Analysis of biomethane business models applicable to the Portuguese natural gas grid

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Abstract
With the global trend from fossil fuels towards renewable energy sources accelerating, traditional fossil fuel companies must adapt and become part of the energy transition movement in order to avoid stranded assets. This study aims at the transition of the natural gas grid, by providing insights for adopting biomethane business models applicable in Portugal based on EU public policies. The six leading EU nations in number of biomethane plants were identified and studied in terms of their ecosystem as a means to assess the key success and failures of incorporating biomethane as an energy carrier. The biomethane potential of Portugal was spatially estimated at municipal level for five different types of waste, namely, cattle, pig, poultry, sheep and urban waste. A decision support tool for optimizing biomethane business models in terms of NPV was developed and applied to the 29 municipalities that constitute the Portgás concession area. Analyzing the leading EU nations in biomethane, it was found that all nations that adopted biomethane have either direct support schemes that promote the adoption of this energy carrier or strict carbon policies that make biomethane cost competitive with natural gas. The biomethane potential for Portugal was estimated to be 410.86 Mm3/yr with most of it attributed to urban solid waste. Moreover, it was found that the 29 municipalities that constitute the Portgás concession area represent 24.1% of this potential. Lastly, the Green Gas Planner decision support tool developed shows that no biomethane plant can be built within Portgás concession with the policies currently operating in Portugal, while for UK, Sweden and French policies many plants can be built in the concession area with a cumulative NPV of 126.5 M€, 56.5 M€ and 192.4 M€, respectively, over a period of 20 years.
Keywords: Biomass, biomethane, decision-making, decision support, EU policy, QGIS, Portugal, Python, spatial distribution, support schemes, techno-economical.

1. Introduction

As it stands today, it is clear that the global trend of countries parting away from traditional fossil fuels and moving towards renewable forms of energy is accelerating; this is especially true for nations within the EU. Hence, it may seem that fossil fuel will be hampered in the future, as they will face tougher regulations and policies that might make the current business model economically unfeasible and result in unused assets. However, considering that energy transition implies a gradual departure from fossil fuels rather than an abrupt departure, it seems that fossil fuel companies have a part to play in reaching sustainability. In fact, fossil fuel companies have many assets that already service a large amount of consumers, hence in some cases they are able to modify these assets to be compatible with renewable sources rather than incurring in additional expenses for new assets that service renewable energies. For natural gas distribution companies this adaptation implies injecting gas produced from renewable sources into their existing grid rather than injecting natural gas from fossil origin. REN Portgás Distribuição is one of these companies that focuses on the distribution of natural gas in the northern coastal region of Portugal. Aware of the previous, and the ease of injecting biomethane into the gas compared to other renewable gases, the Innovation Team within Portgás decided to take the first steps in assessing the feasibility of such a project with this study.

2. Thesis Objective

The objective of this work is to provide decision-making insights for adopting biomethane business models applicable to the Portuguese natural gas grid based on public policies across the EU and Portuguese national data. Moreover, to accomplish this objective the work was divided in three chapters, namely, *Chapter 1: Biomethane Across the Leading EU Nations*, *Chapter 2: Portuguese Landscape* and *Chapter: 3 Locating Biomethane Plants Across the Portgás Concession Area*. The first two chapters are stand-alone studies, which are independent, while the third builds on the results of the previous two. Each chapter has a particular structure in itself, methodology, results and/or findings.

Moreover, the purpose of dividing the work in the aforementioned structure is to form a consistent narrative on how informed decision making should take place for promoting biomethane in a nation according to the authors own opinion. The first chapter can be seen as a lesson learning chapter in which by analyzing the success and failures of past policies one can determine what should be adopted and what should be avoided when promoting biomethane with a desired outcome in mind. The second chapter consists of an analysis of the national environment in order to understand what are the real resources that the nation can account for. Lastly, the third chapter takes the past lessons of the EU, and the present context of Portugal, in order to forecast the future outcomes based on different possible policy decisions that could be eventually adopted in the country.

3. Biomethane Across the Leading EU Nations

The following section summarizes the current landscape of the main European countries that have successfully incorporated biomethane as a carrier in their national energy mix. In general, it provides a country overview of their biogas/biomethane production and use, the support schemes that have allowed for the successful implementation of biogas and biomethane plants, the type of substrate used to produce the gas as well as its final use/demand and review of the future prospects of the biomethane in the nation. The scope of the work is limited to the top six countries in the EU that have the most amount of biomethane plants.

3.1 Germany

Germany is by far the leading country in Europe when it comes to incorporating both biogas and biomethane into their energy mix. As of 2018, Germany produces around 32.15 TWhe from both biogas and biomethane. This account for roughly 14.2% of all the national electricity generates by renewable energy sources. On the other hand, biogas and biomethane supply around 16.7 TWht of heat, which accounts for only 1.4% of the total energy consumption in the heat sector, and around 10% of the total heat supplied by renewable sources [1]. Furthermore, the vast majority of the biogas and biomethane produced in Germany is destined for CHP applications. This landscape is a consequence of the Erneuerbare-Energien-Gesetz (EEG), also known as the Renewable Energy Sources Act.

