**Biogas upgrading to biomethane as a local source of renewable energy to power light marine transport: Profitability analysis for the county of Cornwall**

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**Abstract**

In this work, the use of biomethane produced from local biogas plants is proposed as renewable fuel for light marine transport. A profitability analysis is performed for three real biogas production plants located in Cornwall (United Kingdom), considering a total of 66 different scenarios where critical parameters such as distance from production point to gas grid, subsidies, etcetera, were evaluated. Even though the idea is promising to decarbonize the marine transport sector, under the current conditions, the approach is not profitable. The results show that profitability depends on the size of the biogas plant. The largest biogas plant studied can be profitable if feed-in tariffs subsidies between 36.6 and 45.7 €/MWh are reached, while for the smallest plant, subsidies should range between 65 and 82.7 €/MWh. The tax to be paid per ton of CO2 emitted by the shipping owner, was also examined given its impact in this green route profitability. Values seven times greater than current taxes are needed to reach profitability, revealing the lack of competitiveness of renewable fuels *vs* traditional fuels in this application. Subsidies to make up a percentage of the investment are also proposed, revealing that even at 100% of investment subsidized, this green approach is still not profitable. The results highlight the need for further ambitious political actions in the pursuit of sustainable societies.

**List of abbreviations**

CHP Combined Heat and Power

LNG Liquefied Natural Gas

CNG Compressed Natural Gas

DCF Discounted Cash Flow

NPV Net Present Value (k€)

DPBT Discounted Payback Time (years)

PI Profitability Index (€/€)

It Cash inflows (€)

Ot Cash outflows (€)

rd Discount rate (%)

n Lifetime of the project (years)

t Time (years)

Cinv Investment cost (€)

BU Biogas Upgrading

DB Biogas Distribution

rint Interest rate (%)

Qbiomethane Biomethane flow (m3/h)

Qbiogas Biogas flow (m3/h)

pNG Price of natural gas (€/MWh)

CinvBU Investment cost in BU section (€/m3/h)

CilBU Interest of loan cost (€)

CinvDB Investment cost in DB section (€/km)

CloanBU Cost of the loan in the biogas upgrading section (€)

nl Payback of the loan (years)

M&O Maintenance and Overhead

CmoBU Cost of M&O (€)

CdfBU Depreciation cost in BU section (€)

CinsBU Insurance cost in BU section (€)

CinstBU Installation cost in BU section (€)

pmo Maintenance & Overhead percentage (%)

pdf Depreciation percentage (%)

pins Insurance percentage (%)

CueBU Electricity consumption for biogas upgrading (kWh/m3 biogas)

CloanDB Cost of loan in DB section (€)

CilDB Cost of interest of loan in DB section (€)

CmoDB Cost of Maintenance & Overhead in DB section (€)

CinstDB Cost of installation in DB section (€)

pe Electricity price (€/kWh)

Clab Labour costs (€)

Clabu Unitary labour cost (€/y/worker)

nop Number of workers (worker)

nwh Working hours (h/y)

RTFO Renewable Transport Fuel Obligation

**Keywords:** Biomethane production; Biogas upgrading; CO2 utilization; Green energy production; Waste valorization; Renewable fuels;

1. **Introduction**

Scarcity of fossil fuels and increasing greenhouse gases (GHG) emissions have caused an intensive search for renewable sources of energy (Magazzino et al., 2020; Marazza et al., 2019) sponsored by national and supra-national institutions. The Green Deal Framework (EU) (European Union, 2019), for instance, prioritizes new alternatives for green fuels production and green chemicals from biomass and waste recycling, which are crucial in the transition to bio-based societies. These alternative energy sources are aimed to be flexible low-carbon energy providers in future power systems, that will need further policy support.

