TÉCNICO LISBOA

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

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Abstract (EN)

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 and remain competitive in business. 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.

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 Mm^3/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.

Resumo (PT)

À medida que a tendência global transita dos combustíveis fósseis para fontes de energia renováveis, as empresas tradicionais de combustíveis fósseis devem adaptar-se e tornar-se parte do movimento de transição energética, a fim de evitar ativos ociosos e mantendo-se no ativo. O objetivo deste trabalho é fornecer informações de tomada de decisão para a adoção de modelos de negócio de biometano aplicáveis à rede portuguesa de gás natural com base em políticas públicas, em toda a UE, e dados nacionais portugueses.

Os seis principais países da UE em número de centrais de biometano foram identificados e estudados, em termos de ecossistema, como forma de avaliar o sucesso fundamental e as falhas da incorporação do biometano como vetor energético. O potencial de biometano em Portugal foi estimado espacialmente a nível municipal para cinco tipos diferentes de resíduos, nomeadamente, bovinos, porcos, aves, ovinos e resíduos urbanos. Foi desenvolvida e utilizada uma ferramenta de apoio à decisão para otimizar modelos de negócio de biometano em termos de NPV, aplicada aos 29 municípios que constituem a área de concessão da Portgás.

Analisando os países que lideram o negócio do biometano na UE, verificou-se que todas as nações que adotaram o biometano têm sistemas de apoio direto que promovem a adoção deste vetor energético ou políticas exigentes de carbono que tornam os custos do biometano competitivos com o gás natural. Estimava-se que o potencial de biometano para Portugal seja de 410,86 Mm3/a, com a maior parte preveniente de resíduos sólidos urbanos. Além disso, verificou-se que os 29 municípios que constituem a área de concessão Portgás representam 24,1% desse potencial. Por último, a ferramenta de apoio à decisão desenvolvida “Green Gas Planner” mostra que nenhuma central de biometano será construída na concessão da Portgás, considerando as políticas atuais de Portugal, enquanto que, aplicando as políticas do Reino Unido, Suécia e França muitas centrais apresentariam um NPV positivo, podendo ser construídas na área de concessão com um NPV cumulativo de 126,5 M€, 56,5 M€ e 192,4 M€ respetivamente durante um período de 20 anos.

Palavras-chave: apoio à decisão, biogás, biomethano, distribuição espacial, QGIS, tomada de decisão, política da UE, Portugal, Python, regimes de apoio, tecno-económicos.

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List of abbreviations used

Abbreviations	Definition
a	Per annum used as a unit through the document
AD	Anaerobic Digestion
BMP	Biomethane Potential per annum
CBC	COIN Branch and Cut solver
COIN-OR	Computational Infrastructure for Operational Research
cewep	Confederation of European Waste-to-Energy Plants
CHP	Co-generation of Heat and Power
DSO	Distribution Systems Operator
EEG	German Renewable Energy Sources Act
ETS	Emission Trading System
FIT	Feed-In Tariff
GHG	Green House Gases
GO	Guarantee of Origin
GoOs	Guarantees of Origin
HDVs	Heavy Duty Vehciles
HHV	High Heating Value
INE	Instituto Nacional de Estatísticas
LCOE	Levelized Cost Of Energy
LHV	Low Heating Value
LNEG	Laboratório Nacional de Energia e Geologia
Mm^3	Millions of cubic meters
NPV	Net Present Value
NUTS	Nomenclatura das Unidades Territoriais para Fins Estatísticos
RHI	UKs Renewable Heat Incentive
RTFCs	Renewable Transport Fuel Certificates
SDE+	Stimulering Duurzame Energieproductie
SER	Syndicat des Énergies Renouvelables

SGRU	Sistema de Gestão de Resíduos Urbanos
TSO	Transmission System Operator
USR	Urban Solid Residues
WI	Wobbe Index

Nomenclature

Parameter	Definition	Units
BGY	Biogas yield	[m^3/ton_{vs}]
BMP	Biomethane Potential per annum	[m^3/a]
BMY	Biomethane Yield	[m^3/ton]
$Cash^{in}$	Incoming cash flows in a given year	[€]
$Cash^{out}$	Outgoing cash flows in a given year	[€]
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]
ERW	Waste destined to energy recovery	[ton]
FF	Feedstock fee	[±€/ton]
FR	Annual feedstock revenue	[±€/(a*ton)]
LF	Load Factor	[-]
LW	Landfill waste	[ton]
M	Effective average manure collected	[ton/a per head]
n	Number of livestock	[# head livestock]
OFLW	Organic Fraction of Landfill Waste	[-]
OPEX	Operational Expenditure	[€/a]
OWR	Organic waste destined for recycling	[ton]
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$_{CO2eq}$]
TS	Total solid fraction	[-]
V_{CH4}	Volume fraction of methane	[-]
VS	Volatile solid fraction	[-]
x	Decision variable (x=0 or x=1)	[-]

Sub and super index nomenclature

Index	Definition
c	Cattle
i	Location “i”
j	Type of feedstock
m	Number of different feedstock’s
n	Number of potential locations
p	Pigs
po	Poultry
s	Sheep
u	Urban waste
vs	Volatile solids
,	Used to separate two different sub-indexes

Introduction

REN Portgás Distribuição is a public service company that focuses on the distribution of natural gas in the northern coastal region of Portugal. Particularly, the main activity of the company consists in the development and management of the public gas distribution network within the 29 municipalities that constitute its assigned concession area, these municipalities are:

- Barcelos
- Braga
- Caminha
- Esposende
- Fafe
- Felgueiras
- Gondomar
- Guimarães
- Lousada
- Maia
- Matosinhos
- Paços de Ferreira
- Paredes
- Paredes de Coura
- Penafiel
- Ponte de Lima
- Porto
- Póvoa de Varzim
- Santo Tirso
- Trofa
- Valença
- Valongo
- Viana do Castelo
- Vila do Conde
- Vila Nova de Cerveira
- Vila Nova de Famalicão
- Vila Nova de Gaia
- Vila Verde
- Vizela

In more general terms, the mission of Portgás is to provide energy services that have a positive impact on the Portuguese community that it services. In order to accomplish this mission, Portgás has a vision of becoming the reference utility in innovation, value creation and sustainability. Moreover, Portgás being part of the fossil fuel industry, is in a perfect spot to accomplish this by being part of the energy transition movement.

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 companies like Portgás 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.

Renewable gas is a broad term that is used to refer to any gas that is produced from a renewable source. This term encompasses biogas, biomethane, bio hydrogen, synthetic natural gas and bio-synthetic natural gas, among others. Biogas and biomethane production are the most mature technologies at present. Moreover, biomethane for all intent and purpose can substitute quite well natural gas since they are mostly methane molecules. Hence, it seems obvious that a first step into transitioning the natural gas grid into a sustainable gas grid would imply substituting as much natural gas for biomethane as possible.

Bearing the previous in mind, the Innovation Team within Portgás considers that injecting biomethane into their gas grid would align with the company vision and mission of becoming an innovative and sustainable energy service company. Therefore, it has decided to take the first steps in assessing the feasibility of such a project with this study.

In this sense, the scope of the study is to propose and assess different business models for implementing biomethane into the natural gas grid of Portugal delimited to the concession area of Portgás. Moreover, this study was undertaken to provide decision-making insights into how the company can be part of the energy transition movement based on factual data.

Contents of the work

The work consists mainly of three chapters. 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, each chapter presents a conclusion related to the findings. With this being said, the three chapters are as follows:

Chapter 1 Biomethane Across The Leading EU Nations: In this chapter the top six EU nations with most biomethane plants are studied in terms of their biomethane ecosystem, which encompasses topics related to policy, end-use, feedstock and future prospects.

Chapter 2 Portuguese Landscape: This chapter consists of an assessment of the Portuguese biomethane potential accounting for spatial distribution of waste resources in the country at a municipality level.

Chapter 3 Locating Biomethane Plants Across The Portgás Concession Area: This chapter builds upon the results of Chapters 1 and 2 in order to determine the optimal location for building biomethane plants within the Portgás concession area, considering the different policy and support schemes scenarios of Chapter 1 and the spatially distributed resources of Chapter 2.

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.

Chapter 1: Biomethane Across The Leading EU Nations

Biogas is a mix of different gaseous components that are produced from a biomass, the most widely used technology being anaerobic digestion. The main component of biogas (over 50%) is methane, thus called biomethane, with carbon dioxide being the 2nd most relevant constituent. Others gases present in small amounts are water vapour, hydrogen sulphide and ammonia. Purifying biogas to biomethane is called gas upgrading, and involves the successive removal of water vapour and carbon dioxide (inhibitors of the combustion) and hydrogen sulphide and ammonia, which are quite aggressive substances (in the case of hydrogen sulphide, its combination com water is quite fast and results in sulphuric acid), it is possible to use biogas directly to produce energy (for instance, in CHP units), but the boiler must be able to deal with the aggressive environment and inhibition by carbon dioxide and water vapour. In order to inject the gas in the natural gas grid, then gas upgrading is inevitable as the degree of purity methane reaches 98 %

The following chapter 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.

1.1 Germany

1.1.1 Country Overview

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 generate 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].

By 2018, there were around 8,980 biogas production plants (including biomethane plants) operating in Germany; these produce around 10 billion m3 of gas per year. Around 8,780 of those plants are operating with an on-site electric conversion of biogas and a satellite CHP unit. On the other hand, only 203 of the plants in Germany are coupled with upgrading technologies which produce around 0.9 billion m3 of biomethane a year (2.7 million m^3 per day) [1].

Furthermore, the vast majority of the biogas and biomethane produced in Germany is destined for CHP applications as shown in Figure 1. This landscape is a consequence of to the nature of the policies that have been implemented in the country in the previous decades and will be further discussed in the upcoming sections.

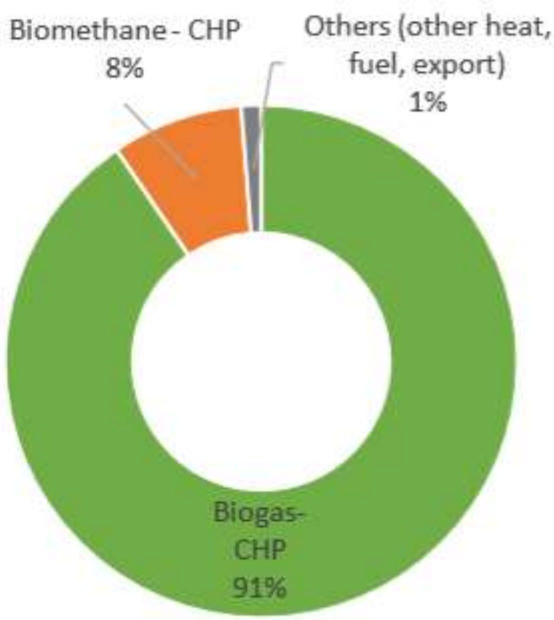

Figure 1. Biogas and biomethane production in Germany 2018 and its utilization path *[2]*

1.1.2 Support Schemes

The Erneuerbare-Energien-Gesetz (EEG), also known as the Renewable Energy Sources Act, is the main support scheme that has played a critical role in the success of the German energy transition. The EEG came into play in the year 2000 as a feed-in tariff scheme to foster generation of renewable electricity. Therefore, the objective of the EEG is solely the production of renewable electricity, and it accomplishes this by focusing of three main pillars, namely:

I. The right of grid connection for renewable energy facilities.
II. The obligation for net operators to preferentially purchase electricity based on renewables.
III. A minimum feed-in-tariff paid for the generated electricity.

However, since its implementation in the year 2000, the EEG has been amended five times in order to promote more renewable energies and to correct undesirable developments. Furthermore, from the biomethane business perspective the latest amendment to the EEG in 2017 is of particular concern, since it changed the traditional guaranteed feed-in tariff scheme into a bidding system. This change has set a limit to the growth of biomass including biogas and biomethane to a maximum of 200 MWh_e; which is considerably smaller when compared to the 2,800 MWh_e of onshore wind or the 2,500 MWh_e of solar.

Hence, in order to understand both the current landscape of biomethane in Germany, as well as to gain insight in the future trend it is necessary to analyze in depth the evolution of the EEG act. Figure 2 shows the evolution of the EEG specified for biomethane during the period of guaranteed feed in tariffs.

Figure 2. Evolution of the Renewable Energy Sources ACT EEG [1]

The years between 2000 and 2012 showed a boom in biogas plants installations in Germany. As seen in Figure 2, those years were characterized with high incentives in the EEG to grow the biogas capacity of the nation. Particularly, the biggest growth can be seen for the period between 2004 and 2011, since the amendments from 2004 and 2009 provided the strongest incentives for increasing biogas and biomethane. These two amendments, incorporated substrate bonuses that included energy crops, manure, waste and residues. Furthermore, the upgrading bonus in 2009 furthered improve the conditions for implementing biomethane. The upgrading bonus range from 1 to 3 ¢€/kWh [3].

On the other hand, after restructuring of the EEG in 2012 and in 2014 there was a clear reduction in the commissioning of new biogas and biomethane plants due to decrease in tariffs and incentives; particularly the upgrading and substrate bonus. Hence, since 2012 the extension of capacity in the biogas sector has mainly been limited to either existing plant expansion, improving flexible plant operation or a slight incorporation of small-scale manure and waste digestion plants [1].

Based on the evaluation of the EEG until 2014, we can conclude that when electricity generation tariffs were coupled with substrate bonuses the highest increase in biogas plants installations was achieved. Furthermore, biomethane installations were only incorporated when clear incentive for upgrading the biogas were available. However, since for the most part the underlying incentives were mostly focused on promoting electricity production with CHP applications, we can notice that natural end use for biomethane would be CHP applications rather than grid injection. Lastly, the electricity generation driven policies of Germany show that these types of incentives lead to a country landscape with more biogas plants than biomethane plants, both with an exclusive focus in CHP utilization as shown in Figure 1.

As previously mentioned, the latest amendment to the EEG in 2017 completely shifted the German support scheme. The shift to a guaranteed feed-in tariff to a pay-as-bid model was undertaken in order to cut down on costs, favor market integration and allow for the establishment of the competitive renewables. The particular policies of this amendment that are relevant to biomethane applications are shown in Figure 3.