The EGG is the main support scheme that has played a critical role in the success of the German energy transition. The latest update of the EEG (2017) limits the maximum bidding value for both new and already existing biomass plants to 14.73 ¢€/kWhe and 16.73 ¢€/kWhe respectively; each with a digression of 1% per annum. Furthermore, only new plants with capacities larger than 150 kWe, as well as already existing facilities, are eligible for participating in the bidding process. In particular, the existing plants can bid to receive a 10-years follow-up funding only if they can comply with flexible operation conditions. Lastly, the EEG 2017 does not offer in prospect for the use of biomethane produced from energy crops, hence the future sell opportunities will be solely limited to biomethane form either residual or waster material. Lastly, by 2030 the fixed remuneration of the EEG will expire for many existing biomethane plants. If there is no chance for economic operation of the existing plants after the expiration of the feed-in tariffs, the required investments and maintenance cost of the plants will be deferred. Hence, after this period it can be expect that the available biogas and biomethane plant capacity in Germany will decrease if no follow-up funding is established [1].

3.2 The United Kingdom

Hence, within Europe the UK is one of the largest producers of both biogas as well as biomethane. In fact, within the United Kingdome around 85 biomethane plants produced around 355 ktoe of biomethane a year. This places the UK as the second greatest producer of biomethane in the EU after Germany [2]. Moreover, the main policy that has led to this success int the Non-Domestic Renewable Heat Incentive (RHI) which supports biomethane injection to the gas grid. Under this scheme, payment for biomethane installations are based on eligible gross calorific value (kWh) of biomethane produced for the injection period. Moreover, the payment is done with a three-tier tariff, which operates over a 12-month period. In this sense, the regulation specifies that during the 12 months the first 40,000MWh of biomethane injected are eligible for tier 1 tariff. Afterwards, the next 40,0000 MWh of biomethane injected are eligible for tier 2 tariff, while any subsequent injection is eligible for tier 3 tariff; these payments are of 4.86 (5.40), 2.86 (3.20) and 2.21 (2.40) p/kWh (¢€/kWh) for tier 1, 2 and 3 injections respectively [3].

On the other hand, the majority of the feedstock used for biomethane production in the UK is obtained from agricultural residues and swage. These two feeds account for roughly 70% of the share of biomethane production in the United Kingdom. Additionally, while there is no clear source that breaks down the end use of the biomethane injected, it can be assume that it will be potentially similar to that of natural gas. This is reasonable since the strategy of the UK to substitute natural gas for biomethane. However, high pressure demand should be excluded for biomethane, since currently all the biomethane is injected to the low-pressure grids [4]. Moreover, it is estimated that biomethane accounts for around 0.4% of the total gas supply in the network [5]. With this in mind, the current policy scenario within the UK seems to hold good prospects for the future of biomethane. Particularly, the nation's Committee on Climate Change (CCC) recommends increasing biomethane injection until 2030, reaching 4% of current supply (21 Twh of biomethane), as a means to transition UKs network into a lower carbon network [6].

3.3 Sweden

Currently, there are around 282 biogas plants in Sweden, which produce altogether 202 million cubic meters of gas (2.1 TWh). Furthermore, with 62 biomethane upgrading plants, Sweden ranks third in total number of upgrading units within the EU after Germany and the UK [7]. However, Sweden's biogas use is quite different from the aforementioned nations, since most of it is used as fuels for vehicles; with smaller shares in other injection applications and direct heat and power use. In particular, the nation aims to increase their biomethane use for vehicles to 12 TWh by 2030, which is considerably higher than today's supply [8]. Furthermore, by 2050 Sweden aims to free both the transportation sector and the national gas from fossil fuel. Therefore, in order to accomplish such lofty goals Sweden has set out a series of policies that create an environment to foster biomethane growth. These policies are mostly taxed based or subsides, with the main ones being the Energy and Carbon Tax of 148.6 € per ton of CO_2, and the Manure base biogas support which gives a subsidy of 0.039 €/kWh of biomethane produced from manure [9].

Under the previous conditions we can expect fossil fuel taxation in the nation to continue and even increase, making biofuels and biomethane more cost competitive with traditional fuels. Furthermore, as part of the Swedish circular economy we can expect an uptake of co-digestion units to process household and industrial waste: especially since the current aim is to process 50% of the nation's food waste [8]. Which is accurate with the current trend, since the majority of biomethane in Sweden is produced from waste streams, particularly from sewage sludge, manure and food waste.

3.4 France

As of 2017, there were a total of 592 biogas production plants registered in France. Out of these 548 units produced heat and electricity directly from the biogas, while the remaining 44 units upgraded the biogas to biomethane for grid injection; with a total injection of 0.1% of the national gas consumption. The main support scheme for biomethane in France is a feed-in-tariff that guarantees producers of biomethane to sell their gas to a natural gas supplier at a fixed rate for a period of 15 years. The purchase price can vary from 46 €/MWh to 139 €/MWh, based on the size of the production facility (Nm^3/h) and the nature of waste or organic matter being treated. Particularly, for anaerobic digestion facilities, the purchase price is made up of a reference tariff and an "input" premium. The reference tariff for biomethane injection is separated into "facilities with non-hazardous waste" and "other facilities. The former receives a tariff between 45 and 95 €/MWh, while the latter receives a tariff between 64 and 95 €/MWh. Furthermore, municipal waste receives a premium of 5 €/MW. Agricultural waste and agro-food receive a premium around 20 to 30 €/MWh depending on flows. Lastly, sewage treatment waste receives a premium from 1 to 39 €/MWh. As mentioned, the final tariff also depends on install capacity [10].

