obtained at around 46 EUR/t CO<sub>2</sub>, which is probably a too high commercial price. Even 55 EUR/t CO<sub>2</sub> would produce little benefits (EUR 282 k NPV) in comparison with other investment options. Figure 4B shows similar behavior for the PI parameter. Therefore, selling all the CO<sub>2</sub> produced is not enough to pay for the investment of transforming an existing biogas/CHP plant into a biomethane plant if we assume a realistic selling price for the CO<sub>2</sub>.

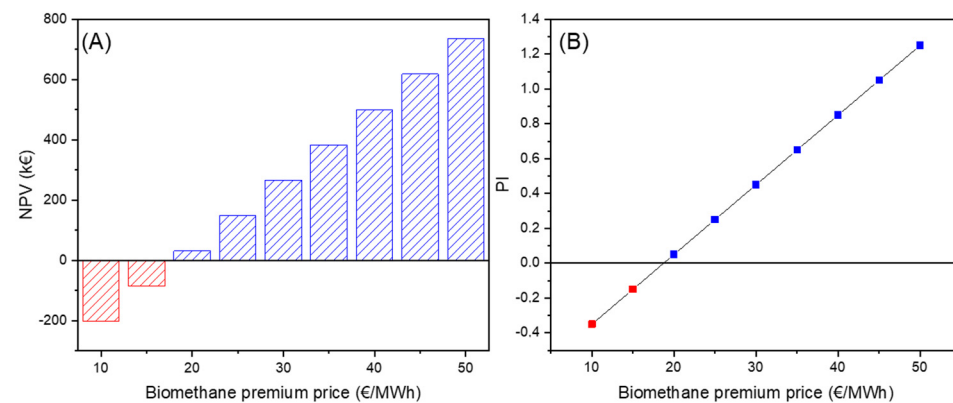
At this point, it is worth mentioning that the rationale underlying the consideration of selling the CO<sub>2</sub> that inevitably results from the upgrading process is not making a profit with the production of CO<sub>2</sub> but to give a use to this GHG. The objective of the biogas/biomethane unit should always be optimizing the CH<sub>4</sub> fraction in the biogas stream, and hence its energy content. This point will be further discussed in Section 6.

### 5.3. Impact of Incentives for Producing Biomethane on the Profitability of the Biomethane Unit Proposed

In this section, incentives for biomethane production will be considered assuming two scenarios: one where all the CO<sub>2</sub> produced is sold at a price of 30 EUR/t CO<sub>2</sub>, and another where the CO<sub>2</sub> is not valorized. It is assumed that the payment structure of the feed-in tariff policy is based on a premium price. Figures 5 and 6 present the NPV and PI results obtained for different biomethane premium prices, when CO<sub>2</sub> is not sold (Figure 5A,B) and when it is sold (Figure 6A,B). As it can be observed, the difference is noticeable. No profitable scenarios were found in those cases in which CO<sub>2</sub> sales were not considered for feed-in premium values below 55.5 EUR/MWh. Indeed, the first feed-in premium value which shifts the profitability sign is 55.5 EUR/MWh. On the other hand, if CO<sub>2</sub> was sold in the market, around 20 EUR/MWh of government incentives would be necessary to achieve profitability. The first NPV positive value would be obtained if the government offered a feed-in premium of 18.67 EUR/MWh. At this value, the DPBT would be 19 years, which is quite high for this kind of investment and still not very attractive. IRR and PI would be 9% and 0.0003, respectively.



**Figure 5.** Economic results dependence on the biomethane premium price (no CO<sub>2</sub> is sold). (A) NPV; (B) PI.



**Figure 6.** Economic results dependence on the biomethane premium price (CO<sub>2</sub> sold at 30 EUR/t). (A) NPV; (B) PI.