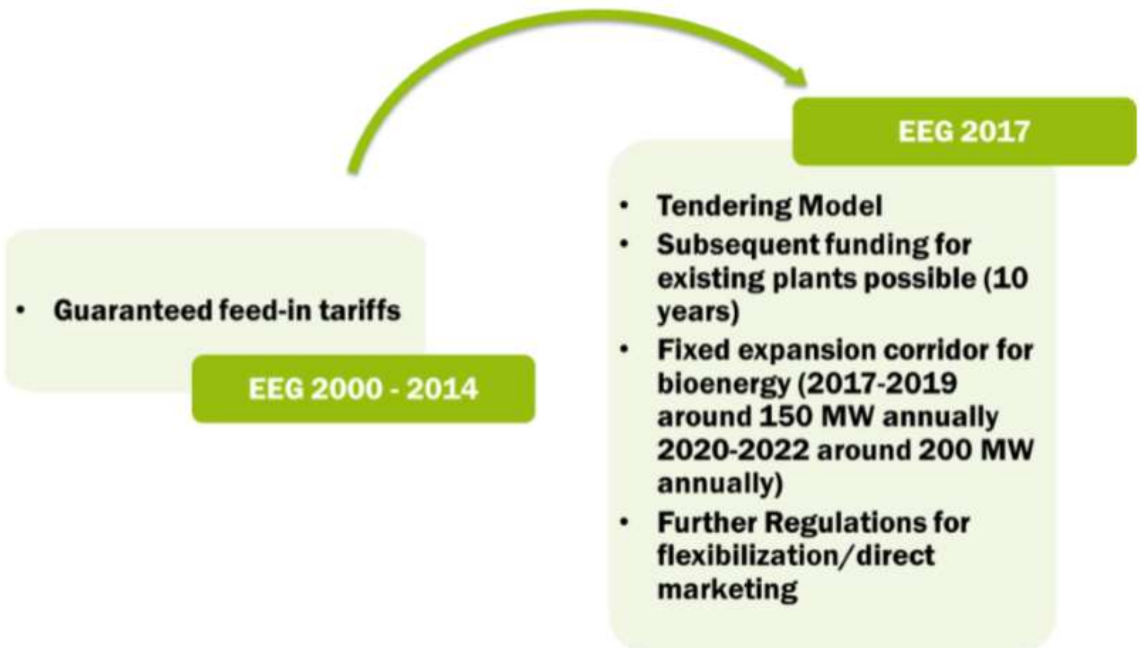

Figure 3. Renewable Energy Sources Act (EEG) change in 2017 [1]

The latest update of the EEG limits the maximum bidding value for both new and already existing biomass plants to 14.73 ¢€/kWh$_e$ and 16.73 ¢€/kWh$_e$ respectively; each with a digression of 1% per annum. Furthermore, only new plants with capacities larger than 150 kW$_e$, 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. This new condition requires plants to install a twofold CHP overcapacity in relation to the average rated power output [1].

This current economic framework has made small-scale biogas upgrading plants economically unfeasible to operate. Moreover, the low remuneration rates of the 2014 amendment, coupled with upper limits for bids of the latest amendment, has made biomethane CHP plants with high heat utilization rarely competitive in Germany. 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.

1.1.3 Feedstock for biomethane production

As seen in Figure 4, most biogas and biomethane produced in Germany comes from anaerobic digestion of energy crops, as well as co-digestion of energy crops coupled animal excrement. This is mainly due to the fact that using maize as crop for digestions leads to high methane yields. Furthermore, since the EEG supported a substrate bonus for energy corps and manure until 2014, there was a clear incentive to commission either pure energy crops biogas plants or co-digestion plants with manure.

However, due to the food versus fuel debate a maize cap that limited the amount of grain and maize to be used for digestion was set in 2012. Initially, the cap stared at a maximum of 60%, while nowadays it set to around 47%. Furthermore, by 2020/2021 the cap will be further reduced to around 44% [4]. This fact couple with the deletion of substrate bonus for energy crops and manure in the EEG 2014, has led to shift towards alternative substrates such as wild plants, agricultural residues and other waste material.

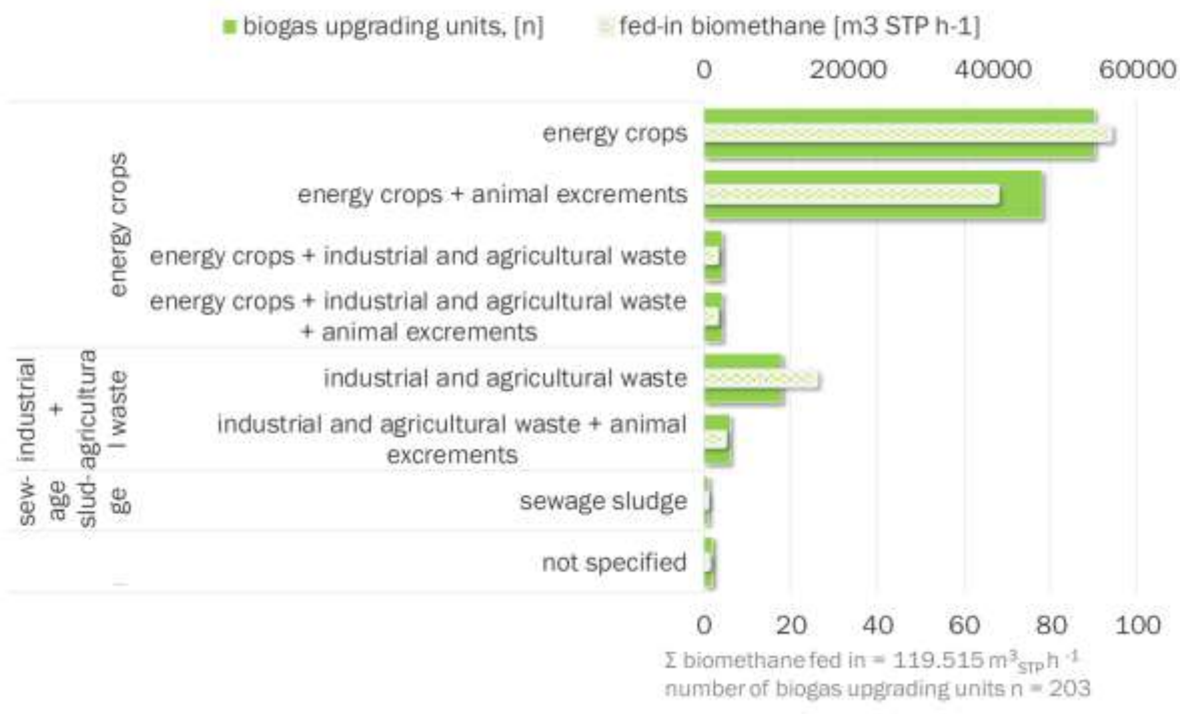

Figure 4. Substrate for biomethane production in terms of the number of upgrading plants and respective amount of feed-in biomethane for Germany 2018 [1]

1.1.4 Biomethane utilization pathways

As previously mentioned, the core focus of the EEG is the production of electricity from renewable sources. Since this is the main support scheme in Germany for renewable energies, it is only natural that most of the use of biomethane is destined to the production of electricity. Furthermore, since there is increased efficiency and incentive to produce heat and electricity from biomethane, the most effective utilization of biomethane is converting it using CHP. In this sense, CHP accounts for 88% of the total use of biomethane in the nation, while other utilizations of biomethane such as heat, transport fuel and exportation play a minor as shown in Figure 5.

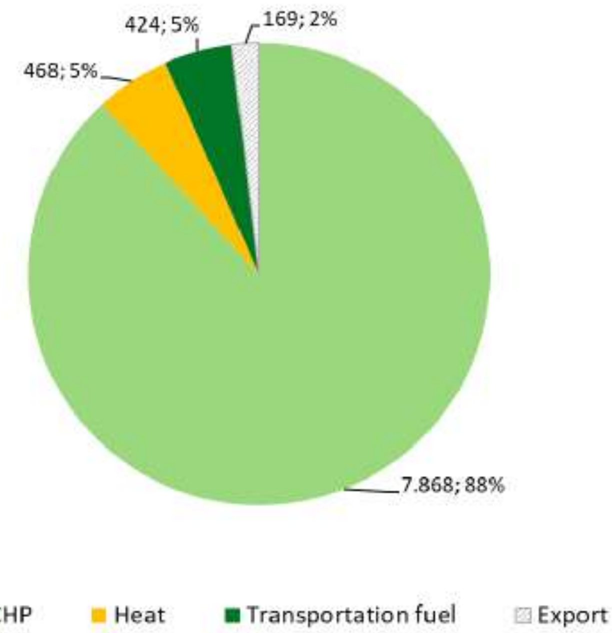

Figure 5. Share of biomethane utilization in Germany 2017 (GWh of biomethane) [1]

In order to inject the gas into the grid it must comply with the legal, technical and comic frame defined by the German Energy Act (EnWG), the Gas Grid Access Ordinance (GasNZV) and the EEG which grants priority to renewable energy sources. Moreover, it is the responsibility of the German regulator (BNetzA) to control and monitor the injection projects [4]. Lastly, the DVGW G 260 and G 262 regulations control the rules governing the gas quality and characteristics, table 1 summarizes the main aspects of these [5].

Table 1. Requirements for gas grid injection in Germany [5]

Characteristics	Unit	Gas value
Wobbe Index	kWh/m^3	13.6 - 15.7
Calorific value	kWh/m^3	8.4 - 13.1
Relative density		0.55 - 0.75
Total sulphur content	mg/m^3	< 8 (short-term up to < 30)
Total hydrogen sulphide content	mg/m^3	< 5
Water content	mg/m^3	< 50 in grids > 10 bar < 200 in grids ≤ 10 bar
Hydrogen content	vol%	< 2 in exceptional case up to < 10
Carbon dioxide content	vol%	in L-gas grids < 10 in H-gas grids < 5
Oxygen content	vol%	< 3 at injection in dry grids < 0.5 at injection in wet grids

On the other hand, as a means to promote biomethane injection the German Gas Grid Acces Ordinace establishes that the biomethane transport costumer is entitled to avoid a power grid fee of 0.7 ¢€/kWh of biomethane; the avoidance fee is set for a period of 10 years [5]. Additionally, to furthered promote gas injection in Germany, the cost for grid connections is usually shared 25/75 between both the biomethane producer and the grid operator respectively. The rest of the cost are carried by the network and shared via the gas transport tariffs [6]

Lastly, biomethane to be used as fuel in the transport sector is promoted by blending regulations as in most countries in the EU. However, in Germany blending obligations are based in terms of emission reductions rather than percentage of renewable share. In particular, Germany aims for a 6% reduction of emissions of fuels by 2020 with no double counting. Under these standards, fuel suppliers that fail to meet this requirements are liable to pay a penalty fee of 470 €/tCo_{2eq} [7].

1.1.5 Biomethane future prospects

As it stands today, biomethane generation costs in Germany vary from 2.5 ¢€/kWh (for residues) to 11.2 ¢€/kWh (for energy crops); with an average cost of 7.5 ¢€/kWh [8]. This means that biomethane is on average 3 times more expensive than natural gas in Germany. Hence, in both the short and medium term biomethane cannot compete with natural gas prices without support and incentives. This is a big concern for existing biomethane plant, since by 2030 the fixed remuneration of the EEG will expire for many of them. Additionally, 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 as shown in Figure 6 [1].

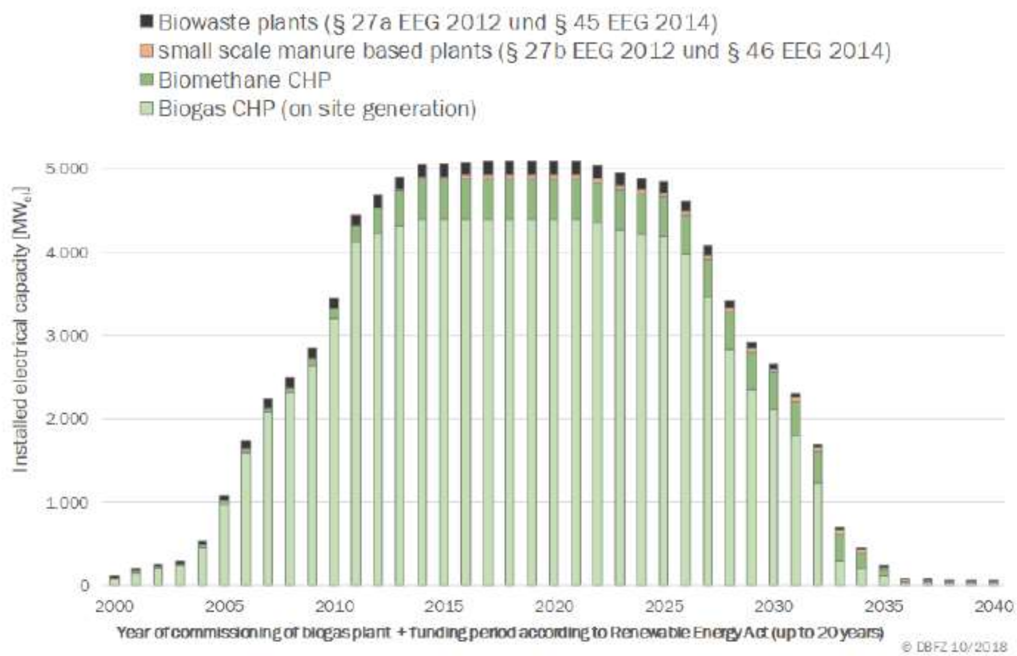

Figure 6. Development of installed capacity of biogas plants after the expiration EEG funding with no follow-up funding [1]

1.2 The United Kingdom

1.2.1 Country Overview

The United Kingdom biogas sector is particular since the majority of the gas is produced from landfills (around 55% of the total gas production). This is in contrast to other countries such as Germany, Sweden and Denmark from which the majority of the gas is produced form anaerobic digestion. In particular, the

United Kingdom has a total production of biogas of around 10.8 TWh per year; out of which 2TWh correspond to biomethane output [9].

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 [10].

1.2.2 Support Schemes

The supports schemes in the UK until now have been driven by the 2009 EU Renewable Energy Directive, which sets a 15 % share target of renewables in the nation's final energy consumption. Moreover, the manner in which to reach the target implied specific renewable share targets for different sectors as seen in Table 2.

Table 2. The United Kingdom renewable share targets [11]

Sector	Share in gross final consumption per sector
Overall target	15%
Heating and cooling	12%
Electricity	30%
Transport	10%

As we can notice from table 2, the manner in which the UK introduces renewables into the energy mix is quite different than Germany. This is in the sense that, while the United Kingdom also focuses greatly in electricity generation, it also sets a great deal of importance to the heating and transport sector. This diversity makes the UK support scheme also quite diverse and can be summarized by the following as they pertain to biomethane [11]:

- **The Renewable Obligation (RO)**: supports renewable electricity projects by placing an obligation to electricity suppliers to either source a proportion of their electricity from a renewable source or to buy a Renewable Obligation Certificates (ROCs). The policy was clearly in place to promote renewable electricity by increasing their demand. However, the RO closed for new generation capacity in 2017.

- **The Contract for Difference (CfD) programme**: was introduced as a means to replace the Renewable Obligations system, as well as support large-scale renewable electricity projects. In a nutshell, the CfD is based in the market price of electricity and an agreed "strike price" for renewable electricity. Hence, when the strike price is higher than the market price, the CfD must pay the difference in price to the renewable generator. On the other hand, when the market price is higher than the strike price the renewable generator must pay the difference.

- **The Feed in Tariff (FIT)**: Is the main mechanism in the UK that promotes small-scale renewable electricity (<5MW or <2MW for CHP). FITs are the main support for anaerobic digestion in the UK, with 168.5 MW accredited to this technology in 2016. However, caps have been introduced since then and less and less funding is being awarded.