Most of the biomethane produced in the country comes from various other wastes such sludge from treatment plants, which account for 40% of the mass of the total substrate use. On the hand, the second most important substrate for biomethane production is household waste, which accounts for 31% of the substrate use. Afterwards, most of the substrate used for biomethane production is from agricultural origin [10].

On the other hand, current French legislation supports Guarantees of Origin (GO) for biomethane, and it states that when a GO is sold as a fuel for vehicles, the supplier retains 100% of its value. On the other hand, if the biomethane is sold for heating applications, 25% of the GO value goes to the supplier, while 75% of the value is paid into a compensation fund managed by the French Government Investment Fund (CDC). This distinction has driven the biomethane market in France into vehicle applications [11].

The future prospects for production of renewable gases (including SNG) in France seem promising due to the ambitious goals set out by the relevant stakeholders in this sector. These goals are: 60 TWH of renewable gas in 2028, out of which 50 TWh are of biomethane and 90 TWH of renewable gas in 2030, out of which 70 TWh are of biomethane [10].

3.5 Denmark

Biogas production in Denmark is around 3.3 TWh/year and the share between electricity production and biomethane injection is nearly equal [12]. Moreover, biogas in the nation is accounted by a total of 144 biogas plants [2]. Out of these, a total of 22 of them have biomethane upgrading systems with injection into the gas grid [13]. The main incentive in denmark is the Energy Agreement of 2012 which consists of a three-part feed-in-premium scheme. These parts are: a *Base Subsidy* which guarantees a tariff annually adjusted (3.9 ¢€/kWh for 2018), a *Temporary Subsidy* of 0.5 ¢€/kWh decreased each year by 0.1 ¢€/kWh (2016 to 2019) and a *Gas Priced Adjusted Subsidy* which has a base subsidy of 0.01€/kWh plus the difference between a set value of 0.026€/kWh and the average price of natural gas of the previous year on Gaspoint Nordic [1]. However, this scheme is only applicable until 2020, and the details of the new scheme have not been disclosed yet.

In 2009 the Danish government established that 50% of the nation's manure derived from livestock should be valorized as energy by 2020. This governmental push to use of manure in biogas production, has led to a scenario in which the majority of biomethane production plants in Denmark are manure based with other agricultural residues [2]. On the other hand, there is no clear source that breaks down the end use of the biomethane injected into the Danish gas grid. Nonetheless, it can be assumed that it will be potentially similar to that of natural gas. This is fairly reasonable considering that currently around 8% of total gas in the grid is biomethane (198 million Nm^3) [14].

Lastly, the landscape for developing biomethane in Denmark is favorable. With the nation's leadership committed to reach carbon neutrality by 2050, coupled with the fact that the gas fields of the North Sea are depleting, it is clear that renewable gases will play rule in the future energy mix of the country. However, the extent of the development of these gases is still uncertain, since a positive development in that sector will require a high subsidy regime, as well as reduction in the manufacturing costs of the gases [14].

3.6 Netherlands

Currently there are over 250 working digesters in the Netherlands with an electrical installed capacity of 219 MW. Out of these, 25 of the plants are installed with upgrading units that either inject the biomethane into the grid or provide it as fuel for vehicles [15]. The Stimulering Duurzame Energieproductie (SDE+), also known as the Stimulation of Sustainable Energy production, is the main support scheme for supporting renewable energy production in the Netherlands. The SDE+ is an operating grant, which ensures financial compensations to producers of renewable energy. Compensation is available for renewable electricity, renewable gas and renewable hear/CHP [16]. The SDE+ compensates the difference between the cost price and the market value of the energy supplied. This is done to account for the higher costs of renewable energy production when compared with energy from fossil fuels. Furthermore, the actual contribution a producer receives is dependent on the energy price trends of the market. Hence, when energy prices are high, SDE+ contributions are higher and vice versa. Moreover, the maximum SDE+ contribution a producer can receive is equal to a base amount of the energy supplied minus the correction of the energy market price. As it pertains to biogas and biomethane, the SDE+ distinguishes the subsidies based on the final energy valorization, as well as the type of biomass treated. The former is distinguished in three categories, namely valorization as heat, gas or CHP [17].

The vast majority of the plants either produced the gas from agricultural waste such as manure or from industrial waste. These two substrates account for roughly 80% of all the biomethane plants in the Netherlands [2]. On the other hand, there is no clear breakdown of the use of biomethane in the country, however to understand its utilization we can analyze the demand of natural gas instead. In this sense, the gas demand is divided into distribution, transmission, power and own energy [18]. Lastly, it is expected that biogas production in the Netherlands will reach 2.2 billion m^3 of natural gas equivalent by 2030. However, the exact type of development of renewable gas in the Netherlands is expected to be location specific. In other words, if there is demand for heat and power, then CHP applications will be prevalent. On the other hand, if there is demand for gas injection or fuel then biomethane upgrading will be prevalent [19].