One of the key aspects to comply with circular economy is the urgent need for waste disposal minimization and biowaste valorization. Yet more, strategies targeting waste conversion to fuels and chemicals are booming showcasing the momentum of circular economy at scientific and social levels. For example, biogas production from the anaerobic digestion of biomass waste plays a key role in the transition towards decarbonized societies (Tansel and Surita, 2019). Anaerobic digestion has been commonly used to convert biomass (including biowaste) into biogas suitable for further use (J. González-Arias et al., 2020). One of the most promising biogas uses is its upgrading to biomethane (Kvist and Aryal, 2019; Lombardi and Carnevale, 2013). In fact, biomethane could be an interesting option to avoid the utilization of fossil natural gas, allowing the development of bioeconomies where biomass and wastes are the axis of the sought-after circular economy. However, the lack of long-term strategies to develop these alternatives gives rise to uncertainties that need to be mitigated by policy-makers (Hoo et al., 2020). For instance, feed-in tariffs can potentially promote the integration of biomethane into the existing gas market. Thus, undoubtedly, would promote the implementation of circular economy strategies since the market volatility of these processes is one of the strongest dilemmas for investors.

To overcome hesitancy in the use of biomethane and facilitate its implementation in the current economies to transform them into circular economies, it is important to consider potential environmental benefits too. For marine transport applications, the use of liquefied/compressed natural gas (LNG/CNG) as an alternative fuel is gathering momentum due to the strict environmental regulations adopted by governments for other traditional fuels (i.e., diesel). As reported by Hagos and Ahlrgren (2018) the use of biomethane as an alternative to LNG fuel could cause a significant reduction in global emissions, both in road transport and marine sectors including fishing and transport (Hagos and Ahlgren, 2018). In particular, well-to-wheel fuel emission conversion factor is 3.3 kg of CO2 per kg of CNG (Cefic & ECTA, 2011). Moreover, it has been found that the greenhouse gas emissions can be lowered by nearly 500 kg of equivalent CO2 per MWh compared to petrol or diesel in a life cycle view. Apart for the environmental benefits of using biomethane as transport fuel, anaerobic digestion for obtaining biogas includes other environmental approaches like the use of the digestate produced in this treatment as fertilizer, thus reducing the amount of mineral fertilizer commonly used (Judith González-Arias et al., 2020). Additionally, some technical reports have stated that the use of biomethane not only allows the reduction of GHG emissions compared to other fuels like diesel, but also the environmental impact of biomethane can become negative if external biogas production results are included in the analysis (EBA, 2020; Giuntoli et al., 2017; Gustafsson and Svensson, 2021; Majer et al., 2015; Rasi et al., 2020).

Back to process’ economy and hence its potential to be implemented in a circular economy societal model, biogas upgrading to biomethane entails extra costs in comparison with the direct utilization of biogas, for example, in a combined heat and power (CHP) unit. Nonetheless, the upgrading strategy is beneficial from a circular economy perspective as its utilization has the potential not only for reducing imports of natural gas and CO2 emissions, but also for boosting the consumption of local renewable resources (Starr et al., 2015). As a matter of fact, the number of biomethane plants in Europe has seen an increase of 51% (from 483 to 729) in the period from 2018 to 2020, revealing increased interest on biomethane production (European Biogas Association, 2021). Among the European countries with more biomethane plants are Germany, France and the United Kingdom. Within the many potential applications of biomethane, a particular alternative is to use biomethane as renewable fuel for light shipping. Indeed, the United Kingdom has already launched a “Clean Maritime Plan” for 2050, aiming at the ambitious target of zero emission shipping to be commonplace globally (UK Government, 2019). In this vein, the utilization of biomethane as renewable fuel for light shipping can help to reduce CO2 emissions in the marine transport sector. This fact is extremely important to establish a sustainable and circular marine transport model.