- **The Renewable Transport Fuel Obligation (RFTO)**: Is the main policy set out to reduce greenhouse gas emissions from fuels supplied in both road vehicles as well as non-road mobile machinery (e.g. waterway vessels and tractors). In short, the policy is aimed at providers of petrol, diesel, gas oil or renewable fuels that supply over 450,000 liters of fuel. These suppliers must meet their obligation by either redeeming Renewable Transport Fuel Certificates (RTFCs) or pay a fixed sum for each liter of fuel they want to "buy-out" from. RTFCs are obtained only by supplying renewable fuels, hence the policy is clearly in place to increase the supply of these fuels.

  Furthermore, obligations are divided in "main obligation" and the "development fuel target". The former is calculated from the total volume of fuel supplied. The total supply is multiplied by a percentage of renewable fuel that must be added as an obligation. The obligation percentage changes in time and depends on the period. In particular, the range of obligation percentages goes from 9.180% for in 2019 to 10.959% in 2032 and subsequent years. Lastly, those who fail to meet there obligation can "buy-out" at price of 30 pence (0.34€) per main RTFC they fail to redeem [12].

  On the other hand, the development fuel target is set to incentivize fuel paths ways which require greater support and fit in to the UK's long term strategy. Similarly to the main obligation, the development target is calculated based on the fuel supply which is multiplied the obligation percentage of the period. The range of the obligation percentage for development goes from 0.05% in 2019 to in 1.4% 2032 and subsequent years. Additionally, those who fail to meet the obligation must buy-out at 80 pence (0.90€) per development RTFC they fail to meet [12]

- **The Renewable Heat Incentive (RHI)**: It is the main mechanism that support and promotes renewable heat production. It was establish with the aim of closing the gap between the cost of fossil fuel heat sources and renewable heat alternatives. Additionally, the scheme itself is divided into Non-Domestic RHI and the Domestic RHI. The former applies to commercial, public sector, industrial and non-profit organizations. Particularly, it applies to biogas and biomethane generators, and those producers eligible are entitled to receive quarterly payments over a period of 20 years.

On the other hand, the Domestic RHI provides house owners payments that compensate the cost of installing low carbon systems. Moreover, it is available to households both on and off the gas grid. Furthermore, the scheme guarantees quarterly payments over a period of seven years.

Out of the two schemes, the Non-Domestic RHI is the one that applies mostly to 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 [13]. The tiers and tariff for the 2019 Non-Domestic RHI accredited plants are shown in Table 3.

Table 3. Non-Domestic RHI tariff table for biomethane injection plants accredited in 2019 [14]

Injection Capacity	Tier	Tariff in p/kWh (¢€/kWh)
First 40,000 MWh	1	4.86 (5.40)
Second 40,000 MWh	2	2.86 (3.20)
Remaining MWh	3	2.21 (2.40)

1.2.3 Feedstock for biomethane production

The majority of the feedstock used for biomethane production in the UK is obtained from agricultural residues; unlike Germany, which depends on energy crops. Furthermore, sewage also plays a role in the biomethane production. These two feeds 70% of the share of biomethane production in the United Kingdom as seen in Figure 7. Information on the remaining 30% of feedstock used, which accounts for the rest of the biomethane production, is not readily available in the literature, and therefore remains unknown [10].

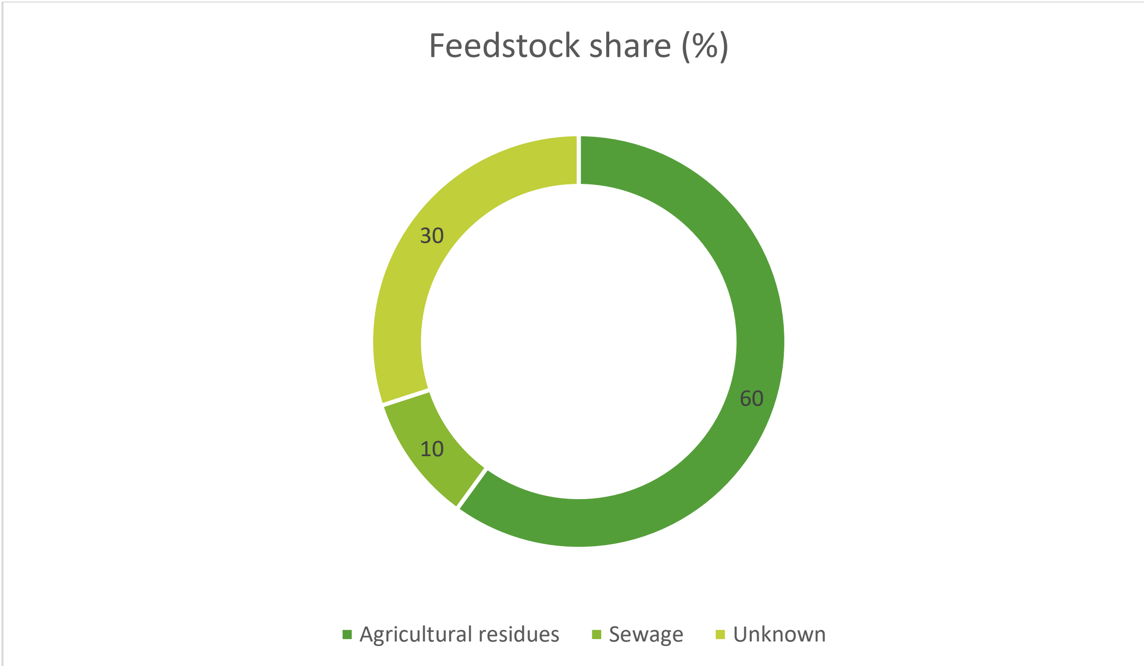

Figure 7. Distribution of feedstock for biomethane plants in the UK [10]

While there is no clear breakdown of the feedstock used for biomethane production in the UK, it is certain the all of the gas produced comes from anaerobic digestion plants. Hence, it is possible to infer that currently no Bio-SNG plants operate in the UK. However, this might not be the case for the futures. It is estimated that only 5% of all current gas demand in the UK can be met by anaerobic digestion, due to the lack of supply of wet feedstock. If Bio-SNG is incorporated, one-fifth of the demand could be met since it allows for wider range of feed [15]

1.2.4 Biomethane utilization pathways

The gas network in the UK supplies services to around 23 million customers. However, most of demand is divided between domestic consumption and gas for electricity generation (transformation) [16]. The actual supply of natural gas in TWh for each sector is shown in Figure 8.

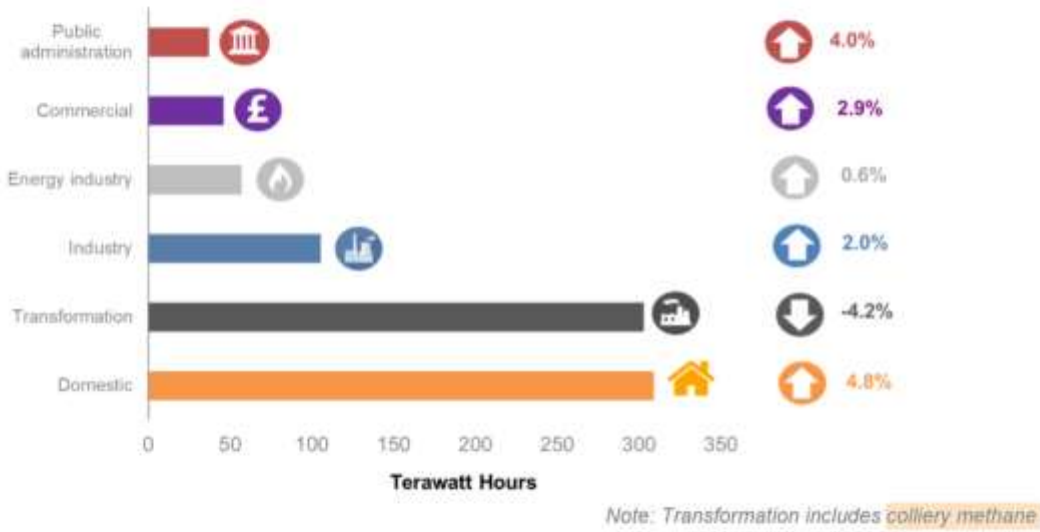

Figure 8. Gas demand breakdown by sector in the UK [16]

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 [15]. Lastly, it is estimated that biomethane accounts for around 0.4% of the total gas supply in the network [16].

1.2.5 Biomethane future prospects

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 [17]. Therefore, with the RHI policies in place we can expect an increase in biomethane plants in the upcoming years. In fact, it has been confirmed that as of 2019 there are around 343 new anaerobic digestion projects currently under development; these include both biogas and biomethane applications [18].

However, post-2030 the government of the United Kingdom is envisioning to reach greater carbon savings that cannot be reached by purely injecting biomethane into the gas grid. Hence, both governmental and industry stakeholders within the nation are advocating for one of two different long-term strategies that would revolutionize the current gas grid. These strategies are [16]:

- **Hydrogen blending**: This solution implies incorporating around 10 to 20% of hydrogen into the gas grid. This allows to further increase carbon savings without changes into the infrastructure. However, it is unlikely that this strategy can meet long-term emission targets.

- **100% Hydrogen**: This strategy would allow for major carbon savings and would be implemented via a city-by-city strategy. However, it would be highly expensive and will require both costumer mandatory switching and a high coordinated workforce.

Both biomethane injection into the gas network, and blending hydrogen into gas network would have minimum impact on end consumers. On the other hand, a pure hydrogen infrastructure would have a major impact and would take a lot of time, in particular due to the infrastructure challenges [16].

1.3 Sweden

1.3.1 Country Overview

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 [19]. 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. The share of use as a percentage of total biogas produced in the country can be seen in Figure 9.

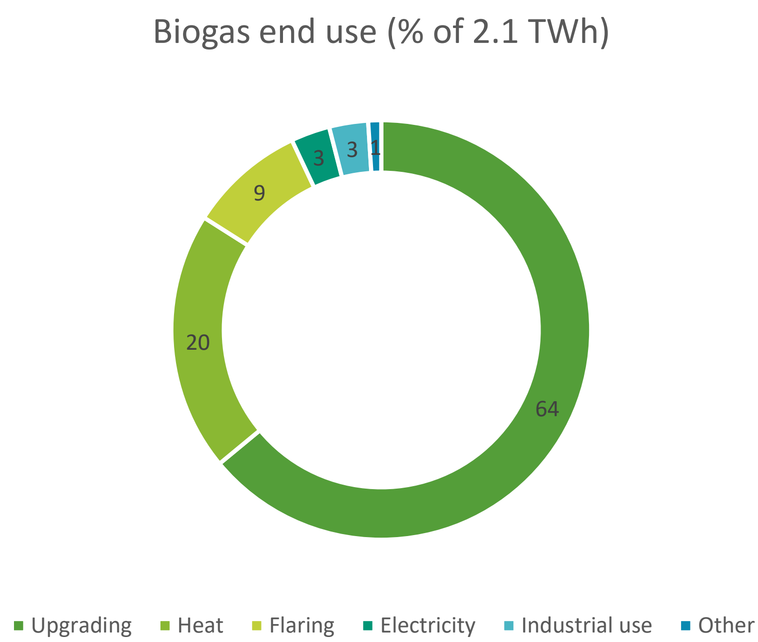

Figure 9. Swedish biogas use as a percent of production [20]

1.3.2 Support Schemes

Sweden is one of the most ambitious countries when it comes to implementing biomethane in their national energy mix. 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 [20]. 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 and are summarized follows [21]:

- **Energy and carbon tax for transport fuel**: This has been the main policy driver for the development of the biomethane fleet within the nation. Currently, all biofuels (including biomethane) are exempt of paying these taxes, making them competitive with petrol. Corresponding taxes for petro are anywhere around 0.72 SEK/kWh (68€/MWh).
- **Energy and carbon tax for heating**: Similarly, to the fuel tax, biogas is exempt of taxation when applied to heating applications (including industrial use). This is done with the intent of making it more competitive with natural gas which payed a tax of around 3.4 SEK/Nm3 (0.31c€/Nm3 or 29€/MWh) in 2017. However, by 2019 the tax is around 148.6 € per ton of CO_2.
- **Manure bases biogas support**: The policy was aimed to reduce methane emissions from manure by establishing a 390 MSEK (36M€) budget from 2015 to 2023. Furthermore, the budget subsides biogas production from manure with a rate of 0.40 SEK/kWh (0.039€/kWh).
- **Biomethane production support**: The policy was implemented for one year only (2018) to level the playing field for domestic biomethane producers that were facing disturbed competition from imported biomethane, which was favored by double subsidies. The budget set out for this policy in was set at 270 MSEK (36M€) and the support was up to 0.40 SEK/kWh (0.039€/kWh). Furthermore, this subside can be coupled on top with the manure production incentive. However, the subsidy does not apply to biogas produced from wastewater treatment sludge.
- **Klimatklivet**: Is a local climate investment program set out from 2015 to 2023. It is an investment support, up to 45%, for all types of measures that lead to GHG reductions. The budget was set in 2018 at 1.5 Billion SEK/year (0.14 Billion €) and is proposed to increase to 2.3 Billion SEK/year (0.21 Billion €) by 2020.
- **Bonus-Malus taxation for vehicles**: Is a taxation system for vehicles set out in 2018. The bonus applies to new low emissions car for up to 60000 SEK (5700€) and 10000 SEK (950€) for gas vehicles. On the other hand, the malus term refers to increased CO2 taxation for the first three years applied to high emissions cars i.e. gasoline and diesel.

1.3.3 Feedstock for biomethane production

Sweden produces around 2TWh of biogas a year, out which two thirds are upgraded. Hence, while the exact breakdown between of feed uses to strictly produce biomethane is not available, using the total share of feed for biogas gives us a good idea of the Swedish biomethane landscape [20].

Observing the share of substrate used for producing biogas reported by the Swedish Energy Agency in Figure 10, we can notice that the majority of biogas produced comes from waste, while energy crops is the source with least share. This is quite different than Germany that is mostly based on energy crops.

In recent years Sweden has mostly increased biogas plants based on co-digestion of household waste, manure and industrial bio-waste which account for around 1 of the 2 TWh of the total biogas produced [20].

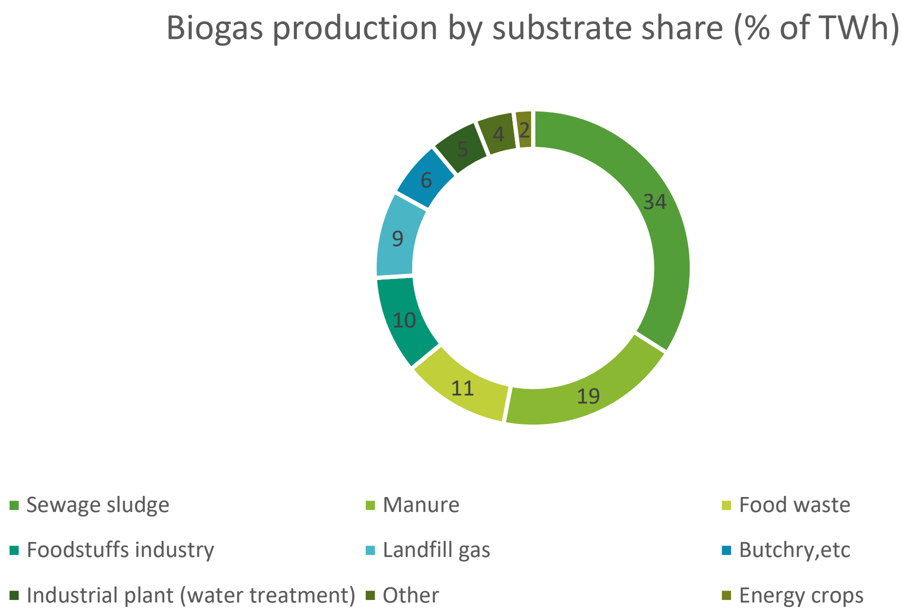

Figure 10. Proportion of biogas produced in Sweden for different substrates [20]

In its short term goals, Sweden aims to increase biogas production from 2 TWh to 7 TWh by means of circular economy. Several studies show that as the country stands today this may actually be possible.