3.7 Biomethane Across the Leading EU Nations Conclusions

After analyzing the findings related to policies, utilization and sources of biomethane across the main EU countries, we can conclude the following:

- Across all countries all biomethane plants require some sort of policy or support scheme in order to be profitable.
- The end use of the biomethane within a country will clearly depend on the type of policy established within the nation.
- The feedstock utilize for biomethane production across the nations is also dependent on the existence of policies that favor or not certain substrate utilization.
- The main countries that have policies in place that promote biomethane injection into the gas grid are the UK, France, Denmark and the Netherlands.
- The main countries that promote specific waste utilization as feedstock for biomethane are France, Denmark and the Netherlands.

4. Portuguese Landscape

This section was developed with the objective of proposing and implementing a framework that will determine the biomethane potential in Portugal. This will allow the company to make informed decisions when it comes to developing biomethane related operations in the region. The key aspect of the model is that it accounts for spatial distributed resources broken-down by municipalities; a work that had not been carried out before. Hence, this chapter provides an up to date and geographic specific assessment of the biomethane potential in the municipalities where Portgás possesses assets. Lastly, the work presented in this document is largely based on the model proposed by both Richard O'Shea [20], and Ferreria et al [21]. Moreover, the vast majority of the data set used to reproduce the Portuguese landscape is based on the archives of the Instituto Nacional de Estatística (INE); which contains most the national statistics relating to agricultural and urban waste [22].

4.1 Overview of previous national assessments

The National Laboratory of Energy and Geology, also known as Laboratório Nacional de Energia e Geologia (LNEG), has previously estimated the total biomethane potential of Portugal in 2015. According to their estimates, the total biomethane potential in the country, based solely on anaerobic digestion, is around 800M m^3/a [23]. Particularly, LNEG estimates that the majority of the potential is associated to Urban solid residues which account for 411.6M m^3/a.
Moreover, biomethane potential estimates associated with agricultural residues are mainly related to animal farming. In particular, the potential refers to the waste produced from farming of cattle, poultry, pigs and sheep. Moreover, the biomethane potential associated to each species has been determine in different studies assuming different capabilities of collecting the manure and methane present in the biogas. The two main studies are those done by LNEG and that done by Ferreria et al. The former assumes that all agricultural waste can be collected and that the biogas produced contains 65% volume of methane. The later assumes 60% of methane in biogas (vol), as well as 60% capability of collecting the manure from cattle and pigs, and 50% capability of collecting it from chickens. The results from both studies can be seen in Table 1.

Table 1. Agricultural biomethane potential in Portugal by type of farm animal

Effluent origin	Biomethane LNEG [23] (Mm^3/a)	Biomethane Ferreria et al [21] (Mm^3/a)
Cattle	170.5	65.4
Pigs	27.8	4.1
Poultry	58.5	3.0[a]
Sheep	1.0	-
Total	**257.8**	**72.5**

a) Poultry refers to only chickens in the study

4.2 Methodology for assessing spatial biomethane potential

The framework developed in this work to determine biomethane potential is based upon the spatially explicated method applied by Richard O'Shea in his worked titled "Pathways to a renewable gas industry in Ireland" [20]. However, since the work developed by O'Shea is specific to Ireland, some gaps have to be fill in order to make it applicable in the Portuguese scenario. Hence, the framework is complemented by the work "Biomass resources in Portugal: Current status and prospects" developed by Ferreira et al [21]. Moreover, most of the data used in the model is obtained from the Instituto Nacional de Estatística (INE). The information collected represents the most recently available statistics.

The model is summarized in three main equations that allow to calculate the biomethane potential for all different livestock, as well as for urban waste. The first equation uses the assumptions made by Ferreira et al and is used to calculate the biomethane potential of all livestock except sheep. Moreover, this equation is as follows

$$BMP_{j,i} = n_{j,i} * M_j * TS_j * VS_j * BGY_j * V_{CH4} \quad (1)$$

Where $BMPj_{,i}$: Biomethane of livestock "j" waste in location "i" [m^3/a], $N_{j,i}$: number of livestock "j" in location "i" [#livestock heads], M_j: Effective of livestock "j" manure collected [tones/a per livestock head], TS_j: average total solids fraction found in livestock "j" manure [-], VS_j: average volatile fraction found in the total solid fraction of of livestock "j" manure [-], BGY_j: Average biogas yield of livestock "j" manure [m^3/ton_{vs}] and V_{CH4}: Volume fraction of methane in biogas [-].

From the previous equation all values are considered constant for all the municipalities with the exception on the number of livestock. The values for these constants are summarized in Table 2.

Table 2. Biomethane potential estimation parameters for Ferreira livestock waste [21].