In this work, we perform a profitability analysis to examine the economic viability of using biomethane locally produced from existing biogas plants as renewable fuel for light marine transport. To the best of the authors’ knowledge, this is the very first study dealing with the techno-economic viability of locally produced biomethane as fuel for shipping. As a real case study for the analysis, we chose Cornwall (United Kingdom). The reasons for selecting this location are explained below. First, Cornwall is located in South West England, bordered to the north and west by the Celtic Sea and to the south by the English Channel. As it is surrounded by many different seas, small harbors are frequent in this region. In these ports there is a predominance of small ships, either for recreation or goods transport purposes. Some examples are Port Isaac or Port Gaverne. Second, there are three main biogas production plants in Cornwall, which are Great Brynn Barton Farm, Sharps Brewery and Pengelly Barton AD (NNFCC, 2020). Currently, the biogas produced in these facilities is sent to a CHP to produce both heat and electricity. Therefore, the upgrading to biomethane does not exist in this region and hence, there is room to analyze the economic viability of our proposal. Figure 1 represents a conceptual scheme of our approach. As indicated in the figure, biogas must be first upgraded to biomethane and then transported to the nearest point of natural gas distribution to its further supply for shipping fuel. Therefore, two stages need to be included in the profitability analysis, namely the upgrading step and the transportation to the final consumer. Technologically, biogas upgrading is the most difficult step in this approach. Many techniques have been commercially developed during the last years, being membrane biogas upgrading, the most promising alternative.

Figure 1. Conceptual scheme of biogas upgrading and transport to its use in light marine transport.

1. **Methodology**
	1. **Economic valuation methodology**

The profitability of this process was analyzed through the Discounted Cash Flow (DCF) method, considering a lifetime of 20 years. Three main indicators were used: Net Present Value (NPV), Profitability Index (PI) and Discounted Payback Time (DBPT). The equations for NPV, PI and DBPT calculations are indicated in Eq. (1), (2) and (3), respectively. In this section, the selected variables and how they are implemented in the economic valuation are explained. The chosen values for these parameters are also discussed and justified. The general equations for the calculation of NPV, PI and DBPT are also included in this section. For sake of further clarity, a more detailed explanation along with the equations are included in Appendix 1. The main parameters needed for estimating these indicators are cash inflows ($I\_{t}$), cash outflows ($O\_{t}$), the discount rate parameter (rd), the lifetime of the project (n) and the investment (Cinv). Concerning the discount rate, it expresses the time value of money invested. Its value can make the difference between whether an investment project is economically viable or not. In this case, consensus was found at 5% as representative value (Cucchiella et al., 2019a, 2019b; Cucchiella and D’Adamo, 2016; Ferella et al., 2019). The estimation of It entails the calculation of the revenues obtained for selling the biomethane produced. This calculation is carried out through multiplying the biomethane produced times the natural gas price. For the estimation of Ot, two stages need to be differentiated: biogas upgrading (BU) and its distribution (DB). The parameters included below were considered for the calculation of Ot: (1) Cost of the loan (CloanBU), assumed to be covered by a third party and calculated through the investment and the number of years taken to pay back the loan (nl). The investment costs were selected in agreement with previous references that has been validated in several works (Baena-Moreno et al., 2020b; Baena-Moreno et al., 2021; Cucchiella et al., 2019b, 2019a, 2018; Cucchiella and D’Adamo, 2016); (2) The interest of the loan (CilBU), based on the remaining loan to return and the interest rate (rint) selected. The interest rate is the percentage set by the loan provider, and it has been carefully selected considering a safe scale within the reported values. A wide range of values (from 3% to 9%) can be found in previous works aimed to estimate biogas upgrading profitability. For example, Scholz et al., 2013, selected an interest rate of 9%, similar to the 8% chosen by Vo et al., 2018. On the other hand, Pääkkönen et al., 2018 estimated initially a 4% interest, and Barbera et al., 2019 fixed this value in 3 and 4% for their analysis. The range is relatively narrow, so we have selected 6% which lays in middle of the range. Still, the influence of this value is later subjected to a sensitivity analysis; (3) The maintenance and overhead (M&O) cost (CmoBU), calculated through a percentage of the investment (pmoBU), as previously done in many works (Baena-Moreno et al., 2020b; Baena-Moreno et al., 2021; Cucchiella et al., 2019b, 2019a, 2018; Cucchiella and D’Adamo, 2016); (4) Furthermore, for biogas upgrading stage, the following parameters must be considered: depreciation (CdfBU), insurance (CinsBU) and installation (CinstBU) costs, usually estimated as percentages of the investment ($p\_{df}$,$ p\_{ins}$, $p\_{inst}$) (Baena-Moreno et al., 2020b); and the electricity consumption for biogas upgrading (Cue), based on data of consumption, gathered from literature (Baena-Moreno et al., 2020b; Baena-Moreno et al., 2021; Cucchiella et al., 2019b, 2019a, 2018; Cucchiella and D’Adamo, 2016), and the electricity price; (5) On the other hand, and similarly to the BU stage, the distribution costs from the biomethane production point to the natural gas grid, correspond to the investment in the form of a loan (CloanDB), interest on the loan (CilDB), M&O (CmoDB) and installation (CinstDB). The investment was again taken, based on several previous works above mentioned. Depreciation and insurance are not considered in the cost for biomethane distribution in agreement with standard policies for grids; (6) Moreover, labour costs ($C\_{lab}$) were considered. Its calculation was based as the number of workers multiplied times the wage of each worker (Clabu). The number of workers was chosen in agreement with previous works and the small plant sizes selected. All the equations used for the calculation of these parameters are collected in Appendix 1.