1.3.4 Biomethane utilization pathway

Sweden is an exceptional country in terms of end use of biomethane, since the majority of gas produced in the nation is destined to be used as fuels in vehicles as can be seen in Figure 11. On the other hand only a minor part of the biomethane produced is injected to the grid for other purposes such as domestic heating.

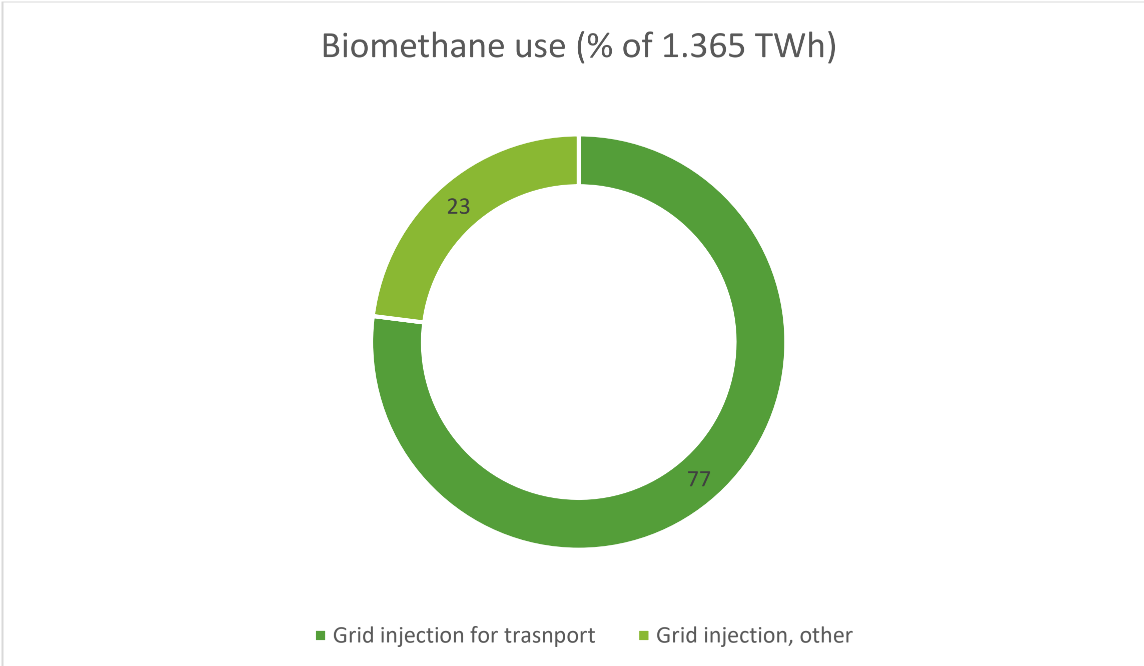

Figure 11. Share of biomethane use [20]

In this sense, the road transport sector is the most important market for Sweden. In fact there are around 55,000 gas vehicles on the road out of which 86% of the energetic value supplied to these comes strictly from biomethane. This exceptional performance has been accomplished by the nation through increased taxation fossil fuels. However, the same use is not seen at the industrial level since taxation policies for this sector is relatively low when compared to the transport sector [20].

1.3.5 Biomethane future prospects

In 2017 the Swedish government laid out a new climate policy framework which consist of new climate goals a Climate Policy Council and a Climate Act. These came into force in early 2018 and consisted of the following goals [20]:

- By 2045 accomplish net zero GHG emissions, and negative emissions the years there after.
- Reduce domestic transport emissions (excluding aviation) by at least 70% lower than 2010 levels.
- By 2030 emissions in Sweden outside the EU ETS (EU Emission Trading System) should be at least 63% lower than 1990 levels, and by 2040 at least 75% lower.

In order to accomplish these lofty goals the Swedish energy sector will need an uptake in renewable biofuels, and in particular in biomethane. As mentioned before, the Swedish government is aware of this and hence has set as a particular target to produce around 15 TWh of biogas by 2030. Out of these, 12TWh will be used in the transport sector while the remaining 3TWh will be used at the industrial level.

Additionally, Sweden is a big proponent of a circular economy and minimizing waste. Hence, it has continue to foster the production of bio-fertilizers from waste; which if exploited completely in the country can reduce up to 10 to 15% of mineral fertilizer imported into the country [20].

Therefore, under these 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. However, it is important to note that without subsidies biomethane cannot compete with natural gas despite heavy taxation. 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 [20].

Lastly, Sweden has invested considerably in gasification technology. With GoBiGas having more than 3 years of operation in the nation, it is one of the largest biofuel gasification plants in the world. Additionally, smaller gasification plants from 1 to 6 MW are also under development in Sweden

1.4 France

1.4.1 Country Overview

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. However, by the end of 2018 these number were expected to grow as a result of the Multiannual Energy Programme (PPE) under the French Energy Transition Act. Particularly, since the program continued biomethane injection into the gas grid starting from 1.7TWh in 2018, to 8TWh in 2023 and 50TWh by 2028 [22].

However, while the French goals are realistic current and future biomethane will still require heavy support. As it stands today, the French biomethane production costs is typically around 95 €/MWh with an average feed-in tariff of 120€/MWh, which is considerably high with respect to the wholesale price of natural gas set at around 17 €/MWh. In fact, to meet its biomethane growth goal over the 2019-2023 period it is estimated that the country will need around 1 to 2€ billion in financing [23].

1.4.2 Support Schemes

Production, supply and use of biomethane in France is fostered and supported mainly by the following two mechanisms:

- **Feed-in tariffs**: The systems set in place in France 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 (Nm3/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 [22].

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 receives 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, Figure 12 shows the final tariff based on both type of was and installed capacity [22].

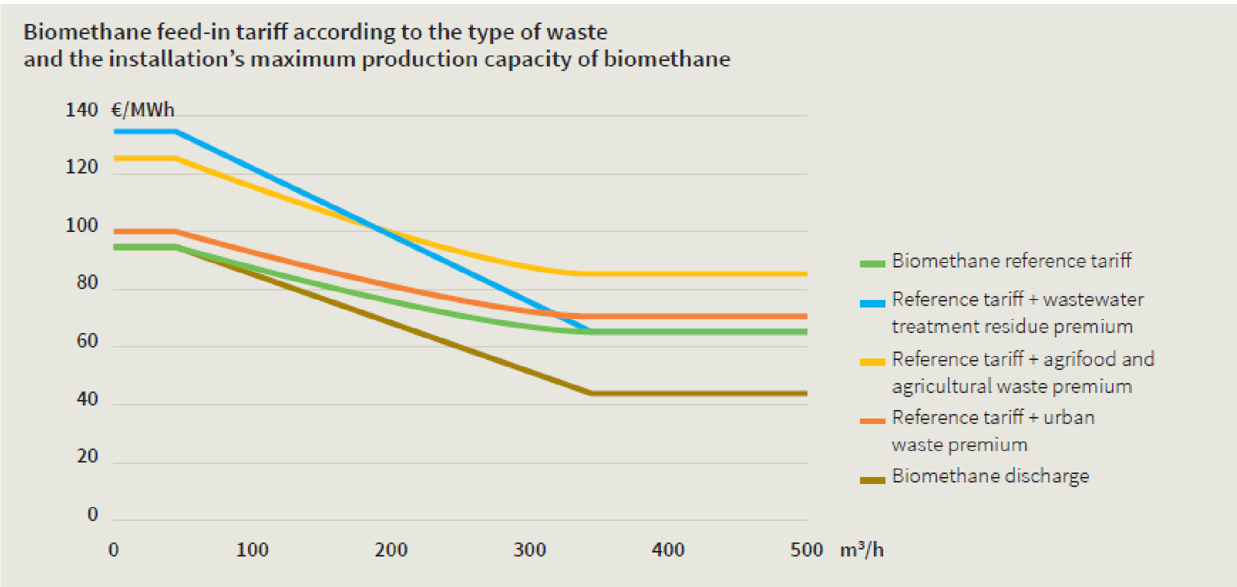

Figure 12. French biomethane feed-in tariff based on the installation capacity and type of waste [22]

- **Guarantees of Origin (GO)**: Is a system set out to support suppliers by decoupling the physical production of biomethane from its contractual sale (between a supplier and a consumer). The system allows biomethane producers to enter into a purchase contract with a gas supplier. Afterwards, a Guarantees of Origen (GO) is granted to the supplier for each MWh of biomethane they purchased and injected into the grid. Moreover, the GOs are valid for 24 months, they can be transfer between suppliers and expire once the consumer uses the renewable gas supply [22].
  Furthermore, GOs support suppliers since they work as an additional source of income. Current French legislation 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 [23].

While the two aforementioned policies are the main drivers of biomethane in France, there are also some other incentives that play a minor role in the development of biomethane in the nation. One of these is the complete exemption form the TICGN (Domestic tax on natural gas consumption) for biomethane injection established in 2016. In addition, users of renewable gas in district heating networks are able to enjoy a reduced VAT rate of 5.5% [23]

1.4.3 Feedstock for biomethane production

Similar to the UK and Sweden, the French biomethane is produced mostly from waste and residues rather than energy crops. This is due to the fact that the French government promoted the recovery of waste regardless of the origin, and therefore minimized the need to cultivate energy crops [23].

In particular, 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. The breakdown of the minor substrates used for biomethane production in France can be further seen in Figure 13.

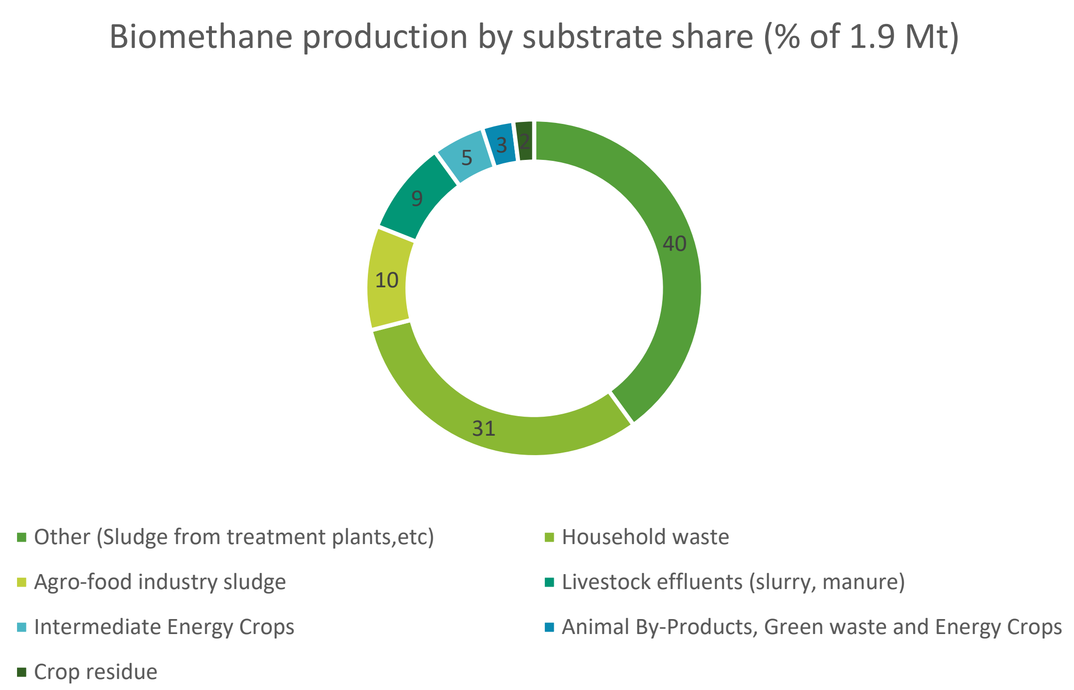

Figure 13.French biomethane feed-in tariff based on the installation capacity and type of waste [22]

1.4.4 Biomethane utilization pathway

Similarly, to Sweden, most of the biomethane produced in France is used as fuel for vehicles, while the remaining is used in heating applications as can be seen in Figure 14. The dominance of fuel applications is due to the fact that the GO system clearly incentivizes more the use of biomethane for vehicle use than heating as we saw in the previous section. The French government sets this preference, since fuel applications are considered the most virtuous use of biomethane in terms of an environmental point of view [23].

Furthermore, the leading consumers of the French biomethane are transport companies that serve mass retail, since they are keen to reducing their GHGs emissions. Afterwards, the second largest consumer is public transport operators. On the other hand, consumers of biomethane for heating applications are mostly public authorities that use it to heat either public buildings or in district heating networks [23]

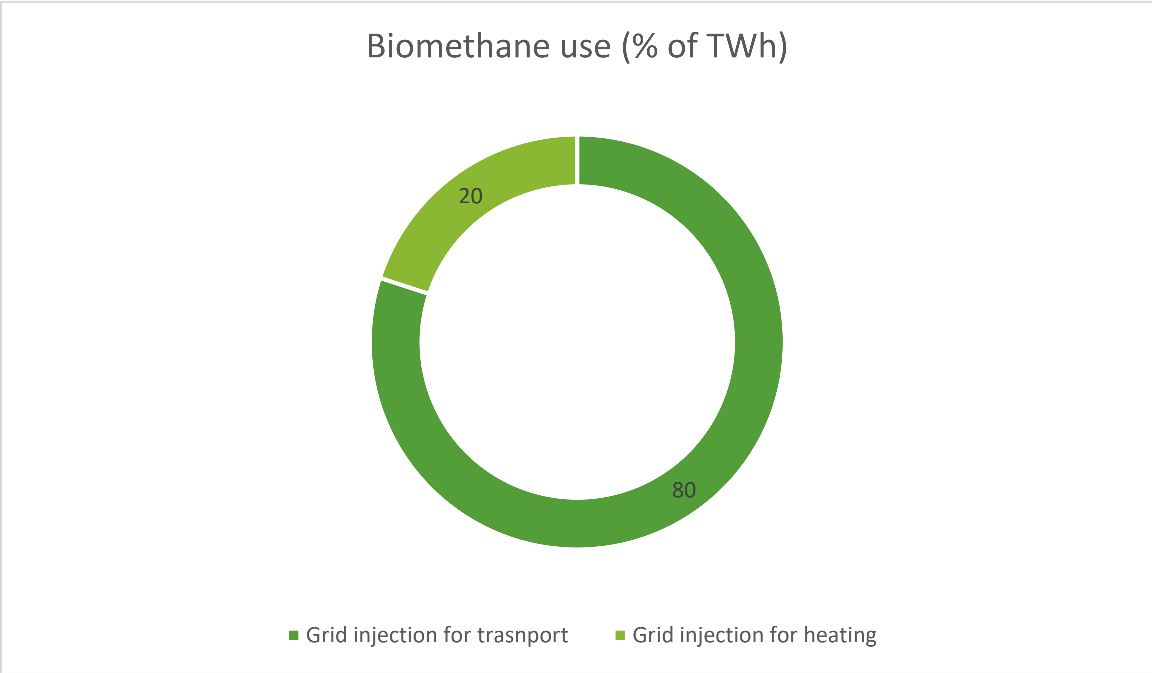

Figure 14. French biomethane use share of production [23]

Additionally, it is estimated that around 90% of all biomethane production sites that will inject gas into the French grid will be connected to distribution networks; regardless of the end use of the gas. In fact, out of 361 network projects commissioned in 2017, 325 of them corresponded to increase in the distribution network, while only 36 corresponded to transmissions networks [22]. These 361 projects represent an 8TWh per annum injection of biomethane into the gas grid, the capacity of each injection into each type of network available in France is shown in Figure 15.

