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

Francisco M. Baena-Moreno [1,2,*], Isabel Malico [2,3,*] and Isabel Paula Marques [4]

[1] Chemical and Environmental Engineering Department, Technical School of Engineering, University of Seville, 41092 Sevilla, Spain
[2] Department of Mechatronics Engineering, University of Évora, 7000-671 Évora, Portugal
[3] Instituto Superior Técnico (IDMEC), Universidade de Lisboa, 1049-001 Lisboa, Portugal
[4] Laboratório Nacional de Energia e Geologia (LNEG), 1649-038 Lisboa, Portugal; isabel.paula@lneg.pt
* Correspondence: fbaena2@us.es (F.M.B.-M.); imbm@uevora.pt (I.M.)

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_2 separated from biogas may result in an additional income, this option was also considered. In this case, a price of 46 EUR/t CO_2 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_2, the project would only be profitable for feed-in premia above 55.5 EUR/MWh. If all the CO_2 produced was sold at 30 EUR/t CO_2, 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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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 CH_4 (50–75%) and CO_2 (25–45%) [17], and when it is burned with air, mainly CO_2, water vapor and nitrogen are released [18]. CO_2 is an important GHG; however, CHP systems are a better solution than emitting 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 CO_2 and producing a high purity 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].

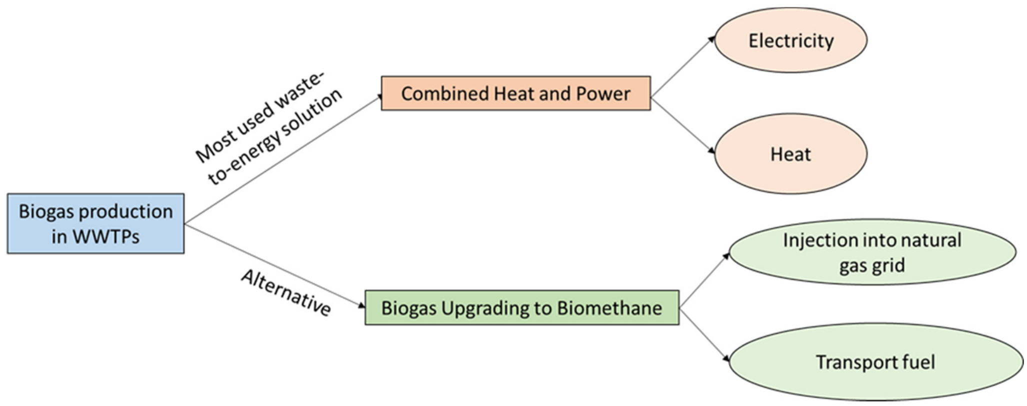

Figure 1. Process scheme of alternatives to valorize biogas.

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 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 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].

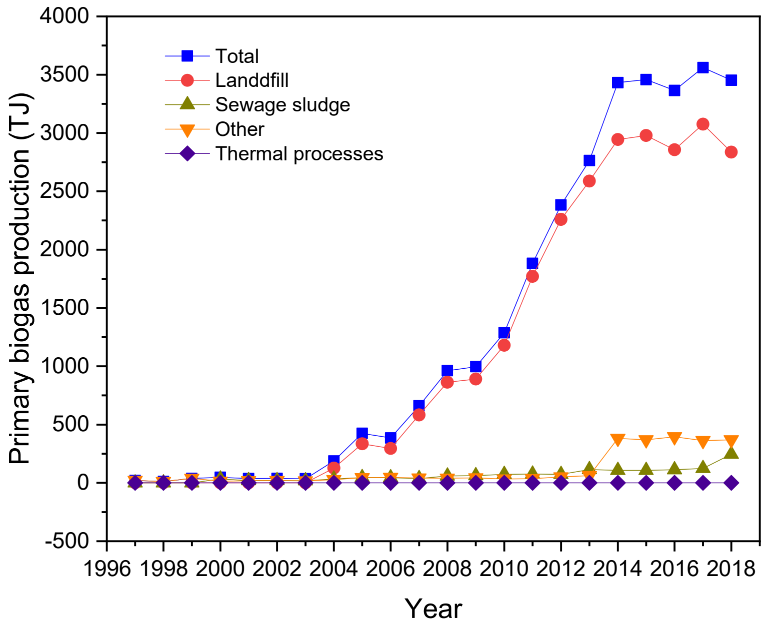

Figure 2. Primary biogas production in Portugal from 1997 to 2018 (Data source: [12]).