The biogas upgrading sizes were estimated in a database elaborated in a previous work of the authors (F. M. Baena-Moreno et al., 2021). As before said, three biogas production plants currently with a CHP system are available in Cornwall: Great Brynn Barton Farm, Sharps Brewery and Pengelly Barton AD (NNFCC, 2020). The estimated biogas production of these plants in our previous database is 122, 94 and 182 m3/h, respectively. From now on, and for sake of clarity, we refer to the different plants with these values. Regarding the distribution stage, extra biomethane compression from the production point to the natural gas grid is not needed, as the grid operates at a similar pressure to the pressure of the biomethane produced (Cucchiella et al., 2018; Cucchiella and D’Adamo, 2016). Table 1 presents the data used as economic inputs.

$NPV=\sum\_{t=0}^{n}\frac{I\_{t}-O\_{t}}{(1+r\_{d})^{t}}$ (1)

$PI=\frac{\sum\_{t=0}^{n}\frac{I\_{t}-O\_{t}}{(1+r\_{d})^{t}}}{C\_{inv}}$ (2)

$\sum\_{t=0}^{DPBT}\frac{I\_{t}-O\_{t}}{(1+r\_{d})^{t}}=0$ (3)

Table 1. Economic inputs.

* 1. **Strategy**

As for the strategy followed to perform our analysis, several scenarios were considered. Table 2 collects all the scenarios analyzed. Each biogas plant size was analyzed independently. Four different baseline cases were defined for each of them in agreement with the distance from the biomethane production point to the natural gas grid: (1) only biogas upgrading (assuming that the natural gas grid is located within the facilities of the biogas production plant); (2) upgrading plus 0.5 kms distribution; (3) upgrading plus 1 km distribution; and (4) upgrading plus 2 kms distribution. The chosen values are selected upon consultation and recommendation of professionals in the sector. Further distances are usually disregarded even for preliminary studies, due to difficulties in obtaining licenses for the civil engineering activities. Therefore, the total number of baseline scenarios is 12 (scenarios 1-12 of Table 2). Afterwards, the influence of subsidies as feed-in tariffs was analyzed (scenarios 13-24 of Table 2). These scenarios were selected to cover all the baseline options selected. Given the results obtained, we propose the analysis of CO2 penalties needed to revert the negative outputs obtained. Shipping’s owners are annually charged a significant tax (carbon tax) per tonne of CO2 emitted, which comes from using traditional fuels. To this end, it was assumed that the fuel used is CNG, which is in fair agreement with data gathered directly from professionals within the sector. In particular, the CO2 reduction coming from switching to biomethane was calculated by using an emission factor of 3.3 kg of CO2 per kg of CNG. This analysis is further explained in the results section and collected in scenarios 25-36 of Table 2. The influence of costs reduction is also examined in scenarios 37-48 through the applying on the project subsidies as percentage of investment. Again, these scenarios were selected to cover the whole range of the baseline scenarios and provide a wide comparison. Finally, a sensitivity analysis was carried out to evaluate the influence of the rest of parameters used (scenarios 49-66). The ranges selected for these variables are based on the following aspects. For the number of workers, as explained previously, four workers are usually assumed for small plant sizes. It would be rather unlikely to find more than five operators in this type of small plants. Equivalently, less than three workers would be not suitable for attending the day-to-day tasks in the plant. The values chosen for the discount rate and for the interest rate were selected in agreement with the discussion given in the previous section. The values chosen for the sensitivity analysis performed on M&O, Ceu, and Ci were selected following recommendation of professional workers in this field. For this type of industrial plants these parameters are very-well optimized and rarely presents big differences from the budget targeted.