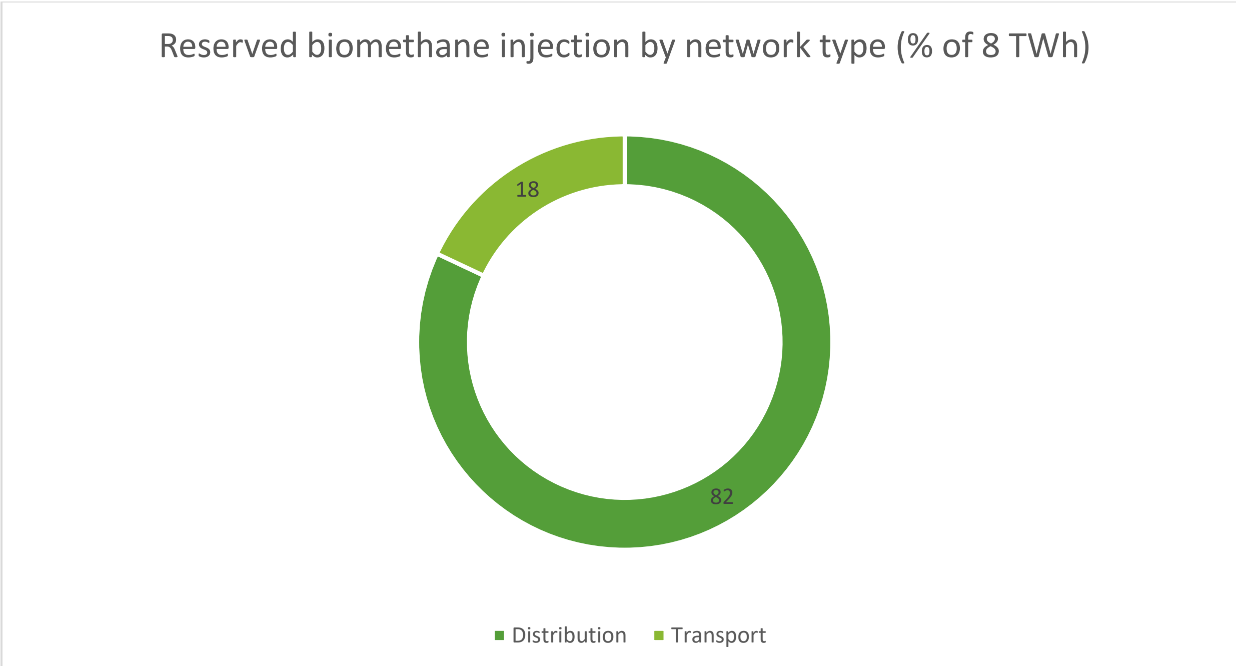

Figure 15.Capacity reserved for biomethane injection by network type [22]

However, this scenario may compromise some the current and future installations that are connected to low consumption network, particularly during summer periods. As a means to overcome this concern, the French network operators have explored a range of solution such as pipeline flexibility, meshing (connection of low demand network to high demand one), backhauling (compressing from distribution to transport network) and storage [23].

1.4.5 Biomethane future prospects

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. In particular both network operators and the Syndicat des Énergies Renouvelables (SER) share a common mission of tripling the 10% objective of the 2015 Energy Transition Act for Green Growth. This ambition implies a 30% share of renewable gas in the grid, which is summed up in the following two main objectives [22]:

- 60 TWH of renewable gas in 2028, out of which 50 TWh are of biomethane
- 90 TWH of renewable gas in 2030, out of which 70 TWh are of biomethane

Particularly, these ambitions are in fact realistic and as it stands today the 50 TWh of biomethane in 2028 is consistent with the trend in capacity reservations that have already been approved. However, it is important to note that like in every other country, biomethane is still not price competitive with the whole sale price of natural gas. Hence, without tariffs the sector is not profitable, and will likely to be so without additional measures [23].

Therefore, as a means to improve biomethane competitiveness in the future the French government has decided to gradually increasing the carbon tax to 100€/tCO2 by 2030. This would lead to a wholesale price of natural gas between 50 and 60 €/MWh. However, even at these prices biomethane would continue to require tariff to remain competitive with natural gas [23].

1.5 Denmark

1.5.1 Country Overview

Denmark is a country with a long history of using biogas that goes all the way to back 1920s. For the most part biogas has been primarily used in the nation to produce electricity. However, due to recent adopted policies it is expected that the focus will shift to biomethane injection to the gas grid over electricity production [24]. In fact the shift can be seen as of 2017, where the total production of biogas in the nation was around 3.3 TWh/year and the share between electricity production and biomethane injection was nearly equal as shown in Figure 16.

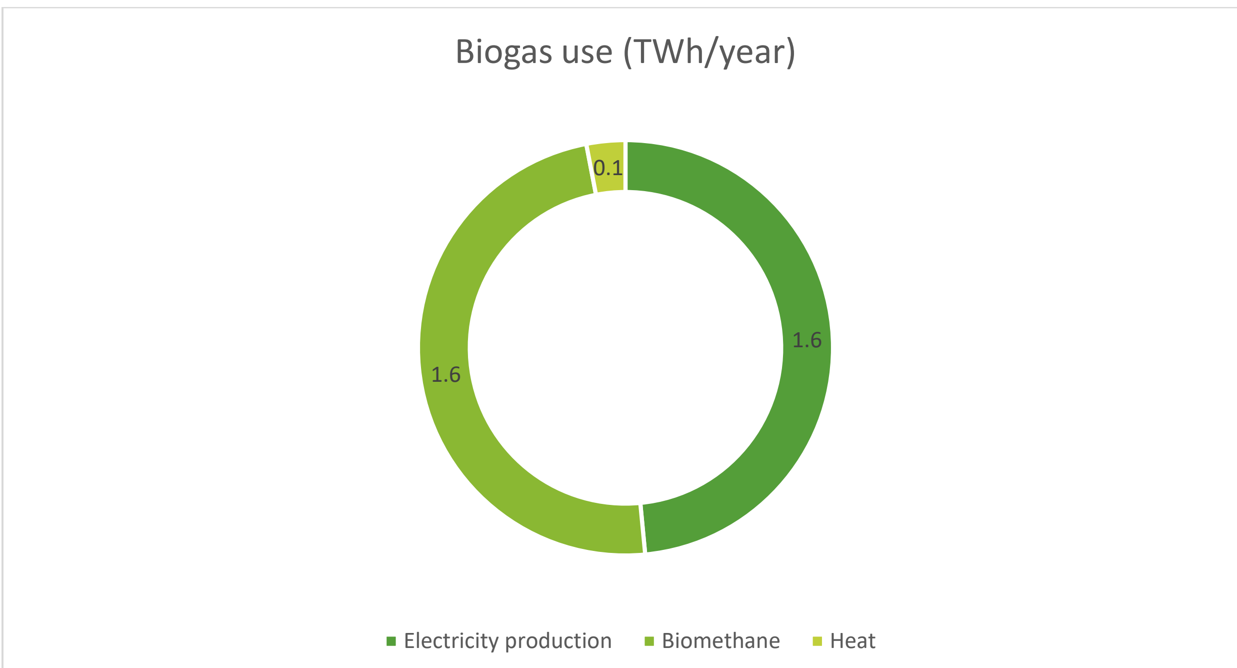

Figure 16.Denmark biogas use in 2017 (TWh/year) [9]

Moreover, the total biogas production in Denmark is accounted by a total of 144 biogas plants [10]. Out of these, a total of 22 of them have biomethane upgrading systems with injection into the gas grid [25].

1.5.2 Support Schemes

Up until 2012, Danish subsidies only supported heat and power usages of biogas. However, once the Energy Agreement of 2012 was introduced into the national legislation in 2013 and was ratified in by the EU in 2014, the biomethane market started to rapidly grow in Denmark. This is due to the fact that the agreement introduced a feed-in-subsidy scheme for injecting biomethane into the gas grid. Moreover, the scheme consists of three feed-in-premiums which are adjusted annually in January. The premiums are as follows [1]:

- **Base subsidy**: The subsidy serves as the base amount which a plant owner is certain to receive in the future. The price is regulated annually with 60% of the change of the consumer price index. The exact amount depends on the application. In particular, for biomethane injection the base is set at 0.038€/kWh in 2013 level. For 2018 the feed-in-premium for this application was 0.039 €/kWh.
- **Temporary subsidy**: This subsidy was applied in other to initiate biogas projects as soon as possible. It set a 0.005€/kWh amount which decreased each year by 0.001€/kWh from 2016 to 2019 to a value of 0.
- **Gas price adjusted subsidy**: This subsidy is set with two objectives in mind. First, to ensure that the income of a biomethane producer is assured even if the price of natural gas prices plummet. Second, to secure the state from overcompensating biogas producer when the natural gas price increases. In particular, the feed-in-premium consists of 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.

However, the aforementioned scheme is only applicable until 2020. Beyond that, the new Energy Agreement approved by the Danish Parliament in 2018 will take over. In this new agreement an annual fund of 32€ million was established over a period of 20 years. The aim of the fund is to promote renewable gases in the nation. Moreover, the subsidy from the fund will be assign via tender with price ceilings.

While the exact details of the new scheme have not been disclosed yet, it is possible to summarize the main aspect of the initiative as follows [1]:

- A guarantee for existing biogas plants to still benefit from the current subsidy regime for a period of 20 years after their commissioning, or until 2032, is in place.
- The current scheme will be phased out by 2020 for newly commission plants.
- Subsidies will be awarded on a tender based principal. The funds for the subsidies is the aforementioned 32€ million over a period of 20 years starting in 2021. Additionally, a part of the funds is strictly reserved for organic based biogas.
- New biogas plants commissioned for power generation will have to compete directly with other renewable sources of power generation such as wind turbines and photovoltaics.

- A strategy solely focused on renewable gas fill be establish. Furthermore, this strategy will include novel technologies such as methanation.

1.5.3 Feedstock for biomethane production

In 2009 the Danish government established that 50% of the nation's manure derived from livestock should be valorized as energy by 2020. Since there are approximately 37 million tons of manure produced annually in Denmark, this would implied that more than 18 million tons should be transformed into biogas. However, in 2017 only around 10% of the nation's manure was transformed into biogas [1]. Notwithstanding, it is clear that the manure potential is very high in the country.

This initiative has led to nation landscape in which more than three quarters of the total feedstock input of agricultural biogas plants is manure based. Furthermore, to foster even more the use of waste, the Danish Energy Agency regulates the amount of energy crops that can be used for gas production to 12%; producers above that amount are not eligible for subsidies [24]

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 as can be noted in Figure 17.

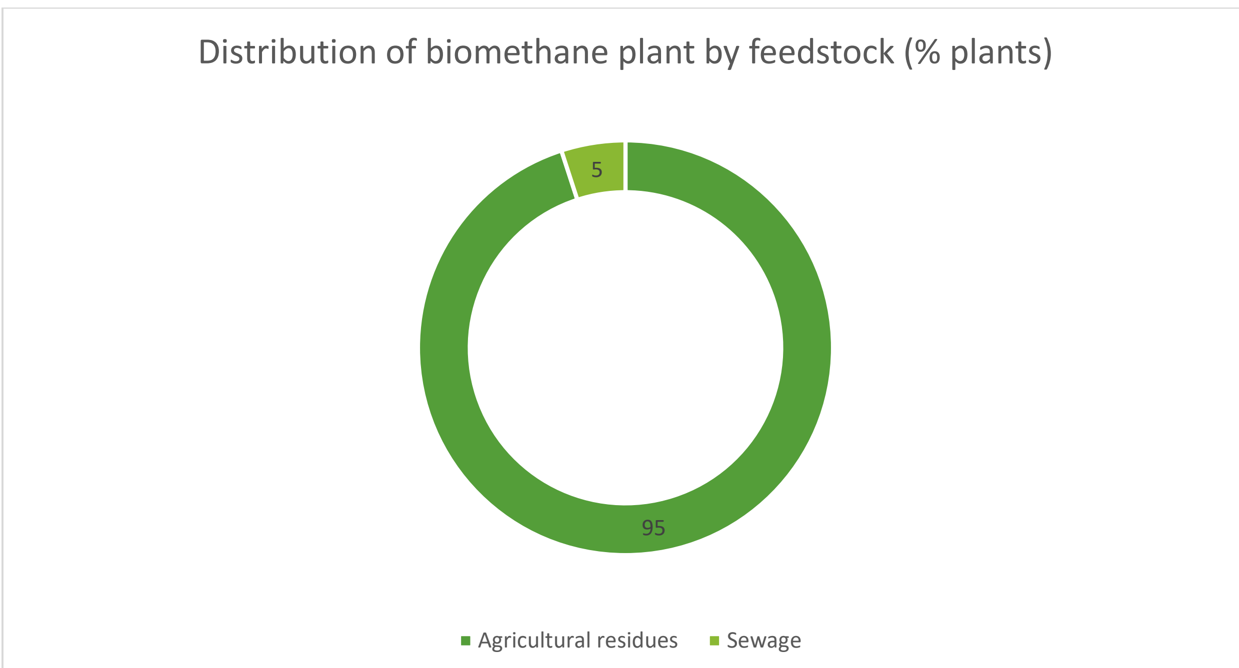

Figure 17. Distribution of biomethane plant by feedstock in Denmark (% of plants) [10]

1.5.4 Biomethane utilization pathway

Similarly to the UK, there is no clear source that breaks down the end use of the biomethane injected into the Danish gas grid. Nonetheless, it can be assume 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). Moreover, by 2040 it is expected that the share of biomethane in the gas grid will be around 30% (436 million Nm^3). However, this increase in share takes into consideration a considerable decrease in gas demand from 2,200 million Nm^3 in 2018 to in 1,500 million Nm^3 in 2040 [26].

In particular, the share of gas demand in Denmark is composed of district heating and CHP production for the corporate sector, the heating systems in households and the transport sector. The share of current and future demand of gas breakdown for each sector can be seen in figure 18.