Parameter	**Cattle**	**Pigs**	**Poultry**
Manure[(a)] (tons/year per head)	5.09	0.23	0.015
Total solids (%)	8.50	6.05	19.50
Volatile solids (% of TS)	76.50	72.50	76.00
Biogas yield (m^3/kg_{vs})	0.23	0.36	0.30

a. These values assum that collectavility of cattle and pig waste is 60% while poultry is 50%.

Biomethane potential from sheep waste was not determine by Ferreira et al. Hence, for the purpose of this model, all the assumptions made by O'Shea will be used. In this sense, the following equation is used to estimate the biomethane potential of sheep.

$$BMP_{s,i} = n_{s,i} * M_s * BMY_s \quad (2)$$

Where $BMP_{s,i}$: Biomethane potential of sheep waste in location "i" [m^3/a], $n_{s,i}$: number of sheep in location "i" [#sheep heads], M_s: Effective average sheep manure collected [0.088 ton/a per sheep], BMY_s: Average biomethane yield of sheep manure [38.6 m^3/ton]

Lastly, to determine the biomethane potential of urban organic waste, the assumptions made by Madalena Soares Pereira Lopes [24] in her work "Evaluation of biogas production from horse manure and assessment of biogas pathways in Portugal" are used. In short, the assumptions are that the volatile solids fraction urban waste is 30%, the biogas yield per ton of volatile solid is 571 m^3, and the methane content in the biogas is 60%vol. With this in mind, and assuming the different types of municipal waste, the biomethane potential is calculated with the following equation:

$$BMP_{u,i} = (LW_i * OFLW + ERW_i + OWR_i) * VS_u * BGY_u * V_{CH4} \quad (3)$$

Where $BMP_{u,i}$: Biomethane potential of urban waste in location "i" [m^3/a], $LW_{,i}$: Landfill waste in location "i" [ton], OFLW: Organic fraction of landfill waste [-], ERW_i: Waste destined to energy recovery [ton] , OWR_i: Organic waste destined to recycling [ton], VS_u: volatile fraction of organic urban waste [-], BGY_u: Biogas yield of organic urban waste [m^3/ton_{vs}], V_{CH4}: Volume fraction of methane in biogas [-]

From the previous equation all values are considered constant for all the municipalities with the exception of the amount of each municipal waste. The values for these constants are summarized in Table 3.

Table 3. Biomethane potential estimation parameters for urban solid residues [24]

Parameter	Value
Organic Fraction of Landfill waste (%)	55.00
Volatile Solids of Landfill Waste (ton_{vs}/ton)	0.30
Biogas yield of organic waste (m^3/t_{vs})	571.00
Methane content of biogas (%vol)	60.00
Biomethane yield per ton of USR (m^3/t)	56.529

4.3 Portuguese Landscape Results

The biomethane potential from different substrates was calculated for Portugal, and are presented in Table 4. Furthermore, for each of the 308 municipalities that constitute the Portuguese nation Biomethane Potential (BMP) was also determine. However, due to the extensive nature of the results, the exact data for each municipality is not presented in this abstract.

Table 4. Portuguese biomethane potential breakdown

Substrate origin	Biomethane Potential [Mm^3/a]
Cattle	65.33
Pigs	4.479
Poultry	14.15
Sheep	4.53
Urban Waste	322.37
Total	**410.86**

Comparing the results from of biomethane potential from different livestock reported in Table 1 with those reported Table 4, we can notice that similar values to those reported by Ferreira where obtained. However, this are quite different from the ones reported by LNEG. This difference will most likely be attributed to an overestimation by LNEG on the amount of waste can be collected. However, since LNEG did not report their calculation methodology no definite conclusion can be made. On the other hand, comparing the potential from urban solid waste reported in Table 4 with that reported by LNEG, we can also notice a difference of 89.2Mm^3/a. However, similarly to the previous case, the procedure on how the LNEG results are obtained are not reported. Hence, it is not possible to comment on the underlying reason behind this difference.

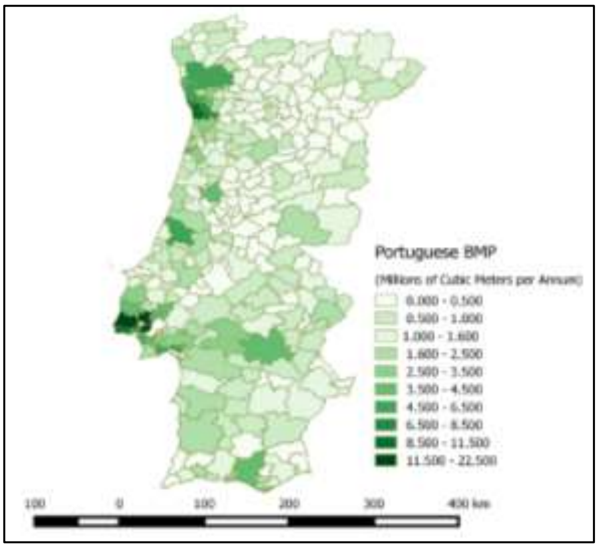

Figure 1. Biomethane potential from all waste in the Portuguese mainland

On the other hand, *Figure 1* shows the biomethane potential spatially distributed for all the municipalities in mainland Portugal. From this figure we can observed that the main potential resides in Lisbon and in Porto. Moreover, the municipalities that constitute the concession area of Portgás have a BMP of 99.062 Mm^3/a mostly attributed to municipal waste (89.5% of total BMP) with some part of it being cattle waste (9.5% of total BMP). Additionally, the most important municipalities for Portgás in terms of BMP are Porto, Gondomar, Vila Nova de Gaia and Matosinhos.