Table 2. Matrix of the scenarios analyzed.

1. **Results**

Figure 2 showcases the economic outputs obtained for NPV and PI for the baseline cases. Although our idea is a promising low-carbon strategy for small shippings, the aproach is not economically appealing (NPV between -4060 and -5524 k€, Figure 2.A). Certainly, these economic results could be improved through the optimization of several parameters (i.e., reducing energy consumption). Yet, it is difficult to surmount the profitability of the project in view of the obtained results. Increasing the plant size is a typical strategy to improve profitability in biogas upgrading schemes (Baena-Moreno et al., 2020e). However, in this particular case, expanding the plant capacity worsen the overall profitability prospects. This is because the difference among revenues and costs is negative during the entire life of the project (Baena-Moreno et al., 2020f). Figure 2.B showcases the PI results obtained. Negative PI outputs are obtained in fair agreement with the NPV values. DPBT were not included because the time to obtain a NPV equal to zero is higher than the lifetime considered (20 years). Anyhow, the process herein proposed is not profitable under the current market circumstances. In view of these results, two alternatives can be explored to achieve profitability: (1) increasing revenues (i.e., through policies to boost renewable energy production), or (2) reducing costs (i.e., reducing electricity consumption or investment).

Figure 2. NPV (A) and PI (B) baseline results. Scenarios 1-12.

Subsidies as feed-in tariffs may be a useful measure for improving the profitability of renewable energy projects. This policy has already been applied on biomethane production in countries such as Slovakia, Austria and Italy (Pablo-Romero et al., 2017). The United Kingdom supported biomethane production through incentives between 2011 and 2018. Indeed, 6.661 GWh of biomethane production were supported to fulfill a quota system called the Renewable Transport Fuel Obligation (RTFO). Nonetheless, installations commissioned as off 2018 cannot claim the feed-in-tariff. This has caused a reduction in the production of biomethane (REGATRACE, 2020). Nevertheless, feed-in tariffs incentives influence on profitability results is an interesting analysis. Figure 3 shows the evolution of the NPV value with feed-in tariffs for biomethane production. Table 3 collects the DPBT values obtained for those scenarios in which a positive NPV value was obtained. The analysis have been performed for the four baseline scenarios (only upgrading, upgrading plus 0.5, 1 and 2 km distribution), and for the three biogas plant sizes (122, 94 and 182 m3/h). As shown, bigger plants need lower subsidies to reach profitability. In the case of only upgrading, 182 m3/h biogas plant would be profitable with 36.6 €/MWh, whereas 65 €/MWh are needed for 94 m3/h biogas plant. Concerning DPBT, values varying from 2 to 19 years were obtained. Likely, in the higher end of this range investors would not be attracted due to the long time needed to get a positive NPV. Considering the values offered in other countries such as Austria (12.51–16.51 €/MWh) and Slovakia (10.75 €/MWh), biomethane production plants would still be unprofitable in Cornwall. Nonetheless, under the Italian scenario, where 61 €/MWh are offered, the largest plant size (182 m3/h) here studied would be profitable in all the cases. In this scenario, also 122 m3/h plant size would reach profitability, except for the case of upgrading plus 2 kms distribution (65.8 €/MWh needed to reach profitability). This fact reveals the pivotal importance of the natural gas grid availability nearby the biogas facilities to reduce distribution costs. For the smallest biogas plant size, even under the Italian scenario, profitability would not be reached. Therefore, feed-in tariffs incentives cannot be a standalone measure, and other potential revenues improvements – cost reductions must be considered. To properly understand the previous discussion, one should focus on the differences among power purchasing within the compared countries. For instance, electricity prices in UK are 34% and 15% higher in comparison with Austria and Slovakia, respectively (PORDATA, 2019), while the difference with Italy is narrow (2%). Therefore, in terms of power rates, Italy-UK represent a fair comparission.