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 Netherland 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 Southwestern Iberia. The municipality of Évora occupies an area of 1307 km^2 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^3 [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^3/day and of sludge to digest of 87 m^3/day (74 and 13 m^3/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^3 of biogas per month [44]. The Évora WWTP CHP system started operating in 2007 and has 180 kWe 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^3 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_2 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_2 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_2. A discussion on the CO_2 price needed to make the project profitable in comparison with the realistic CO_2 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_2. Furthermore, a comparison between the biomethane incentives needed to make the project profitable with and without selling the CO_2 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.

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

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

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

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

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

Cash inflows are calculated by Equation (5).

$$I_t = R_{\mathrm{biomethane}} + R_{\mathrm{CO_2}} + R_{\mathrm{CHP\ avoided\ cost}} \tag{5}$$

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 ($Q_{\mathrm{biomethane}}$) and its unit selling price (p_{NG}) plus the potential incentives that may be provided by the Portuguese government (p_{premium}). The quantity of biomethane was calculated assuming a complete separation of 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 1×10^6 and 4×10^6 GJ) [12].

$$R_{\mathrm{biomethane}} = Q_{\mathrm{biomethane}} \times \left(p_{\mathrm{NG}} + p_{\mathrm{premium}}\right) \tag{6}$$

The revenues obtained by selling CO_2 to other industries (Equation (7)) are obtained by the multiplication of the amount of CO_2 produced yearly ($Q_{\mathrm{CO_2}}$) and the unitary CO_2 selling price ($p_{\mathrm{CO_2}}$). It was considered that 40% of the biogas is CO_2 and that this gas can be completed separated from the biogas.

$$R_{\mathrm{CO_2}} = Q_{\mathrm{CO_2}} \times p_{\mathrm{CO_2}} \tag{7}$$

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 ($C_{\mathrm{u,CHP}}$) by the average electricity produced by the CHP system monthly ($Q_{\mathrm{e,CHP}}$) 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.

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

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).

$$\begin{aligned} O_{\text{t}} = {} & (C_{\text{loan},1} + C_{\text{il},1} + C_{\text{om},1} + C_{\text{df},1} + C_{\text{ins},1}) \\ & + (C_{\text{loan},2} + C_{\text{il},2} + C_{\text{om},2}) + C_{\text{e}} + C_{\text{lab}} \end{aligned} \tag{9}$$

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_{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_{l}) (Equation (10)).

$$C_{\text{loan},i} = \frac{C_{\text{inv},i}}{n_{\text{l}}} \tag{10}$$

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 $C_{\text{u,inv},i}$ 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)).

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

where time (t) and interest rate (r_{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_{ins}, respectively, for O&M and insurance). Similarly, the depreciation costs were calculated as a percentage of the loan (p_{df}) (Equations (12)–(14)).

$$C_{\text{om},i} = C_{\text{inv},i} \times p_{\text{om},i} \tag{12}$$

$$C_{\text{df},1} = C_{\text{loan},1} \times p_{\text{df}} \tag{13}$$

$$C_{\text{ins},1} = C_{\text{inv},1} \times p_{\text{ins}} \tag{14}$$

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_{biogas}), the consumption of electricity per unit of biogas upgraded ($C_{\text{u,e}}$), 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.

$$C_e = 12 \times Q_{biogas} \times C_{u,e} \times p_e + 12 \times Q_{e,\, CHP} \times p_e \tag{15}$$

Additionally, the labor cost (C_{lab}) was calculated by multiplying the number of extra operators needed to run the upgrading unit (n_{op}) by the annual cost of an operator ($C_{lab,u}$). 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]).