## 6. Discussion

From the results presented above, one can conclude that, under the current circumstances, it is not economically viable to replace the existent CHP unit with a plant that upgrades biogas to biomethane at the Évora WWTP. The capital expenditure is too high, the revenues would not be enough, and the investment would only be feasible if there were support measures for the development of the biomethane market in Portugal. One possibility in the context of a circular economy would be to investigate the opportunities of selling the CO<sub>2</sub> that inevitably would be separated from the methane. But even if this could be done, the present results show that economic viability was only obtained if the WWTP would simultaneously receive a feed-in premium for the biomethane injected in the local grid. Alone, the current CO<sub>2</sub> market price is not enough to make the investment profitable. CO<sub>2</sub> is needed for a wide range of industrial applications; the most important of them are described below. In the metal industry, CO<sub>2</sub> can be used to improve the hardness of casting molds [60]. For construction purposes, CO<sub>2</sub> is also used as dry ice pellets for removing extra paint. Within the chemical-oil industry, methanol industrial manufacturing also employs CO<sub>2</sub> in considerable quantities, as well as it is used for enhanced oil recovery (EOR) in oil wells [61]. In the food and beverages industry, CO<sub>2</sub> is typically used to carbonate soft drinks, beers and wine. In the production processes, it can also be used as supercritical fluid [62,63]. The fertilizer industry is another important CO<sub>2</sub> consumer [59]. Even though CO<sub>2</sub> can be used in the aforementioned applications, the necessities are not high when compared to the world's CO<sub>2</sub> emissions. Globally, around 230 Mt of CO<sub>2</sub> are used each year industrially; with the fertilizer industry (i.e., urea) being the largest consumer (130 Mt CO<sub>2</sub>/year). The oil and gas sector consumes around 70–80 Mt yearly for EOR activities. Yearly global CO<sub>2</sub> emissions are over 36,000 Mt nowadays, and this value is expected to

increase during the forthcoming years [64]. Thus, only a small percentage of CO<sub>2</sub> total emissions are currently used for industrial purposes. In this context, selling CO<sub>2</sub> should not be seen as a means of investments in biomethane upgrading units reaching profitability.

Under the current market conditions, the replacement of the CHP unit with an upgrading plant is not recommended. However, the existing CHP unit is already 14 years old and when it needs to be replaced or stops working, considering its substitution by another technology would be interesting. If the CHP stopped working today and was not substituted, the NPV of the investment on upgrading and transporting biomethane would be EUR −643 k without government incentives and without valorizing the CO<sub>2</sub> produced. Under these premises, 27.5 EUR/MWh of feed-in premium would be needed to render the project profitable. In the scenario where all the CO<sub>2</sub> could be sold at 30 EUR/t, EUR 220 k of NPV would be obtained with this government support. This would allow for the replacement of the CHP unit by a biogas upgrading plant.

The existence of a stable and reliable legal and political framework and effective support schemes is the greatest driver for the development of the biomethane market [41]. To date, the biomethane sector does not have a lot of support in EU member states, and the existent support is focused on the transport sector [41]. Portugal, having no specific regulations for biomethane injection into the grid and no specific support scheme for biomethane yet does not promote the conversion of wastes into this energy source. In fact, not even the conversion of wastes in biogas is promoted in the country. If the 2030 targets defined in the National Climate and Energy Plan are to be reached, the promotion of biogas and biomethane is an important step. Renewable gases are one of the ways for renewable energies to penetrate into the heating and transport sectors. These (especially the latter) are the sectors where the market uptake of renewable energies has been more difficult. Decarbonizing the Portuguese energy system will require decarbonizing the gas industry, and biomethane produced from waste has important environmental advantages. For the scenarios studied in this work, the injection of biomethane into the Évora gas grid could replace around 4% of fossil fuel.

To put the results of the present work into context, the feed-in premium that is necessary to make biomethane production in the Évora WWTP profitable (with and without selling CO<sub>2</sub>) is lower than the feed-in premium currently offered by the Italian government for biomethane production, which is 61 EUR/MWh [65]. In Italy, biogas is well-established as a renewable energy source, but only a few biomethane plants exist [65]. With the objective of increasing the production of biomethane and advanced biofuels for transport, a new incentive scheme based on a biofuel certificate system came into effect in 2018 [66]. If the Portuguese government supported biomethane in a similar way, it would be profitable for the Évora WWTP to upgrade the biogas it produces to biomethane even without selling CO<sub>2</sub>. This type of incentive is important for developing the biomethane market in the first stage. However, other types of support schemes need to be designed so that there is a market for biomethane beyond the end of this kind of financial support. One possibility is the establishment of quotas for biomethane in the gas that is supplied by natural gas grids or an increase in the price for emission allowances [67].

Another chance of improving the profitability of the project herein presented would be the production of a bigger biogas stream. This could be achieved by receiving in the WWTP the sludge of other nearby regions. Nevertheless, this option would require equipment with much more capacity, trucks that would bring the sludge to Évora or the construction of facilities to transport them, and higher labor costs to accomplish the different tasks. Inasmuch as that the scenario herein assumed would change drastically, this idea opens new windows for further research in future works.

The present results were obtained for an existent WWTP, the Évora WWTP; however, they can serve as an indication of the viability of biogas upgrading in other WWTP in regions far from the national natural gas grid. In the country, several other regasification units with different distances to the high-pressure natural gas grid exist [68–70]. Investi-

gating the profitability of implementing biomethane plants close to WWTP would be an interesting future work.