Figure 3. NPV evolution with feed-in tariffs subsidies. Scenarios 13-24.

Table 3. DPBT (years) evolution with feed-in tariffs subsidies. Only the feed-in tariffs for which positive values were obtained are included.

Another potential alternative to increase the revenues (as an avoided cost) is increasing the CO2 tax to be paid by the boat owners. Shipping’s owners are annually charged with a significant tax (carbon tax) per tonne of CO2 emitted. Currently, this tax is 24.6 €/tonne of CO2 emitted (Sandbag, 2020; Theice, 2020; UK Investing, 2020). Upon increasing the carbon tax, biomethane becomes a more interesting fuel from an economic perspective. Indeed, it is expected that CO2 tax will reach 55 €/tonne of CO2 by 2030 (Carbontracker, 2018). Considering this forecast, we have explored the CO2 penalties needed to reach profitable scenarios. The analysis has been performed for all the cases collected in the baseline scenario. Figure 4.A represents the CO2 penalties needed to reach profitability (NPV equal to zero). As shown, in the best case scenario (182 m3/h biogas plant and considering only upgrading stage), CO2 tax should be as high as 174.65 €/tonne. This value is seven times greater than the current tax and three times greater than the forecasted values for 2030. Question is, would this value be close to the actual figure in 2050 when net-zero emissions are meant to be mandatory in Europe and the UK? In any case, this fact reveals the lack of competitiveness of renewable sources under the present circumstances when compared to a combination of traditional fuels plus current CO2 penalties. Based on these results, it is evident that a radical change of the current fuel paradigm is needed to step ahead towards a bio-based marine transport.

Once the alternatives to increase revenues have been analyzed, the next natural step is to check potential costs reductions. In this sense, two main alternatives arises: (i) new technological improvements towards finding cheaper technical solutions for biogas upgrading to biomethane; (ii) political measures which may help to reduce overall costs and reach profitability. When different end-products are targeted, some other options could be considered such as finding cheaper raw materials or consumables (Baena-Moreno et al., 2020d). However, for biogas upgrading, unexpensive raw materials and auxiliaries are needed. The first alternative is unrealistic for the forthcoming years. Biogas upgrading has been thoroughly studied in the past decades (Starr et al., 2012; Sun et al., 2015). In this sense, chemical absorption with amines or caustic solvents as well as adsorption and membrane separation technologies represent the state of the art options. The maturity of these technologies has already reached commercial scale. Therefore, it seems rather difficult that another breakthrough technology will come up in the near future. Nonetheless, the second option seems more viable as there are some political tools to reduce the costs of renewable energy alternatives and there is a general consensus in the UK and EU towards a low-carbon future. For example, subsidies as percentage of investment is a powerful political action to reduce the overall investment costs and hence, to attract investors. This alternative is explored in our analysis and could be a partial solution for reaching profitability and implementing biomethane as renewable fuel for light shipping. Figure 4.B, 4.C and 4.D shows the NPV evolution with different percentages of investment subsidies for every plant size studied. As depicted in the figure, even if 100% of the investment is covered, the approach would still be unprofitable. Indeed, none of the several cases studied is close to reach a NPV equal to zero. Based on these results and the current circumstances, the alternative of subsidies as percentage of investment can almost be demeed unpractical.