4.4 Portuguese Landscape Conclusions

After observing an analyzing the results presented in the previous section, we can make the following conclusions related to biomethane potential of Portugal, as well as the biomethane potential in the municipalities of interest of Portgás:

- The Portuguese biomethane potential is estimated to be 410.86 Mm^3/a
- The greatest potential for producing biomethane in the country resides in the processing of urban solid waste.
- The metropolitan areas of Lisbon and Porto, as well as their vicinities, have the highest biomethane potential in the country.
- Cattle manure has the highest biomethane potential in the nation when compared to processing other livestock waste.
- The total biomethane potential in the municipalities where Portgás owns assets is estimated to be 99.059 Mm3/a, which accounts for 24.1% of the national potential.
- Most of the biomethane potential of the municipalities where Portgás owns assets is attributed to processing urban solid waste, with 89.5% share of the total BMP of the area.
- Processing cattle waste is the second substrate with highest biomethane potential in the municipalities of interest for Portgás, with 9.5% share of the total BMP of the area.
- Pig, poultry and sheep waste combined represent 1% of the total biomethane potential in the municipalities of interest for Portgás.
- The municipalities with highest biomethane potential where Portgás owns assets are Porto, Gondomar, Vila Nova de Gaia and Matosinhos.

5. Locating Biomethane Plants Across The Portgás Concession Area

This section was developed with the objective of determining the optimal locations for building central biomethane production plants that inject gas into the Portgás grid. In order to do so a model was developed that considered spatially explicit data of all of the 29 municipalities which form the Portgás concession area. The model is characterized for assessing the order in which plant locations should be chosen based on Net Present Value (NPV). Furthermore, the model also provides insights on the Levelized Cost of Energy (LCOE) as well as biomass transport emissions fir each plant. Additionally, the model also takes into account spatial resources utilization/depletion and grid demand. Hence, this chapter provides an assessment tool that will help inform stakeholders on the manner in which to approach biomethane development in the Portgás concession area. Moreover, the tool also provides quantitative values that can be further used in Multi-Criteria Decision Analysis for final assessment of biomethane facility selection.

5.1 Model Characteristics

The work developed in this section is largely based on the model proposed by Richard O'Shea [25]. However, some modifications where included to improve the model such as using real distances to transport biomass with the Bing Maps API, as well as accounting for emission cost, carbon tax and guarantees of origin. Moreover, the data used for assessing the feedstock and biomethane corresponds to the results of chapter #2: "Portugal Landscape". Bearing this in mind, the equations that describe the model are summarized as follows (see Annex 1 for nomenclature):

Equation 4: Annual Transport Cost

$$TC_t = \sum_i^n \sum_j^m x_{i,j} * M_{i,j} * (RTP_{i,j} * D_{i,j} * STC + LC)$$

Equation 5: Annual Transport Emissions

$$TE_t = \sum_i^n \sum_j^m x_{i,j} * RTP_{i,j} * M_{i,j} * D_{i,j} * STE$$

Equation 6: Feedstock Revenue

$$FR_t = \sum_i^n \sum_j^m x_{i,j} * M_{i,j} * FF_{i,j}$$

Equation 7: Plant Annual Energy Output

$$P_t = \sum_i^n \sum_j^m x_{i,j} * RMY_j * M_{i,j} * LF * E$$

Equation 8: CAPEX

$$CAPEX = Cc + \sum_i^n \sum_j^m x_{i,j} * RMY_j * M_{i,j} * LF * E * Sc$$

Equation 9: OPEX

$$OPEX = Co + \sum_i^n \sum_j^m x_{i,j} * RMY_j * M_{i,j} * LF * E * So$$

Equation 10: Revenue streams

$$R_t = (NGP + I_{tax} + I) * P_t - TEt * CO_{2_{tax}}$$

Equation 11: Net Present Value (Optimization function)

$$NPV = DF * (R_t + FR_t - OPEX_t - TC_t) - CAPEX$$

Equation 12: Discount factor

$$DF = \frac{(1+dr)^L - 1}{dr * (1+dr)^L}$$

Equation 13: Cash Flow

$$CF = R_t + FR_t - OPEX_t - TC_t$$

Equation 14: Discounted Payback Period

$$\boldsymbol{DPP = \frac{ln\left(\frac{1}{1-(CAPEX * \frac{dr}{CF})}\right)}{ln(1+dr)}}$$

Constrains

$$P_t \leq Cap\ in\ MWh\ per\ annum\ uploaded\ by\ user\ per\ muncipality$$

5.2 Solving Algorithm

To solve and optimize the previous equations a the "*Green Gas Planner*" decision support tool was developed. The algorithm can behind the tool can be broken down in three main blocks namely: (i) Input Data, (ii) Outer loop for building plants and (iii) Inner loop for maximizing NPV. Moreover, the flow diagram of this algorithm can be seen in Annex 2. The first block consists of three different input data: User Input Data, CSV Loaded Data and Intrinsic Model Data. The second block of the algorithm consists of selecting and building each plant in an order of highest NPV to lowest NPV based on the results obtained in the third block. Hence, in this block the final results of the model are stored which includes both the plant characteristics as well as the optimal decisions variables obtained for each plant.