$$C_{lab} = C_{lab,u} \times n_{op} \tag{16}$$

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

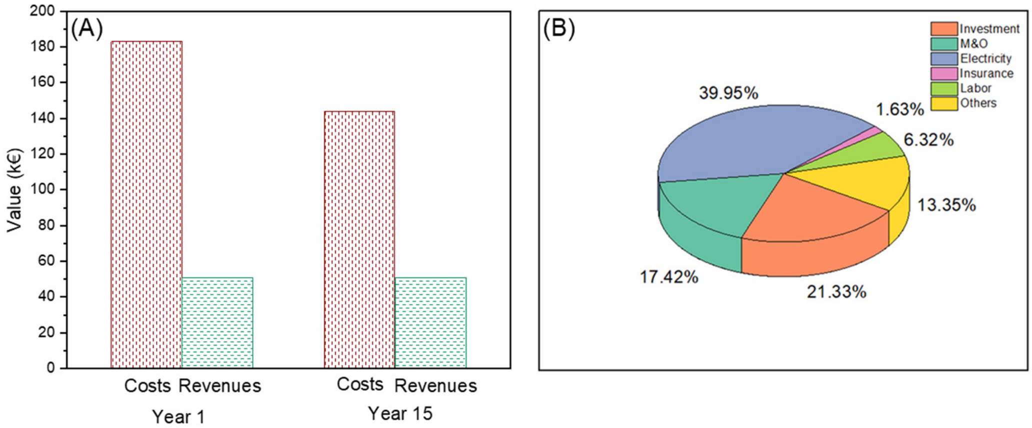

Figure 3. Analysis of results obtained for the baseline scenario. (**A**) Annual costs and revenues for the baseline scenario. (**B**) Total cost disaggregation.

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_2 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_2 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_2 produced is sold. In order to properly examine the dependence of the project feasibility on the CO_2 selling price, a wide range of prices was considered in the analysis (from 10 to 70 EUR/t CO_2). The commercial price of CO_2 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_2 from ammonia producers, the highest to small amounts of CO_2 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_2 was assumed. Figure 4 shows the results obtained for the NPV (Figure 4A) and PI (Figure 4B) as a function of the CO_2 price considered.

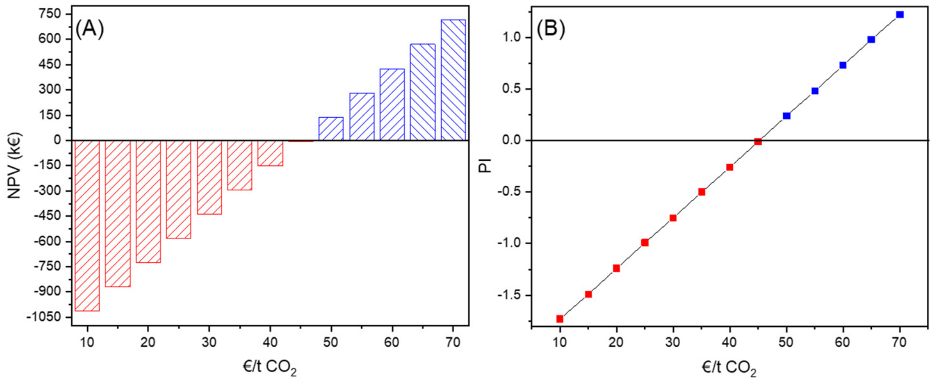

Figure 4. Economic results as a function of the CO_2 selling price. (**A**) NPV; (**B**) PI.

At 30 EUR/t CO_2, the price considered as the reference price for CO_2 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_2, which is probably a too high commercial price. Even 55 EUR/t CO_2 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_2 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_2.

At this point, it is worth mentioning that the rationale underlying the consideration of selling the CO_2 that inevitably results from the upgrading process is not making a profit with the production of CO_2 but to give a use to this GHG. The objective of the biogas/biomethane unit should always be optimizing the CH_4 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_2 produced is sold at a price of 30 EUR/t CO_2, and another where the CO_2 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_2 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_2 sales were not considered for feed-in premium values below 55 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_2 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.

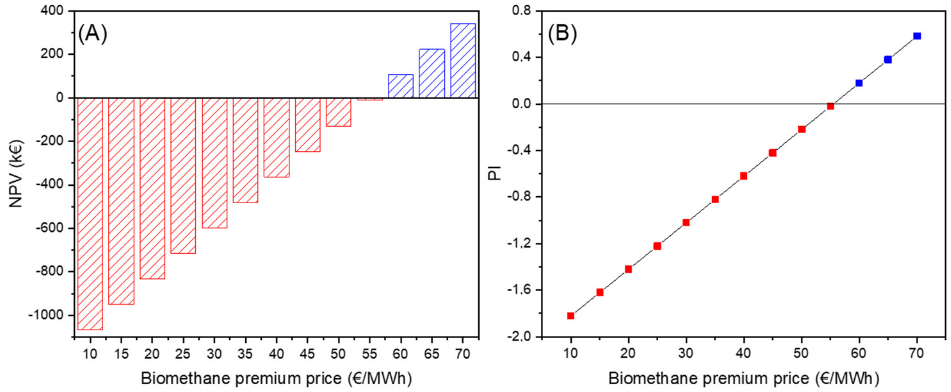

Figure 5. Economic results dependence on the biomethane premium price (no CO_2 is sold). (**A**) NPV; (**B**) PI.