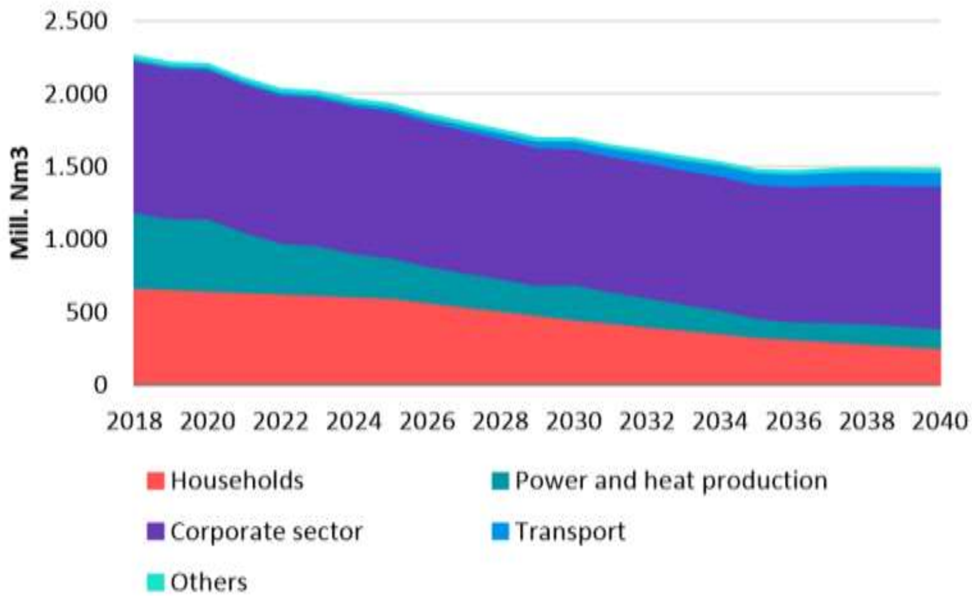

Figure 18. Distribution of biomethane plant by feedstock in Denmark (% of plants) [26]

As can be seen from the previous figure, the majority of the gas demand in Denmark is attributed to the corporate sector. Moreover, it is expected that demand for this sector will remain stable in the upcoming years. On the other hand, the use of gas for power and heat production is expected to fall significantly from 500 million Nm^3 to 137 million Nm^3. This is primarily due to the decommissioning of natural-gas-fired CHP plants, as well as the gradual incorporation of other renewable sources of energy. Similarly, household demand is also expected to decrease due to increased energy savings and adoptions of heat pump technologies. Lastly, we can notice that the transport sector has low demand, however it is expected to increase to 100 million Nm^3 (mostly for heavy road transport) [26].

1.5.5 Biomethane future prospects

Currently, the landscape for developing biomethane in Denmark is favorable. With the nations 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 [26].

In particular, the fear of subsidies spiraling out of control has led the Danish government switch its model to tender system as previously mentioned. The adoption of this new type of model will most likely limit the sectors growth potential [1].

Furthermore, while the Danish biogas sector has overcome many challenges in the past there are still many issues that must be addressed for future success of this technology. In general, these issues revolve around the grid connection structure and can be summarized as follows [1]:

- **Financing**: The biggest barrier of entry into the biogas market is the construction cost. This is particular true for plants which connect to the gas grid, since grid connection can be anywhere between 10% and 30% of the total CAPEX of the plant. For Danish plant owners this is even more of an issue since they must bear the full cost connecting to the grid, while the ownership of this connection is then transferred directly to the grid owner. This is unlike other nations where costs are shared between network operators and plant owners.
- **Competition for industrial biomasses**: Increased competition for industrial biomass gas lead to increase prices, which has made some biogas plants unable to keep affording their feed. Hence, as a means to ensure profitability of biogas plants it is imperative to keep a cheap and stable supply of industrial biomass in the nation.
- **Grid connection monopoly**: There is a lack of completion of grid owners. This causes the prices of connecting to the gas grid to be higher than necessary since it is solely decided by the supplier of the technology. This is in contrast to other nations, such as the Netherlands where increased competition has driven the prices down.
- **Professional operation**: Many farmers operate the plants by themselves, this has led to operational issues, especially during busy farming periods. This leads to many operational issues which led to plants performing subpar, hence many plants are now opting to hire external operators for their plants in order to resolve this issue.

1.6 Netherlands

1.6.1 Country overview

The Netherlands is a leading country when it comes to applying the principles of a circular economy as well as promoting strong waste management initiatives. 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 [27]. The share of energy converted from biogas in the Netherlands can be seen in Figure 19.

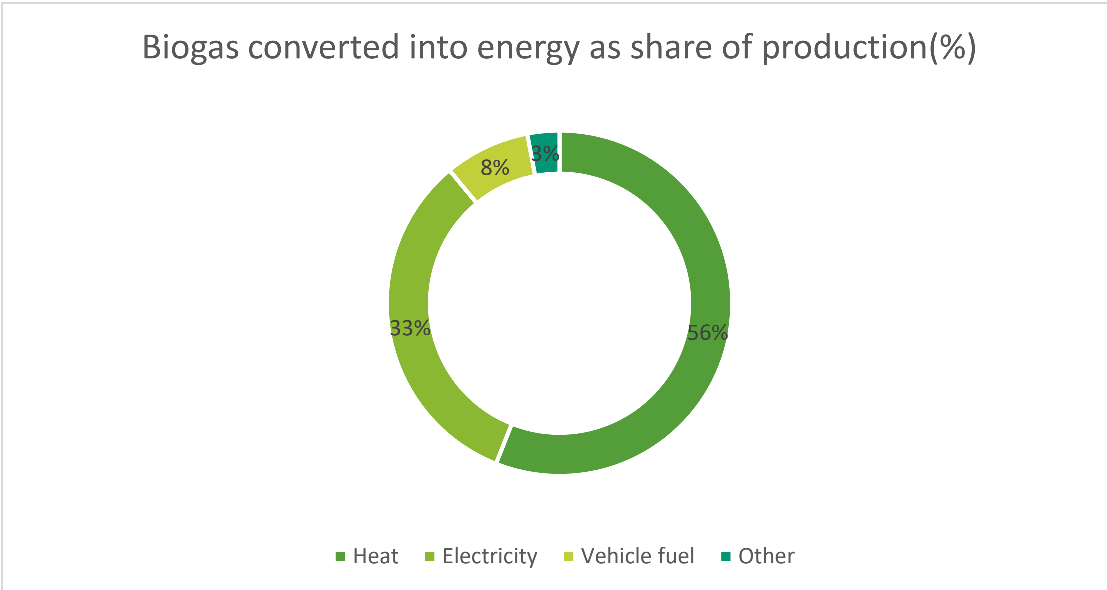

Figure 19. Distribution of biomethane plant by feedstock in Denmark (% of plants) [27]

1.6.2 Support schemes

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 [28].

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 shown in Figure 20 [29].

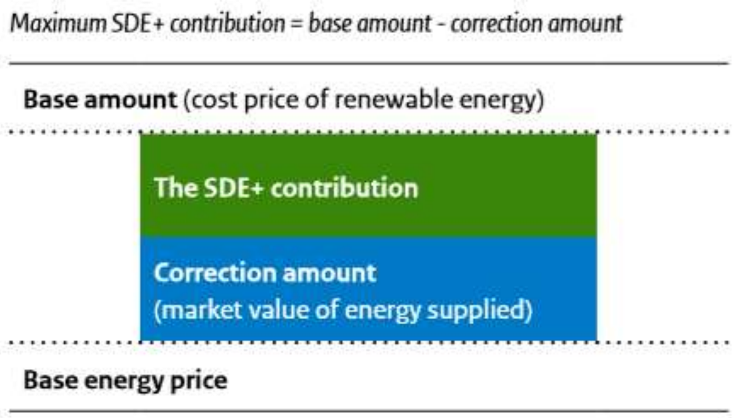

Figure 20. SDE+ contribution diagram [29]

The base amount of the SDE+ is set during the application for the subsidy scheme and last through the entire duration of the period granted. The maximum is set based on capacity and load hour of each technology. On the other hand, the correction amount is re-established each year. Lastly, the base energy price is a sort of limit for the correction amount, and therefore the correction amount cannot be lower than the set value; when it is equal the maximum subsidy is reached [29].

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. The latter on the other hand is categorize in a more a complex way, and can be summarized as follows:

- Mono-fermentation of manure: it applies for fermentation solely of manure, with no co-fermentation of other substrates allowed. Moreover, this category is further dived based on capacity. A category, for small-scale mono-fermentation is set for installed capacities of 400kW and lower, while a category for large-scale mono-fermentation is set for plants with installed capacities higher than 400kW.
- Sewage sludge fermentation: is set for renewable gas, hear and CHP applications that derive from treatment of sewage water. However, it is divided between traditional treatment and improved sludge fermentation. The difference being that the latter technology should be able to produce at least 25% more biogas than the former technology.
- All purpose fermentation: This category applies for the fermentation of most other type of biomass that was not previously mentioned in the previous categories. Furthermore, it also includes co-fermentation applications.

The exact subsidy scheme for each of the aforementioned categories of the SDE+ are shown in Table 4. Furthermore, it is important to note that deepening on the time of application for the SDE+ different rates are applicable.

Table 4. SDE+ scheme for fermentation of biomass [29]

	Phase 1 From 9 am 12 March	Phase 2 From 5 pm 18 March	Phase 3 From 5 pm 25 March to 5 pm 4 April	Base energy price	Provisional correction amount 2019	Maximum full load hours per annum	Maximum subsidy period (years)	Operation must start at the latest within (years)
Renewable heat, gas and CHP from Biomass	**Maximum base amount / phase amount (€/kWh)**			**(€/kWh)**				
All purpose fermentation								
• heat	0.062	0.062	0.062	0.019	0.026	7,000	12	4
• gas	0.062	0.062	0.062	0.013	0.019	8,000	12	4
• CHP	0.070	0.070	0.070	0.025	0.036	7,622	12	4
Mono-fermentation of manure (100% animal manure) ≤ 400 kW								
• heat	0.090	0.103	0.103	0.052	0.059	7,000	12	4
• gas	0.064	0.078	0.087	0.013	0.019	8,000	12	4
• CHP	0.090	0.110	0.127	0.041	0.053	6,374	12	4
Mono-fermentation of manure (100% animal manure) > 400 kW								
• heat	0.065	0.065	0.065	0.019	0.026	7,000	12	4
• gas	0.064	0.071	0.071	0.013	0.019	8,000	12	4
• CHP	0.077	0.077	0.077	0.025	0.036	7,353	12	4
Sewage treatment, existing sludge fermentation	0.032	0.032	0.032	0.013	0.019	8,000	12	4
Sewage treatment, improved sludge fermentation								
• heat	0.034	0.034	0.034	0.019	0.026	7,000	12	4
• gas	0.048	0.048	0.048	0.013	0.019	8,000	12	4
• CHP	0.051	0.051	0.051	0.028	0.041	5,729	12	4

1.6.3 Feedstock for biomethane

The vast majority of the feed used for biomethane production in the Netherlands comes from different types of waste that varies from plant to plant. However, 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. The rest of the share per type of substrate can be seen in Figure 21.

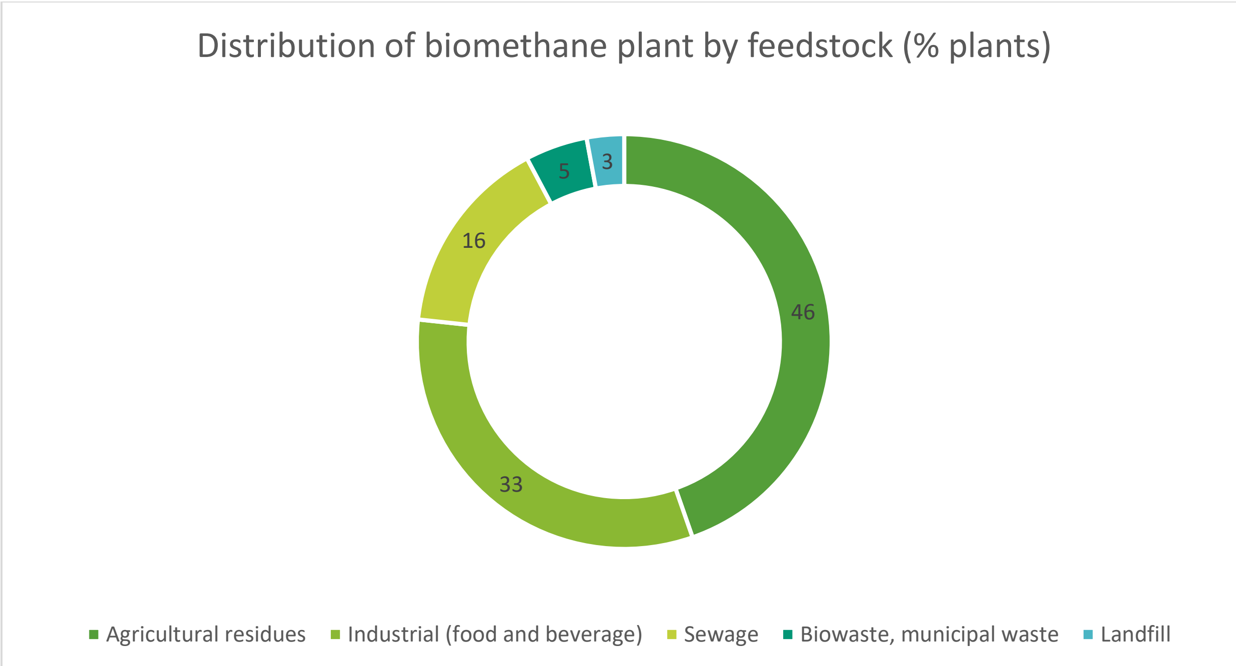

Figure 21. Distribution of biomethane plants by feedstock in the Netherlands (% of plants) [10]

1.6.4 Biomethane utilization pathways

Natural gas plays an enormous role in the Dutch energy mix. In fact natural gas alone provides around 41% of the total primary energy used in the nation [30]. Therefore, as the nation looks to meet environmental goals and slowly phase out fossil fuels, we can expect biomethane to use in a similar way to natural gas.

As it stands today, 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 use as seen in Figure 22.