Figure 4. CO2 tax and investment subsidized analysis: (A) CO2 penalties for NPV equal to zero (scenarios 25-36); (B), (C), and (D) NPV evolution with percentage of investment subsidies (scenarios 37-48).

Examining the impacts of other parameters that may influence on the economic results, is important to cover all the possible variations. To this end, a sensitivity analysis in terms of a tornado plot is performed over the three biogas plants studied. The parameters analyzed were the ones previously not intensively studied: labour, rd, rint, M&O, Ceu, and insurance costs (Ci). We studied those cases where only biogas upgrading is needed, as the varied parameters exclusively affect this stage. The distance was previously evaluated all along the paper. Figure 5 shows the tornado plots obtained for the three different biogas plants. Overall, the impact of these parameters is not as important as the impact of other parameters previously studied. The major influence is caused by labour (number of workers), which can be of up to 800 k€ for the entire life of the project. This result envisages that optimization of the number of required workers could help to stablish cost variations. Following this parameter, rd can impact the project on about 350 k€. Nonetheless, this parameter rather depends on circumstances beyond the biomethane production plant owner.

Figure 5. Tornado analysis. Scenarios 49-66.

1. **Conclusions**

Herein, we examined the profitability of a particular application to use local biomethane as renewable fuel for light marine transport. Even though our proposal is a promising idea to decarbonize marine transport sector, the approach is not profitable under the current circumstances. Subsidies as feed-in tariffs could boost the profitability of the largest plant studied (182 m3/h) at reasonable values (36.6-45.7 €/MWh). Nonetheless, the smallest biogas plant analyzed would need out-of-market incentives to reach positive economic outputs (65-82.7 €/MWh). The increase of CO2 emissions tax in the final fuel consumer was also considered. Values seven times greater than the current penalties are required to reach profitability. Subsidies as percentage of investment were also evaluated, revealing a poor improvement even at 100% of investment subsidized. Despite being geographically focused on the region of Cornwall (England), our approach provides fundamental insights on bio-menthane as green fuel for shipping, a proposal that can easily be extrapolated elsewhere. Indeed, the trends herein observed are useful to spark the debate on green shipping, a cornerstone for many local economies. Overall, this pioneering study confirms the need of more ambitious policy-making actions to ensure a smooth and prompt transition towards a sustainable society.

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Figure 1. Conceptual scheme of biogas upgrading and transport to its use in light marine transport.



Figure 2. NPV (A) and PI (B) baseline results. Scenarios 1-12.



Figure 3. NPV evolution with feed-in tariffs subsidies. Scenarios 13-24.



Figure 4. CO2 tax and investment subsidized analysis: (A) CO2 penalties for NPV equal to zero (scenarios 25-36); (B), (C), and (D) NPV evolution with percentage of investment subsidies (scenarios 37-48).



Figure 5. Tornado analysis. Scenarios 49-66.

Table 1. Economic inputs.

|  |  |  |
| --- | --- | --- |
| **Variable** | **Value** | **Reference** |
| rd (%) | 5 | (Cucchiella and D’Adamo, 2016; D’Adamo et al., 2019) |
| pNG (€/MWh) | 16.83 | (Energy brokers, 2020) |
| CinvBU (€/m3/h) | 122 m3/h – 579994 m3/h – 6153182 m3/h – 5086 | Scaled from (Cucchiella and D’Adamo, 2016) |
| *C*invDB (€/km) | 237500 | (Ferella et al., 2019) |
| nl (y) | 15 | (Baena-Moreno et al., 2020d) |
| rint (%) | 6 | Assumed |
|  |  |  |
| pmo (%) | 10 | (Baena-Moreno et al., 2020e) |
|  |  |  |
| pdf (%) | 20 | (Cucchiella et al., 2019a) |
| pins (%) | 1 | (Baena-Moreno et al., 2020c) |
| pinst (%) | 20 | (Pérez-Fortes et al., 2016) |
| CueBU (kWh/m3 biogas) | 0.29 | (Cucchiella and D’Adamo, 2016) |
| pe (€/kWh) | 0.16 | (PORDATA, 2019) |
| Clabu (€/y/worker) | 62400 | (Kingdom, 2020) |
| nop (worker) | 4 | (Baena-Moreno et al., 2020b) |
| nwh (h/y) | 8000 | Assumed |