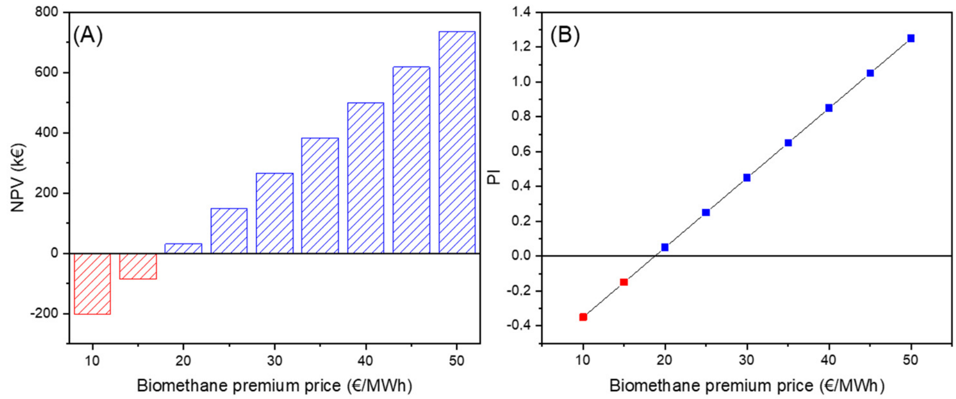

Figure 6. Economic results dependence on the biomethane premium price (CO_2 sold at 30 EUR/t). (**A**) NPV; (**B**) PI.

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_2 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_2 market price is not enough to make the investment profitable. CO_2 is needed for a wide range of industrial applications; the most important of them are described below. In the metal industry, CO_2 can be used to improve the hardness of casting molds [60]. For construction purposes, CO_2 is also used as dry ice pellets for removing extra paint. Within the chemical-oil industry, methanol industrial manufacturing also employs CO_2 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_2 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_2 consumer [59]. Even though CO_2 can be used in the aforementioned applications, the necessities are not high when compared to the world's CO_2 emissions. Globally, around 230 Mt of CO_2 are used each year industrially; with the fertilizer industry (i.e., urea) being the largest consumer (130 Mt CO_2/year). The oil and gas sector consumes around 70–80 Mt yearly for EOR activities. Yearly global CO_2 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_2 total emissions are currently used for industrial purposes. In this context, selling CO_2 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_2 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_2 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_2) 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_2. 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]. Investigating 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_2. If CO_2 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_2 at this price. Additionally, selling the CO_2 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_4 production to the detriment of CO_2 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^3
C_{ueBU}	Unitary Electricity Consumption for Biogas Upgrading	kWh/m^3 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_{CO2}	Carbon Dioxide Price	EUR/t
$p_{premium}$	Incentives price	EUR/MWh
Q_{biogas}	Biogas Flow	m^3/h
$Q_{biomethane}$	Biomethane Flow	m^3/h
Q_{CO2}	Carbon Dioxide Flow	m^3/h
$Q_{e,CHP}$	Average Electricity Produced by Combined Heat and Power	kWh/month
$R_{biomethane}$	Biomethane Revenues	EUR
$R_{CHP\ avoided\ cost}$	Avoided Cost for Combined Heat and Power	EUR
R_{CO2}	Carbon Dioxide Revenues	EUR
r_d	Discount Rate	%
r_{int}	Interest rate	%
t	Time	years