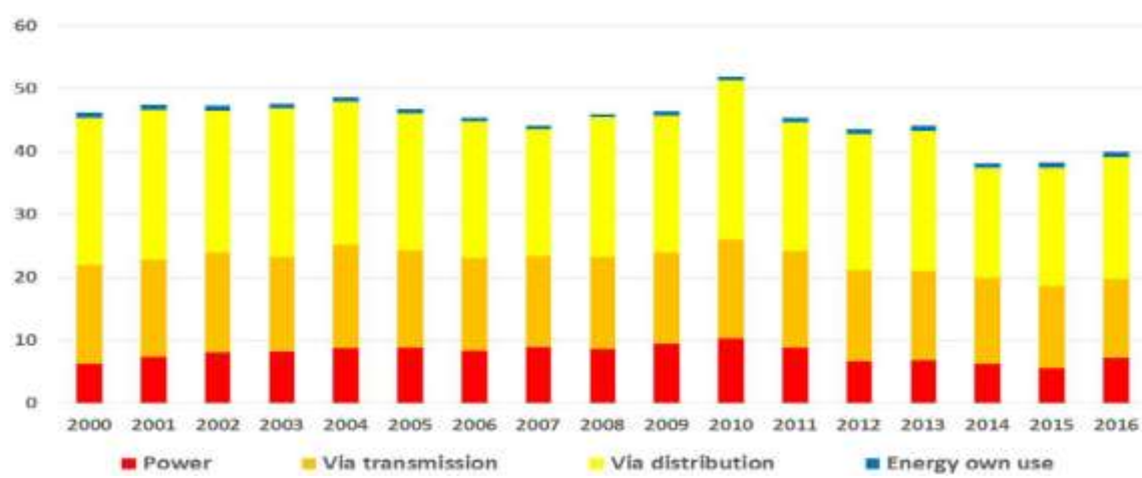

Figure 22. Natural gas consumption by sector in the Netherlands (bcm Geq) [31]

Distribution accounts for the majority of the gas consumption in the country (around 49%), these are mainly household owners and small commercial consumers. On the other hand, the transmission demand refers to all the end users that receive gas directly from the transmission network excluding power plants, this is mostly large industries or exports and they account for around 32% of all consumption. Moreover, while power plants receive their natural gas from the transmission network, their consumption is accounted in a different category known as power that represents 18% of total gas consumption. Lastly, the remaining consumption is energy used to operate the networks [31].

Furthermore, it is important to understand the pressures of each of the grids in the Netherlands to understand where biomethane demand most likely resides in. In order to do so we can refer to figure 23 where the supply chain of natural gas is shown. As it can be seen the transmission network operates at very high pressures above 40 bar, while the DSO operates at lower pressures. Hence, since biomethane is usually produced at lower pressures we can expect that most of the injections occurs in the distribution network. However, in case of low demand in the distribution network, biomethane may be compressed and send to the transmission network in a process called back hauling, however, the amount of gas the under goes this will surely be minimum.

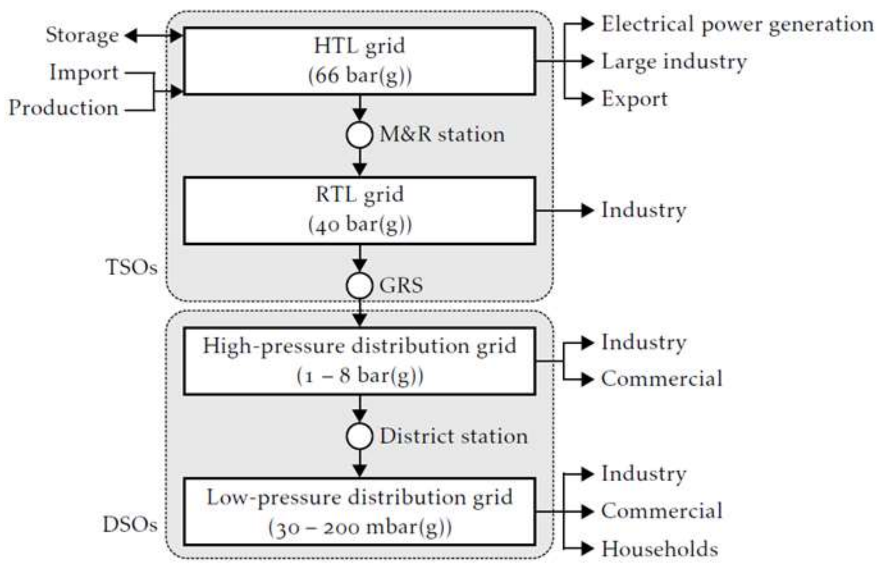

Figure 23. Dutch gas grid supply chain [32]

Lastly, it is important to note two main characteristics when it comes to injecting biomethane into the Dutch gas grid. Firstly, the methane purity in the gird is around 80% due the production of low calorific gas in Groningen [33]; which is the major gas field of the Netherlands. This implies that the upgrading operations can be done under less sever conditions. However, it is the responsibility of the producer to meet with purity requirements and not the DSO. Secondly, the investment and operational cost of injecting the gas into the grid are undertaken by the producer of the biomethane; this is known as “deep charring method” [34].

1.6.5 Biomethane future prospects

The Netherlands is currently one of the top consumers and exporters of natural gas in the EU. However, as the main gas field (Groningen field) of the country is expected to be depleted in the upcoming years, both biogas and biomethane production is expected to increase as seen in Figure 24.

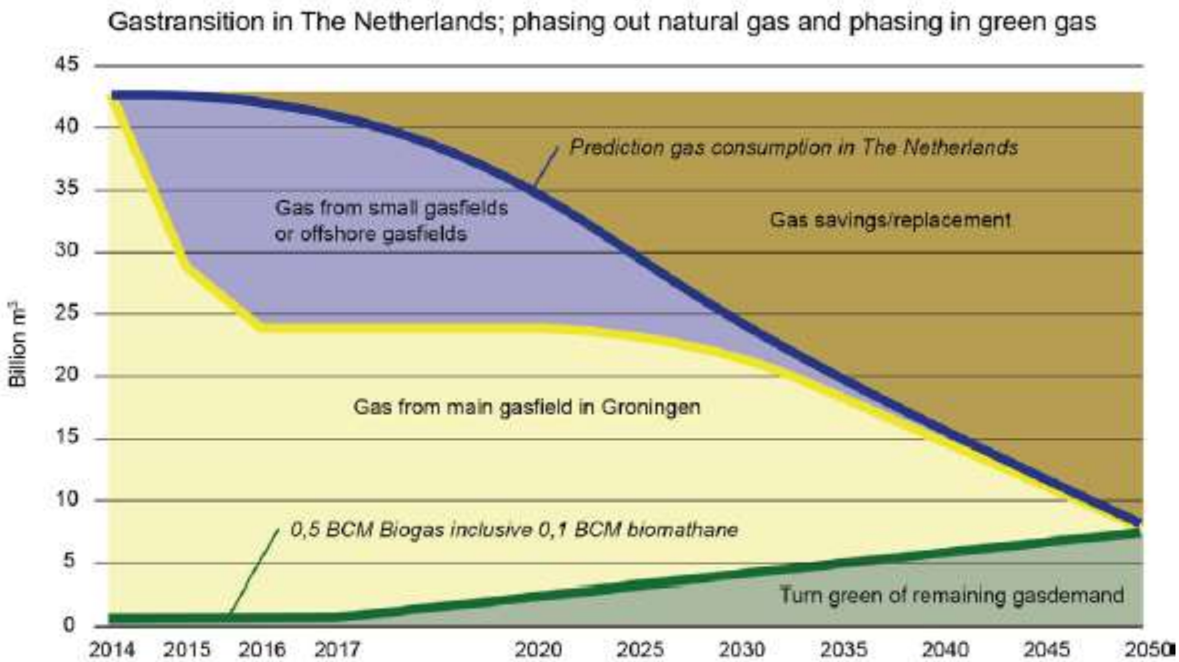

Figure 24. Gas transition in the Netherlands in the upcoming years [35]

The previous figure is similar to the scenario expected in many countries. In general, natural gas demand is expected to decrease, energy savings are expected to increase and the remaining demand for gas can potentially be met by renewable gas.

Moreover, it is expected that biogas production 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. The maximum potential for these different applications are shown in Figure 25 based on different digestion feeds for production the biogas [35].

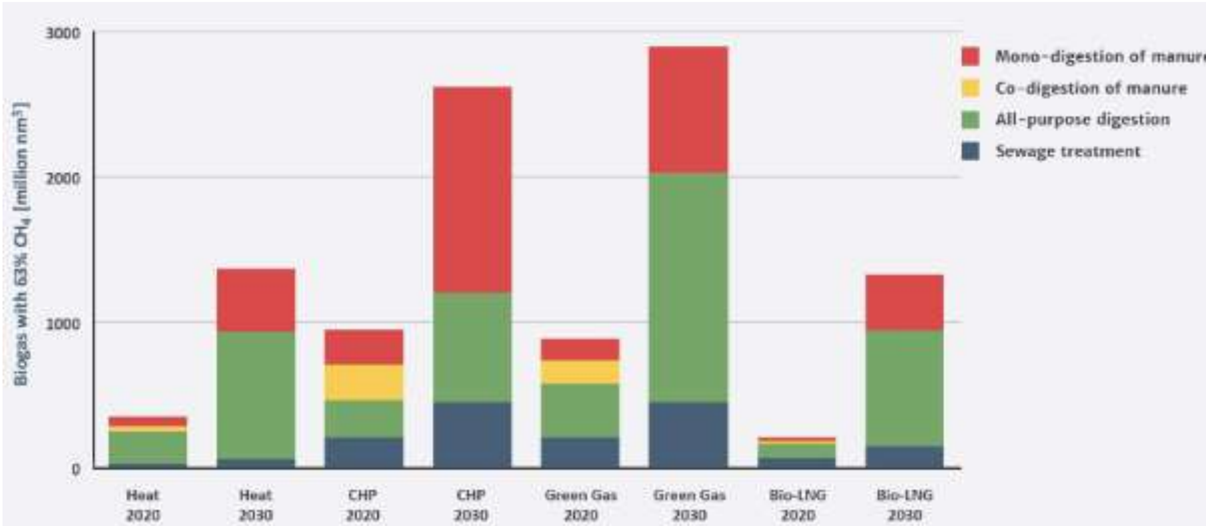

Figure 25. Maximum potential in the Netherlands of biogas divided per use [35]

However, while an increase in biogas and biomethane application is expected to increase within the Netherlands, there are still some barriers that are slowing down their deployment. The main barriers to the successful implementation of renewable gas in the country can be summarized as follows [27]:

- **Reliability of financial incentives**: The schemes for supporting anaerobic digestion in the nation have changed with different governments. This has made it more difficult to evaluate long-term profitability of biogas and biomethane plants.
- **Excessive focus on cost**: The existing incentive schemes are implemented in a manner that promote maximum energy generation with minimum cost. However, this do not take in to account the GHGs abetment benefits of AD technologies
- **Inconsistent gas specification**: The heating value requirements of upgraded biogas to be injected into the grid varies from region to region. This leads to inconsistent biomethane development across the nation.

1.7 Biomethane across the EU: 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.

Chapter 2: Portuguese Landscape

The chapter 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 [36], and Ferreria et al [37]. 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 [38].

2.1 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 m3/a [39].

Moreover, the vast majority of that potential can be attributed to urban solid residues (USR) and agricultural residues. The remaining potential of biomethane can be attributed to minor sources such as waste from the food industry and domestic effluents. A clear breakdown of the share of the total biomethane potential of the country by source of biomass waste can be seen in Figure 26.

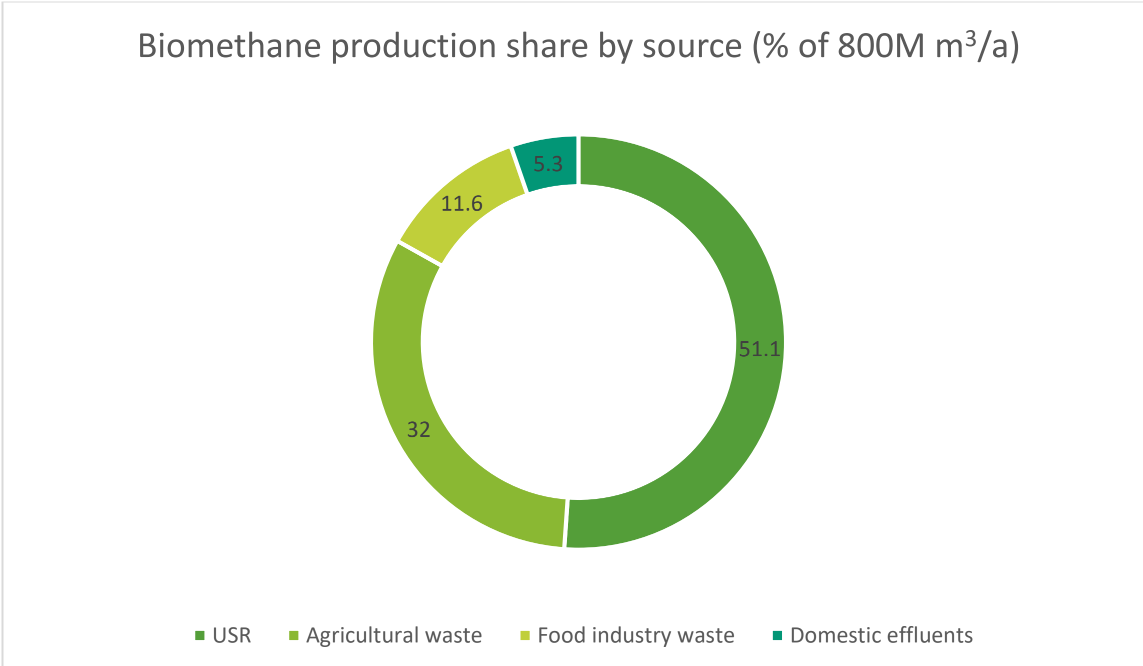

Figure 26. Yearly potential of biomethane from anaerobic digestion [39]

As can be seen from the previous figure, urban solid residues have the biggest potential for generating biomethane within the nation by means of anaerobic digestion. However, it is important to note that the USR refer to the organic fraction of the solid residues which are suitable for anaerobic digestion, hence segregation of waste is necessary. Furthermore, if we analyze the total biomethane potential from municipal waste i.e. USR and domestic water effluents, we can see that the solid waste is way higher than that of water effluents. In fact, USR accounts for roughly 91% of the total biomethane potential from municipal waste as can be deducted from Table 5.

Table 5. Municipal biomethane potential in Portugal [39]

Effluent	Biomethane (Mm^3/a)
Urban Solid Residues	411.6
Domestic water effluents	42.7
Total	**454.3**

On the other hand, the 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 6.

Table 6. Agricultural biomethane potential in Portugal by type of farm animal

Effluent origin	Biomethane LNEG [39] (Mm^3/a)	Biomethane Ferreria et al [37] (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

As can be seen from the previous table, most of the biomethane potential from agricultural waste can be attributed to cattle alone, with the remaining big potential covered mostly by pig and poultry waste. Moreover, comparing both studies we can notice that taking into account actual availability of manure can greatly affect the overall potential determined.

2.2 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" [36]. 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 [37].

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. However, the information is presented in a map divided by the 2002 NUTS, which is not the most recent division of Portugal as seen in Figure 27. This representation is taken since it is the manner in which the INE has also presented the data. However, in terms of municipalities per se the 2002 and 2013 NUTS representation have no relevant difference other than the manner in which they are grouped. In this sense, both the NUTS 2002 and 2013 consist of the same 308 municipalities.