The third block is where the optimization process occurs for each of the plants that have not been built yet. Optimization of the equations presented in the previous subsection is done via integer linear programming using the pulp python package. The solver determines from where the feedstock is sourced from as well as what type of feedstock is source from said location. Hence if there are "n" possible source locations and "m" types of feedstock's there are a total of "nxm" variables. For the purpose of this model there are 29 municipalities and 5 different types of feedstock's which represent a total of 145 decision variables. Moreover, decision variables are of the type 0-1 (zero or one) where 0 represents that a specific feedstock from a given location will not be taken and 1 that it will be taken.

Lastly, the COIN Branch and Cut solver (CBC) developed by the Computational Infrastructure for Operational Research (COIN-OR) was selected to solve the linear programming. This solver was selected for practicality reasons, since it was the only open source solver that was managed to be installed effectively. Furthermore, as the name suggests, the CBC solver uses branch-cut-algorithms which implies using a bound-and-branch algorithm with cutting planes to tighten the linear programming relaxations [26][27].

5.3 Case Studies

To understand the extent of policy influence, a set of case studies considering different policy scenarios from the leading EU nations in biomethane were proposed. Based on the findings of Chapter 1: "Country Profile for Biomethane Applications", the main countries that have policies that directly promote biomethane injection into gas grid are the UK, France Sweden, Netherlands and Denmark. In order to limit the scope of the case study, the policies of the top three nations with most biomethane will be selected. In this sense, the case studies will focus on applying the policies of the UK, Sweden and France in the Portuguese context. Additionally, a base case which consist of the current Portuguese scenario will also be studied. The set of this case studies will be referred to as "General Policy Scenarios" and will all consider a natural gas price and landfill gate fees corresponding to that of the Portuguese market of 32.5 € per MWh and 11€/ton respectively.

5.4 Locating Biomethane Plants Across The Portgás Concession Area Results

When analyzing the feasibility of building biomethane plants within the Portgás concession area using the Green Gas Planner model it was found that no plant with a positive Net Present Value can be built. Hence, under current Portuguese policies no plants should be built since the investment will result in a net loss for the company. Moreover observing Figures 2, 3 and 4 we can notice that the cumulative NPVs for all general case scenarios accounting for resource depletion was 126.5 M€ for the UK scenario, 56.5 M€ for the Swedish scenario and 192.4 M€ for the French scenario. Moreover, for all cases it was found that Porto and Vila de Nova Gaia are the first and second choice for investment.