References

1. Pestana, C.; Barros, L.; Scuri, S.; Barreto, M. Can HCI Help Increase People's Engagement in Sustainable Development? A Case Study on Energy Literacy. *Sustainability* **2021**, *13*, 7543. [CrossRef]
2. Baena-Moreno, F.M.; Sebastia-Saez, D.; Pastor-Pérez, L.; Ramirez-Reina, T. Analysis of the potential for biogas upgrading to syngas via catalytic reforming in the United Kingdom. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110939. [CrossRef]
3. Maraqa, M.A.; Albuquerque, F.D.B.; Alzard, M.H.; Chowdhury, R.; Kamareddine, L.A.; El Zarif, J. GHG Emission Reduction Opportunities for Road Projects in the Emirate of Abu Dhabi: A Scenario Approach. *Sustainability* **2021**, *13*, 7367. [CrossRef]
4. Tsiakiri, E.P.; Mpougali, A.; Lemonidis, I.; Tzenos, C.A.; Kalamaras, S.D.; Kotsopoulos, T.A.; Samaras, P. Estimation of Energy Recovery Potential from Primary Residues of Four Municipal Wastewater Treatment Plants. *Sustainability* **2021**, *13*, 7198. [CrossRef]
5. Rosas, J.G.; Gómez, N.; Cara-Jiménez, J.; González-Arias, J.; Olego, M.Á.; Sánchez, M.E. Evaluation of joint management of pine wood waste and residual microalgae for agricultural application. *Sustainability* **2020**, *13*, 53. [CrossRef]