Table 2. Matrix of the scenarios analyzed.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Scenario** | **Biogas plant (m3/h)** | **Distance to the grid (km)** | **Purpose of the scenario** | **Sensitivity analysis** | **Parameter analyzed (value range and units)** |
| **1-12** | 122-94-182 | 0-0.5-1-2 | Baseline | No | - |
| **13-24** | 122-94-182 | 0-0.5-1-2 | Influence of feed-in tariffs subsidies | No | Feed-in tariffs subsidies (10-70 €/MWh) |
| **25-36** | 122-94-182 | 0-0.5-1-2 | Analysis of CO2 tax | No | CO2 prices to reach profitability (0-400 €/t) |
| **37-48** | 122-94-182 | 0-0.5-1-2 | Influence of investment subsidies | No | Subsidies as percentage of investment (10-100 %) |
| **49** | 122 | 0 | Influence of labour cost | Yes | Number of workers (±1) |
| **50** | 122 | 0 | Influence of rd | Yes | rd (±1%) |
| **51** | 122 | 0 | Influence of rint | Yes | riint (±3%) |
| **52** | 122 | 0 | Influence of M&O | Yes | M&O (±1%) |
| **53** | 122 | 0 | Influence of Ceu | Yes | Ceu (±10%) |
| **54** | 122 | 0 | Influence of Ci | Yes | Ci (±0.5%) |
| **55** | 94 | 0 | Influence of labour cost | Yes | Number of workers (±1) |
| **56** | 94 | 0 | Influence of rd | Yes | rd (±1%) |
| **57** | 94 | 0 | Influence of rint | Yes | riint (±3%) |
| **58** | 94 | 0 | Influence of M&O | Yes | M&O (±1%) |
| **59** | 94 | 0 | Influence of Ceu | Yes | Ceu (±10%) |
| **60** | 94 | 0 | Influence of Ci | Yes | Ci (±0.5%) |
| **61** | 182 | 0 | Influence of labour cost | Yes | Number of workers (±1) |
| **62** | 182 | 0 | Influence of rd | Yes | rd (±1%) |
| **63** | 182 | 0 | Influence of rint | Yes | riint (±3%) |
| **64** | 182 | 0 | Influence of M&O | Yes | M&O (±1%) |
| **65** | 182 | 0 | Influence of Ceu | Yes | Ceu (±10%) |
| **66** | 182 | 0 | Influence of Ci | Yes | Ci (±0.5%) |
|  |  |  |  |  |  |

Table 3. DPBT (years) evolution with feed-in tariffs subsidies. Only the feed-in tariffs for which positive values were obtained are included.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Plant size (m3/h) | Feed-in tariffs (€/MWh) | DPBT only upgrading | DPBT upgrading + 0,5 kms distribution | DPBT upgrading + 1 kms distribution | DPBT upgrading + 2 kms distribution |
| 122 | 60 | 6 | 12 | 18 | - |
|  | 70 | 3 | 4 | 6 | - |
| 94 | 70 | 11 | 19 | - | - |
| 182 | 40 | 12 | 18 | - | - |
|  | 50 | 3 | 4 | 6 | - |
|  | 60 | 2 | 2 | 3 | 4 |
|  | 70 | 2 | 2 | 2 | 3 |