In connection with the recent COVID-19 pandemic, the investment in renewable energy production plants is a need to boost the sustainability and the resilience of our society. As recently claimed by some authors, air quality improved considerably after three months of the pandemic, revealing that our energy sector must shift towards a more sustainable one [71]. However, this is not a task only for the energy sector but a global effort of our society, including other sectors, such as the transport [72] or food industry [73].

## 7. Conclusions

This study shows that, under the current conditions, producing biomethane from biogas in the Évora WWTP is unprofitable without the existence of support measures. Indeed, the analysis reveals that a 55.5 EUR/MWh feed-in premium would be needed to reach profitability without selling CO<sub>2</sub>. If CO<sub>2</sub> was sold at 30 EUR/t, the feed-in premium needed would be decreased to 20 EUR/MWh. However, there is a high uncertainty that the WWTP would be capable of selling CO<sub>2</sub> at this price. Additionally, selling the CO<sub>2</sub> should not be seen as a means of making the investments in biomethane plants profitable. In any case, the goal of a biogas/biomethane plant should be to optimize CH<sub>4</sub> production to the detriment of CO<sub>2</sub> production.

The results herein presented invite the reflection upon the need for new policies to boost the presence of biomethane in regions far from a high-pressure grid. In this sense, the consumption of biomethane would not only avoid the consumption of fossil resources but would also minimize the external dependence of many regions on natural gas, which is currently supplied by road transport. As proved in our analysis, the evolution towards a bio-economy society needs large economic efforts. Thus, the Portuguese government should play an important role in the development of biomethane production plants in the coming years.

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## List of Abbreviations

### Abbreviation Name

CHP	Combined heat and power
COVID-19	Disease caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)
EOR	Enhanced oil recovery
GHG	Greenhouse gas
LNG	Liquefied natural gas
O&M	Operation and maintenance
WWTP	Wastewater treatment plant

## Nomenclature

Symbol	Name	Units
BOD5	Biochemical Oxygen Demand	mg/L
$C_{df}$	Depreciation Cost	EUR
$C_e$	Electricity Cost	EUR
$C_{il}$	Interest of Loan Cost	EUR
$C_{ins}$	Insurance Cost	EUR
$C_{inv}$	Investment Cost	EUR
$C_{lab}$	Labor Cost	EUR
$C_{labu}$	Unitary Labor Cost	EUR/worker
$C_{loan}$	Cost of Loan	EUR
$C_{om}$	Maintenance & Overhead Cost	EUR
$C_{u,CHP}$	Unitary Cost for Combined Heat and Power	EUR/kWh
$C_{u,e}$	Unitary Cost for Electricity	EUR/kWh
$C_{u,inv}$	Unitary Investment Cost	EUR/m <sup>3</sup>
$C_{ueBU}$	Unitary Electricity Consumption for Biogas Upgrading	kWh/m <sup>3</sup> biogas
DPBT	Discounted Payback Time	years
IRR	Internal Rate of Return	%
$I_t$	Cash Inflow at year $t$	EUR
$N$	Number of Years	years
$n_l$	Loan Years	years
$n_{op}$	Number of workers	workers
NPV	Net Present Value	EUR
$n_{wh}$	Working hours	h/y
$O_t$	Cash Outflow at year $t$	EUR
$p_{df}$	Depreciation Percentage	%
$p_e$	Electricity Price	EUR/kWh
PI	Profitability Index	EUR/EUR
$p_{ins}$	Insurance Percentage	%
$p_{mo}$	Maintenance & Overhead Percentage	%
$p_{ng}$	Natural Gas Price	EUR/MWh
$p_{CO_2}$	Carbon Dioxide Price	EUR/t
$p_{premium}$	Incentives price	EUR/MWh
$Q_{biogas}$	Biogas Flow	m <sup>3</sup> /h
$Q_{biomethane}$	Biomethane Flow	m <sup>3</sup> /h
$Q_{CO_2}$	Carbon Dioxide Flow	m <sup>3</sup> /h
$Q_{e,CHP}$	Average Electricity Produced by Combined Heat and Power	kWh/month
$R_{biomethane}$	Biomethane Revenues	EUR
$R_{CHP \text{ avoided cost}}$	Avoided Cost for Combined Heat and Power	EUR
$R_{CO_2}$	Carbon Dioxide Revenues	EUR
$r_d$	Discount Rate	%
$r_{int}$	Interest rate	%
$t$	Time	years

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