6. International Energy Agency. Renewables Information: Overview. 2019. Available online: https://iea.blob.core.windows.net/assets/6959bcb0-d298-404c-80e1-2afaa784798e/Renewables_Information_2019_Overview.pdf (accessed on 4 July 2021).
7. D'Adamo, I.; Rosa, P. How do you see infrastructure? Green energy to provide economic growth after COVID-19. *Sustainability* **2020**, *12*, 4738. [CrossRef]
8. González-Arias, J.; Carnicero, A.; Sánchez, M.E.; Martínez, E.J.; López, R.; Cara-Jiménez, J. Management of off-specification compost by using co-hydrothermal carbonization with olive tree pruning. Assessing energy potential of hydrochar. *Waste Manag.* **2021**, *124*, 224–234. [CrossRef]
9. Zhang, J.; Mao, L.; Nithya, K.; Loh, K.C.; Dai, Y.; He, Y.; Wah Tong, Y. Optimizing mixing strategy to improve the performance of an anaerobic digestion waste-to-energy system for energy recovery from food waste. *Appl. Energy* **2019**, *249*, 28–36. [CrossRef]
10. Ali, S.M.H.; Lenzen, M.; Sack, F.; Yousefzadeh, M. Electricity generation and demand flexibility in wastewater treatment plants: Benefits for 100% renewable electricity grids. *Appl. Energy* **2020**, *268*, 114960. [CrossRef]
11. Kacprzak, M.; Neczaj, E.; Fijałkowski, K.; Grobelak, A.; Grosser, A.; Worwag, M.; Rorat, A.; Brattebo, H.; Almås, Å.; Singh, B.R. Sewage sludge disposal strategies for sustainable development. *Environ. Res.* **2017**, *156*, 39–46. [CrossRef]
12. Eurostat. 2020. Available online: https://ec.europa.eu/eurostat/data/database (accessed on 4 March 2020).
13. Ning, C.; You, F. Data-driven Wasserstein distributionally robust optimization for biomass with agricultural waste-to-energy network design under uncertainty. *Appl. Energy* **2019**, *255*, 113857. [CrossRef]
14. Schopf, K.; Judex, J.; Schmid, B.; Kienberger, T. Modeling the bioenergy potential of municipal wastewater treatment plants. *Water Sci. Technol.* **2018**, *77*, 2613–2623. [CrossRef] [PubMed]
15. Mills, N.; Pearce, P.; Farrow, J.; Thorpe, R.B.; Kirkby, N.F. Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies. *Waste Manag.* **2014**, *34*, 185–195. [CrossRef]
16. Vasco-Correa, J.; Khanal, S.; Manandhar, A.; Shah, A. Anaerobic digestion for bioenergy production: Global status, environmental and techno-economic implications, and government policies. *Bioresour. Technol.* **2018**, *247*, 1015–1026. [CrossRef] [PubMed]
17. Baena-Moreno, F.M.; Rodríguez-Galán, M.; Vega, F.; Vilches, L.F.; Navarrete, B.; Zhang, Z. Biogas upgrading by cryogenic techniques. *Environ. Chem. Lett.* **2019**, *17*, 1251–1261. [CrossRef]
18. Baena-Moreno, F.M.; le Saché, E.; Pastor-Pérez, L.; Reina, T.R. Membrane-based technologies for biogas upgrading: A review. *Environ. Chem. Lett.* **2020**, *18*, 1649–1658. [CrossRef]
19. Hobson, J. *CH_4 and N_2O Emissions from Waste Water Handling. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*; Intergovernmental Panel on Climate Change (IPCC) Publications: Geneve, Switzerland, 2000.
20. Baena-Moreno, F.M.; Rodríguez-Galán, M.; Ramirez-Reina, T.; Zhang, Z.; Vilches, L.; Navarrete, B. Understanding the effect of Ca and Mg ions from wastes in the solvent regeneration stage of a biogas upgrading unit. *Sci. Total Environ.* **2019**, *691*, 93–100. [CrossRef]
21. Nguyen, L.N.; Kumar, J.; Vu, M.T.; Mohammed, J.A.H.; Pathak, N.; Commault, A.S.; Sutherland, D.; Zdarta, J.; Tyagi, V.K.; Nghiem, L.D. Biomethane production from anaerobic co-digestion at wastewater treatment plants: A critical review on development and innovations in biogas upgrading techniques. *Sci. Total Environ.* **2020**, *765*, 142753. [CrossRef] [PubMed]
22. Awe, O.W.; Zhao, Y.; Nzihou, A.; Minh, D.P.; Lyczko, N. A Review of Biogas Utilisation, Purification and Upgrading Technologies. *Waste Biomass Valoriz.* **2017**, *8*, 267–283. [CrossRef]
23. Calderón, C.; Colla, M.; Jossart, J.-M.; Hemelleers, N.; Martin, A.; Aveni, N.; Caferri, C. *European Bioenergy Outlook 2019*; Biogas: Brussels, Belgium, 2019.
24. Prussi, M.; Padella, M.; Conton, M.; Postma, E.D.; Lonza, L. Review of technologies for biomethane production and assessment of EU transport share in 2030. *J. Clean. Prod.* **2019**, *222*, 565–572. [CrossRef]
25. Baena-Moreno, F.M.; Reina, T.R.; Rodríguez-Galán, M.; Navarrete, B.; Vilches, L.F. Synergizing carbon capture and utilization in a biogas upgrading plant based on calcium chloride: Scaling-up and profitability analysis. *Sci. Total Environ.* **2021**, *758*, 143645. [CrossRef]
26. Baena-Moreno, F.M.; Rodríguez-Galán, M.; Vega, F.; Ramirez-Reina, T.; Vilches, L.; Navarrete, B. Understanding the influence of the alkaline cation K^+ or Na^+ in the regeneration efficiency of a biogas upgrading unit. *Int. J. Energy Res.* **2019**, *43*, 1578–1585. [CrossRef]
27. Cucchiella, F.; D'Adamo, I.; Gastaldi, M.; Miliacca, M. A profitability analysis of small-scale plants for biomethane injection into the gas grid. *J. Clean. Prod.* **2018**, *184*, 179–187. [CrossRef]
28. Ferella, F.; Cucchiella, F.; D'Adamo, I.; Gallucci, K. A techno-economic assessment of biogas upgrading in a developed market. *J. Clean. Prod.* **2019**, *210*, 945–957. [CrossRef]
29. Venkatesh, G.; Elmi, R.A. Economic-environmental analysis of handling biogas from sewage sludge digesters in WWTPs (wastewater treatment plants) for energy recovery: Case study of Bekkelaget WWTP in Oslo (Norway). *Energy* **2013**, *58*, 220–235. [CrossRef]
30. Collet, P.; Flottes, E.; Favre, A.; Raynal, L.; Pierre, H.; Capela, S.; Peregrina, C. Techno-economic and Life Cycle Assessment of methane production via biogas upgrading and power to gas technology. *Appl. Energy* **2017**, *192*, 282–295. [CrossRef]
31. Michailos, S.; Walker, M.; Moody, A.; Poggio, D.; Pourkashanian, M. Biomethane production using an integrated anaerobic digestion, gasification and CO_2 biomethanation process in a real waste water treatment plant: A techno-economic assessment. *Energy Convers. Manag.* **2020**, *209*, 112663. [CrossRef]
32. EBA. *European Biogas Association Statistical Report for Year 2019*; European Biogas Association: Brussels, Belgium, 2020.