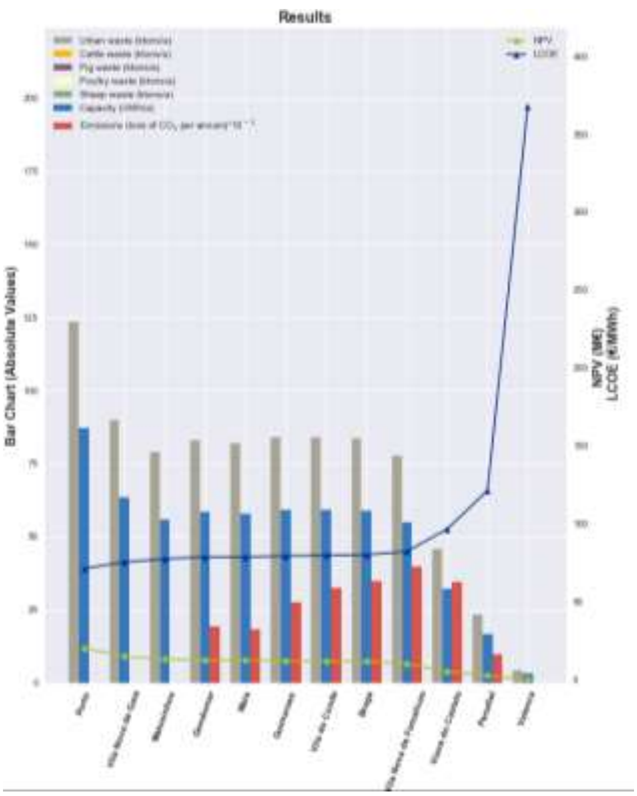

Figure 2. UK policy scenario with resource depletion

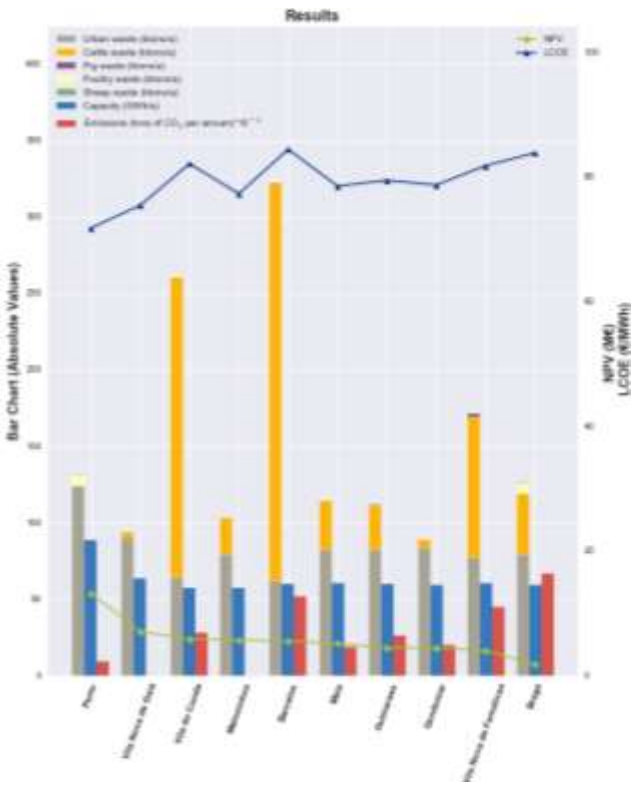

Figure 3. Sweden policy scenario with resource depletion

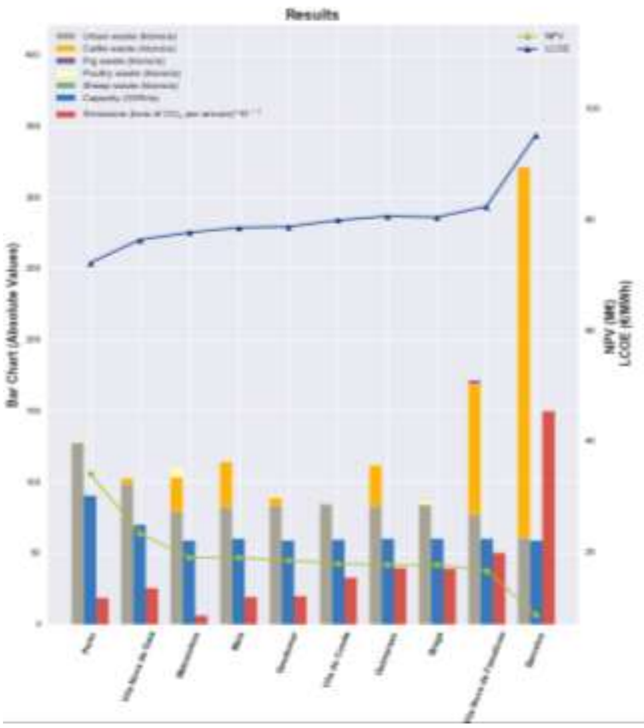

Figure 4. France policy scenario with resource depletion

5.5 Locating Biomethane Plants Across The Portgás Concession Area Conclusions

After analyzing the results presented, we can make the following conclusions regarding investing in different biomethane business models across the Portgás concession area:

- Under the current Portuguese policies no plant with a positive NPV can be built, hence no investment should be done.
- With UK policies in Portugal leads to 10 out of the 29 municipalities in Portgás to have Positive NPV when considering resource depletion.
- Considering Portugal under Swedish policy results in to 9 out of the 29 municipalities in Portgás to have Positive NPV when considering resource depletion.
- Portugal under French policies leads to 9 out of the 29 municipalities in Portgás to have Positive NPV when considering resource depletion.
- Comparing all three General Policy scenarios we can notice that the best case is the French policy scenario with a cumulative NPV of 192.4 M€, followed by the UK with a cumulative NPV of 126.5 M€, while the worst case is the Swedish scenario with a cumulative NPV of 56.5 M€.

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Annexes.

Annex 1. List of symbols for the model presented in section 5.2

Symbols	Definition	Units
CAPEX	Capital Expenditure	[€]
Cc	CAPEX linear intersection constant	[€]
Co	OPEX linear intersection constant	[€/a]
D	Distance	[km]
DF	Discount Factor	[-]
dr	Discount rate	[-]
E	Energy content of biomethane	[MWh/m^3]
FF	Feedstock fee	[±€/ton]
FR	Annual feedstock revenue	[±€/(a*ton)]
LF	Load Factor	[-]
M	Annual tonnage of feedstock collected	[ton/a]
m	Number of different feedstock's	[#]
NPV	Net Present Value	[€]
n	Number of potential locations	[#]
OPEX	Operational Expenditure	[€/a]
Pt	Plant capacity	[$MWh*a^{-1}$]
RTP	Return Trip Multiplier	[-]
RMY	Real Methane Yield	[m^3/ ton_{vs}]
Sc	CAPEX linear slope constant	[€/($MWh*a^{-1}$)]
So	OPEX linear slope constant	[€/MWh]
STC	Specific Transport Emissions	[€/(ton*km)]
STE	Specific Transport Emissions	[ton_{CO2eq}/(ton*km)]
TC	Annual Transport Cost	[€/a]
TE	Annual Transport Emissions	[ton_{CO2eq}]
x	Decision variable (x=0 or x=1)	[-]

Annex 2. Solving Algorithm of the Green Gas Planner