33. GIE. EBA European Biomethane Map. Available online: https://www.europeanbiogas.eu/eba-gie-biomethane-map/ (accessed on 4 July 2021).
34. Scarlat, N.; Dallemand, J.F.; Fahl, F. Biogas: Developments and perspectives in Europe. *Renew. Energy* **2018**, *129*, 457–472. [CrossRef]
35. Terlouw, W.; Peters, D.; van Tilburg, J.; Schimmel, M.; Berg, T.; Cilhar, J.; Rehman Mir, G.U.; Spöttle, M.; Staats, M.; Lejaretta, A.V.; et al. *Gas for Climate. The Optimal Role for Gas in a Net-Zero Emissions Energy System*; Navigant Consulting Inc.: Utrecht, The Netherlands, 2019; Volume 231.
36. Cabrita, I.; Silva, L.M.; Marques, I.P.R.; Di Berardino, S.; Gírio, F.M. *Avaliação do Potencial e Impacto do Biometano em Portugal*; LNEG: Lisbon, Portugal, 2015.
37. European Union. Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. *Off. J. Eur. Union* **2018**, *2018*, 1–128.
38. Europe Union. Orientations towards the First Strategic Plan for Horizon Europe. 2019. Available online: https://ec.europa.eu/info/sites/default/files/research_and_innovation/strategy_on_research_and_innovation/documents/ec_rtd_orientations-he-strategic-plan_122019.pdf (accessed on 4 July 2021).
39. Cabrita, I.; Pinto, F.; Lopes, H.; Oliveira, F.; Marques, I.P. *Resíduos Industrias*; INETI, DGEG: Lisbon, Portugal, 2000.
40. Ferreira, M.; Marques, I.P.; Malico, I. Biogas in Portugal: Status and public policies in a European context. *Energy Policy* **2012**, *43*, 267–274. [CrossRef]
41. Kampman, B.; Leguijt, C.; Scholten, T.; Tallat-Kelpsaite, J.; Brückmann, R.; Maroulis, G.; Lesschen, J.P.; Meesters, K.; Sikirica, N.; Elbersen, B. *Optimal Use of Biogas from Waste Streams—An Assessment of the Potential of Biogas from Digestion in the EU beyond 2020*; European Commission: Luxembourg, 2017. [CrossRef]
42. PNEC Plano Nacional de Energia e Clima. Available online: https://apambiente.pt/_zdata/Alteracoes_Climaticas/Mitigacao/PNEC/PNECPT_TemplateFinal201930122019.pdf (accessed on 23 January 2020).
43. DGEG. Consumo de Gás Natural no Mercado Interno em 2018 (Provisório). Available online: http://www.dgeg.gov.pt/ (accessed on 4 July 2021).
44. Monte, M.M.D. Contributo para o Estudo da Valorização Energética de Biogás em Estações de Tratamento de Águas Residuais. Master's Thesis, Nova University of Lisbon, Lisbon, Portugal, 2010.
45. Assembleia da República. *Diário da República*; Lei n.o 88/2017; Assembleia da República: Lisbon, Portugal, 2017; pp. 3190–3228.
46. CertiTecna. *Avaliação de Compatibilidade de Localização*; Dianagás; Unidade Autónoma de Gás Natural (UAG); CertiTecna: Lisbon, Portugal, 2016.
47. Costa, C.M.d.E. Estudo de Melhorias em ETAR com Produção de Biogás e Geração de Eletricidade ETAR Municipal de Abrantes. Master's Thesis, Universidade da Beira Interior, Covilhã, Portugal, 2014.
48. Baena-Moreno, F.M.; Rodríguez-Galán, M.; Vega, F.; Vilches, L.F.; Navarrete, B. Review: Recent advances in biogas purifying technologies. *Int. J. Green Energy* **2019**, *16*, 401–412. [CrossRef]
49. Cucchiella, F.; D'Adamo, I. Technical and economic analysis of biomethane: A focus on the role of subsidies. *Energy Convers. Manag.* **2016**, *119*, 338–351. [CrossRef]
50. European Central Bank (ECB). *Survey on the Access to Finance of Enterprises in the Euro Area—April to September 2019*; ECB: Frankfurt am Main, Germany, 2019.
51. Segurança Social Segurança Social. Available online: www.seg-social.pt/ (accessed on 4 July 2021).
52. Baena-Moreno, F.M.; Malico, I.; Rodríguez-Galán, M.; Serrano, A.; Fermoso, F.G.; Navarrete, B. The importance of governmental incentives for small biomethane plants in South Spain. *Energy* **2020**, *206*, 118158. [CrossRef]
53. Kraussler, M.; Pontzen, F.; Müller-Hagedorn, M.; Nenning, L.; Luisser, M.; Hofbauer, H. Techno-economic assessment of biomass-based natural gas substitutes against the background of the EU 2018 renewable energy directive. *Biomass Convers. Biorefinery* **2018**, *8*, 935–944. [CrossRef]
54. Bortoluzzi, G.; Gatti, M.; Sogni, A.; Consonni, S. Biomethane production from agricultural resources in the Italian scenario: Techno-Economic analysis of water wash. *Chem. Eng. Trans.* **2014**, *37*, 259–264. [CrossRef]
55. D'Adamo, I.; Falcone, P.M.; Ferella, F. A socio-economic analysis of biomethane in the transport sector: The case of Italy. *Waste Manag.* **2019**, *95*, 102–115. [CrossRef] [PubMed]
56. Cucchiella, F.; D'Adamo, I.; Gastaldi, M. Profitability analysis for biomethane: A strategic role in the Italian transport sector. *Int. J. Energy Econ. Policy* **2015**, *5*, 440–449.
57. PORDATA. Electricity Prices for Households and Industrial Users (Euro/ECU). Available online: https://www.pordata.pt/en/Europe/Electricity+prices+for+households+and+industrial+users+(Euro+ECU)-1477 (accessed on 18 July 2019).
58. Skorek-Osikowska, A.; Martín-Gamboa, M.; Iribarren, D.; García-Gusano, D.; Dufour, J. Thermodynamic, economic and environmental assessment of energy systems including the use of gas from manure fermentation in the context of the Spanish potential. *Energy* **2020**, *200*, 117452. [CrossRef]
59. International Energy Agency. *Putting CO2 to Use. Creating Value from Emissions*; International Energy Agency: Paris, France, 2019.
60. Universal Industrial Gases CO2 Industrial Uses. Available online: http://www.uigi.com/carbondioxide.html (accessed on 4 July 2021).

61. Baena-moreno, F.M.; Rodríguez-galán, M.; Vega, F.; Alonso-fariñas, B.; Arenas, L.F.V.; Navarrete, B. Carbon capture and utilization technologies: A literature review and recent advances. *Energy Sources Part A Recover. Util. Environ. Eff.* **2019**, *41*, 1403–1433. [CrossRef]
62. Yan, J.; Zhang, Z. Advances in carbon capture, utilization and storage. *Appl. Energy* **2020**, *278*, 115627. [CrossRef]
63. Zhang, Z.; Pan, S.Y.; Li, H.; Cai, J.; Olabi, A.G.; Anthony, E.J.; Manovic, V. Recent advances in carbon dioxide utilization. *Renew. Sustain. Energy Rev.* **2020**, *125*, 109799. [CrossRef]
64. Ritchie, H.; Roser, M. *CO_2 and Greenhouse Gas Emissions Resource*; Our World in Data: Oxford, UK, 2020.
65. Marc, A.; Carole, M. *Biogas and Biomethane in Europe: Lessons from Denmark, Germany and Italy*; Ifri: Paris, France, 2019.
66. Cucchiella, F.; D'Adamo, I.; Gastaldi, M. Sustainable Italian cities: The added value of biomethane from organic waste. *Appl. Sci.* **2019**, *9*, 2221. [CrossRef]
67. Horschig, T.; Adams, P.W.R.; Gawel, E.; Thrän, D. How to decarbonize the natural gas sector: A dynamic simulation approach for the market development estimation of renewable gas in Germany. *Appl. Energy* **2018**, *213*, 555–572. [CrossRef]
68. Entidade Reguladora dos Serviços Energéticos ERSE. Available online: https://www.erse.pt/ (accessed on 5 March 2020).
69. GALP. Available online: https://galpgasnaturaldistribuicao.pt/ (accessed on 5 March 2020).
70. Sonorgás. Available online: https://www.sonorgas.pt/ (accessed on 5 March 2020).
71. Debone, D.; da Costa, M.; Miraglia, S. 90 Days of COVID-19 Social Distancing and Its Impacts on Air Quality and Health in Sao Paulo, Brazil. *Sustainability* **2020**, *12*, 7440. [CrossRef]
72. Moslem, S.; Campisi, T.; Szmelter-Jarosz, A.; Duleba, S.; Nahiduzzaman, K.; Tesoriere, G. Best–Worst Method for Modelling Mobility Choice after COVID-19: Evidence from Italy. *Sustainability* **2020**, *12*, 6824. [CrossRef]
73. Giudice, F.; Caferra, R.; Morone, P. COVID-19, the Food System and the Circular Economy: Challenges and Opportunities. *Sustainability* **2020**, *12*, 7939. [CrossRef]