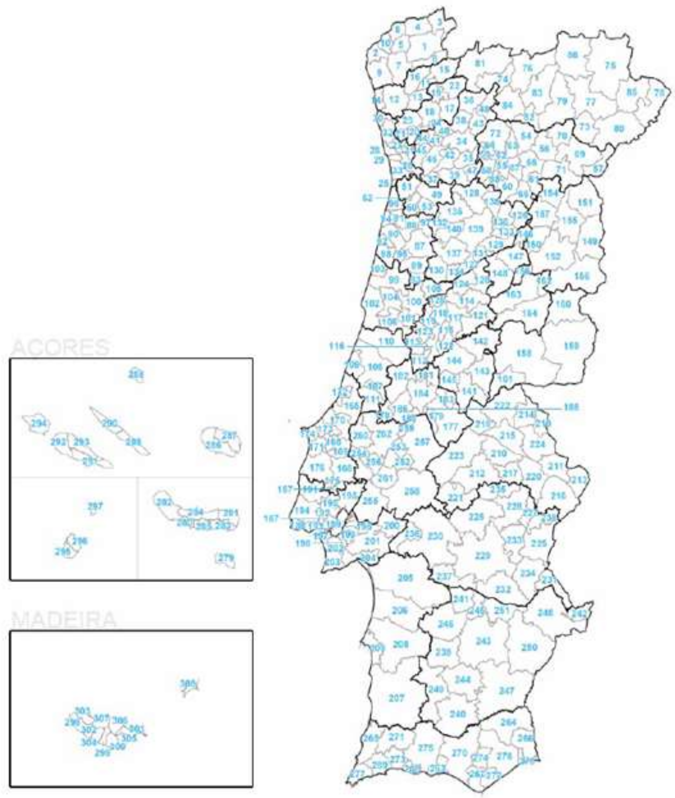

Figure 27. Portugal map as divided by NUTS 2002 used for the data representation [40]

The data used to determine the biomethane potential in the region is limited to only that of livestock and urban solid waste. This is done due to the fact that the INE does not have relevant statistical data to which can help determine either waste from the food industry or waste water. Nonetheless, the model would still be accurate since these two sources have low share of the nation's biomethane potential as seen in Figure 27, and can always be retrofitted to incorporated new sources of waste when information becomes available. Additionally, it assumed that no upgrading loses are incurred, therefore the framework represents the total theoretical potential of biomethane in the nation.

Finally, as seen in the previous section, it is estimated that agricultural livestock waste accounts for around 32% of the full biomethane potential of the Portuguese nation. Moreover, most of the potential comes from waste produced by cattle, pig, poultry and sheep, while other animals such as rabbits and horses are not accounted for. Hence, the model for regional biomethane potential from agricultural waste is limited to the waste from the main types of livestock available in the country

2.2.1 Cattle potential methodology

The biomethane yield from processing cattle waste depends on the age of the cattle [36]. However, specific information in regards to the age of cattle is spread unevenly in regions of interest. Hence, for purpose of this model the assumptions made by Ferreira et al for biomethane potential of cattle waste will be used for the model [37]. These assumptions are summarized as follows:

Table 7. Biomethane potential estimation parameters for cattle waste [37]

Parameter	Min value	Max Value	Average Value
Manure (kg/day per head)	6.75	40.00	23.25
Total solids (%)	6.00	11.00	8.50
Volatile solids (% of TS)	68.00	85.00	76.50
Biogas yield (m^3/kg_{vs})	0.20	0.26	0.23

Furthermore, similarly to Ferreira it is assumed that only 60% of the daily manure waste can be collected. Hence, the average effective manure produced for cattle used is 13.83 kg/day per head of cattle. For practical reasons, the previous value is used in terms of tons per year, which corresponds to an equivalent value of 5.09 tons/a per cattle head. With the previous information the total biomethane potential for a given region "i" can be calculated as:

$$BMP_{c,i} = n_{c,i} * M_c * TS_c * VS_c * BGY_c * V_{CH4} \quad (1)$$

Where:

- $BMP_{c,i}$: Biomethane potential of cattle waste in location "i" [m^3/a]
- $n_{c,i}$: number of cattle in location "i" [#cattle]
- M_c: Effective average cattle manure collected [ton/a per cattle]
- T_{Sc}: average total solids fraction found in cattle manure [-]
- V_{Sc}: average volatile fraction found in the total solid fraction of cattle manure [-]
- BGY_c: Average biogas yield of cattle manure [m^3/ton_{vs}]
- V_{CH4}: Volume fraction of methane in biogas [-]

2.2.2 Pigs potential methodology

Analogous to the previous livestock, biomethane potential of pigs in Portugal are estimated based on the assumptions made by Ferreira et al [37]. These assumptions are summarized as follows:

Table 8. Biomethane potential estimation parameters for pig waste [37]

Parameter	Min value	Max Value	Average Value
Manure (kg/day per head)	0.60	1.50	1.05
Total solids (%)	2.50	9.60	6.05
Volatile solids (% of TS)	60.00	85.00	72.50
Biogas yield (m^3/kg_{vs})	0.26	0.45	0.36

Similarly, to the previous livestock, it is assumed that only 60% of total manure produced can be collected. Hence, the effective average value of manure that can be collected is 0.64 kg/day (0.23 tons/a) per pig head. Furthermore, the biomethane potential for pigs is calculated similarly to that of cattle with the following equation:

$$BMP_{pi} = n_{pi} * M_p * TS_p * VS_p * BGY_p * V_{CH4} \quad (2)$$

Where:

- $BMP_{p,i}$: Biomethane potential of pig waste in location "i" [m^3/a]
- $n_{p,i}$: number of pigs in location "i" [#pigs]
- M_p: Effective average pig manure collected [ton/a per pig]
- TS_p: average total solids fraction found in pig manure [-]
- VS_p: average volatile fraction found in the total solid fraction of pig manure [-]
- BGY_p: Average biogas yield of pig manure [$m3/ton_{vs}$]
- V_{CH4}: Volume fraction of methane in biogas [-]

2.2.3 Poultry potential methodology

The work developed by Ferreira et al estimates the biomethane potential of chickens in Portugal, yet it does not take into account other type poultry such as ducks, turkeys or geese in the nation. However, it can be assumed that biomethane produced from poultry waste will be similar to that of chicken. This seems accurate, since the assumptions of the work done by Ferreira et al imply that one head of chicken can yield up to 2.6 m^3/a of biomethane a year, which is similar to the yield of 2.8 m^3/a of biomethane reported by the World Biogas Association (WBA) for head of poultry [40].

In this sense, the assumptions used by Ferreira et al to determine the biomethane potential of chicken waste will be used in this work to determine the biomethane potential of poultry waste. Those assumptions are summarized in Table 9.

Table 9. Biomethane potential estimation parameters for poultry waste [37]

Parameter	Min value	Max Value	Average Value
Manure (kg/day per head)	0.07	0.09	0.08
Total solids (%)	10	29	19.50
Volatile solids (% of TS)	75.00	77.00	76.00
Biogas yield (m^3/kg_{vs})	0.20	0.40	0.30

Unlike previous livestock's, it is assumed that only 50% of total manure produced from poultry can be collected rather than 60%. Hence, the effective average value of manure that can be collected from poultry is 0.04 kg/day (0.015 tons/a) per head of poultry. Moreover, the potential per se is calculated similarly to the previous cases with the following equation:

$$BMP_{po,i} = n_{po,i} * M_{po} * TS_{po} * VS_{po} * BGY_{po} * V_{CH4} \quad (3)$$

Where:

- $BMPp_{o,i}$: Biomethane potential of poultry waste in location "i" [m^3/a]
- $n_{po,i}$: number of pigs in location "i" [#poultry heads]
- M_{po}: Effective average poultry manure collected [tones/a per poultry head]
- TS_{po}: average total solids fraction found in poultry manure [-]
- VS_{po}: average volatile fraction found in the total solid fraction of poultry manure [-]
- BGY_{po}: Average biogas yield of poultry manure [m^3/tonvs]
- V_{CH4}: Volume fraction of methane in biogas [-]

2.2.4 Sheep potential methodology

Biomethane potential from sheep waste was not determine by Ferreira et al. However, as seen in Table 6, the LNEG study does consider it a small source of biomethane within the nation. Hence, in order to take into account sheep waste as a source of biomethane into the model, the assumptions made by O'Shera [36] are used.

In short the work done by O'Shea assumes that a head of sheep can produce 0.088tones/a of manure. The dry solid contents of sheep manure is assumed to be 35%, while the volatile solids is assumed to be 22.6% of total manure. Moreover, the biomethane yield is assumed to be 0.171 m^3/kg_{vs}. O'Shea rearranges this assumptions and estimates that a ton of manure from sheep can produce 38.559 m^3 of biomethane.

For the purpose of this model, all the aforementioned assumptions made by O'Shea will be used. However, the additional assumption made by Ferreira, which considers that only 60% of manure can be collected, will not be used. Since O'Shea already considers that collection can only be done during 6 weeks a year [36]. In this sense, the biomethane potential of a region with sheep can be calculated using the following equation:

$$BMP_{s,i} = n_{s,i} * M_s * BMY_s \quad (4)$$

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 [ton/a per sheep]
- BMY_s: Average biomethane yield of sheep manure [m^3/ton]

2.2.5 Urban waste

As discussed in section 2.1, biomethane from urban waste can be obtained from either Urban Solid Residues (USR) or effluents from waste water. However, for the purpose of this model only the former substrate will be considered in the calculations of municipal BMPs. This is done as simplification since waste water is treated in specific locations of each municipality. Hence, adding this information to the model, would increase the complexity and detail in a manner that is not consists with the level of detail of the other substrates used in the model. Moreover, at national level, it is estimated that USR represents the vast majority of the BMP in the nation [39], therefore the accuracy and usefulness of the model is not really compromised by this simplification.

To determine the biomethane potential for urban solid residues it is assumed that all organic urban waste may be used for biomethane production regardless if it is currently being valorized in a different manner. In this sense, from the 2019 data presented by the INE (which breaks down municipal urban waste based on destination) the landfill, energy recovery and organic recycling columns are used for calculations of urban biomethane potential.

Biomethane potential from anaerobic digestion can only be determine from organic waste. However, landfill waste contains both organic and inorganic matter. Hence the organic fraction of landfill waste must be used. For the purpose of this mode it is assumed that 55% of all landfill waste is organic. This assumption is in accordance to estimates of organic matter in Portuguese landfills reported by the Portuguese environmental agency APA [42].

Moreover, to determine the biomethane potential of urban organic waste, the assumptions made by Madalena Soares Pereira Lopes [43] 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.

Bearing in mind the previous, we can estimated the biomethane potential of each municipality in Portugal based on the total amount of landfill waste, waste used for energy recovery and organic waste recycle by the following equation

$$BMP_{u,i} = (LW_i * OFLW + ERW_i + OWR_i) * VS_u * BGY_u * V_{CH4} \quad (5)$$

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 [-]

The constant parameters, which are the assumptions made in equation (5), are summarized in Table 10.

Table 10. Biomethane potential estimation parameters for urban solid residues [43]

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

2.3 Portuguese Landscape Results

The biomethane potential from different substrates was calculated for the whole country, and are presented in Table 11. Furthermore, for each of the 308 municipalities that constitute the Portuguese nation BMP was also determine. However, due to the extensive nature of the results, the exact data for each municipalities is not presented in this document. If needed this information can be consulted in the excel files of the support material.

Table 11. 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 11 with those reported Table 6, 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 11 with that reported by LNEG in Table 5, 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.

Moreover, as it pertains to the remaining of this document, the results of biomethane potential are either presented in tables or graphically in maps developed in QGIS. Table results only entail the total biomethane potential for 29 municipalities where Portgás owns assets. On the other hand, QGIS results are presented for all municipalities that are located in the Portuguese mainland.

NOTE: Special attention should be made to the range of the values in the legends of each of the graphical results presented in QGIS. This is particularly true when comparing one map with another, since comparing color gradients alone will be misleading to the reader.

2.3.1 Cattle potential results

Figure 28 shows the dispersion of biomethane potential from cattle substrate per Portuguese municipality. Observing the figure we can notice that the majority of the municipalities in the higher ranges of BMP are located in the Alentejo region of the country, and to a lesser extent in the northern region of the country.

Moreover, we can also notice from the legend in Figure 28, that the biomethane potential from cattle varies for all mainland municipalities from a minimum value of 0.000 Mm^3/a to roughly 2.500 Mm^3/a.

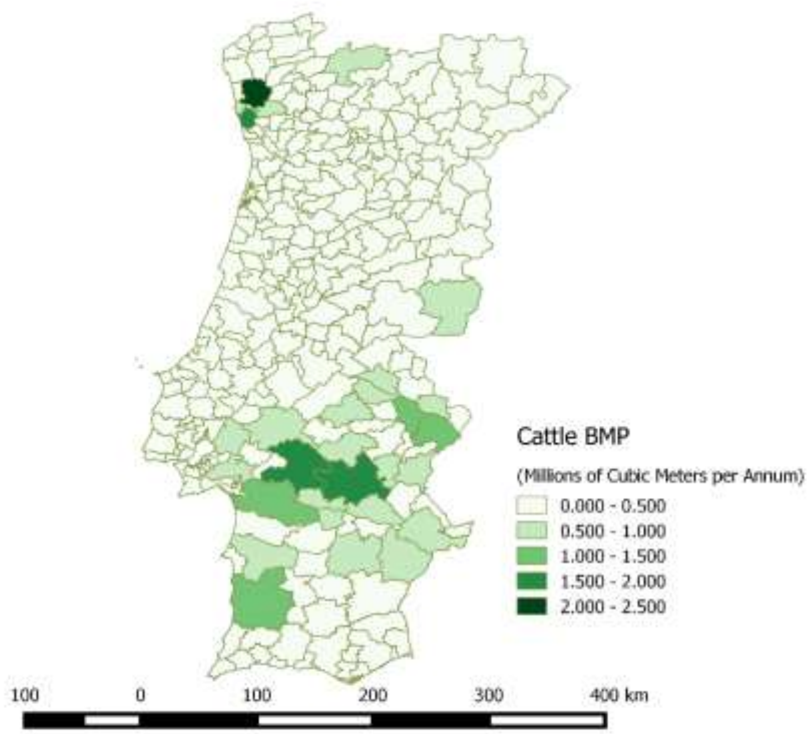

Figure 28. Biomethane Potential from cattle waste in the Portuguese mainland

On the other hand, Table 12 explicitly shows the BMP from cattle waste available in each of the municipalities where Portgás owns assets. From this table we can notice that the total BMP of the region of interest is around 9.479 Mm3/a. This represents around 14.5% of the total BMP available from cattle waste in the nation.

Moreover, comparing the map shown in Figure 28 with the values shown in Table 12, we can notice that four municipalities where Portgás owns assets stand out. The main municipality that stands out is Bacerlos since it is the municipality with the highest BMP available from cattle waste in the nation. Afterwards, the municipality of Vila do Conde also stands out for being a municipality in the higher ranges of BMP, as well as its proximity to Barcelos. Lastly, the municipalities of Vila Nova de Famalicão and Póvoa de Varzim stand out for being adjacent to the municipality of Barcelos, but also being in the mid ranges of BMP.

Table 12. Biomethane potential from cattle waste in Portgás municipalities

Municipality	BMP [Mm^3/a]	Municipality	BMP [Mm^3/a]
Barcelos	2.338	Ponte de Lima	0.302
Braga	0.357	Porto	0.002
Caminha	0.023	Póvoa de Varzim	0.831
Esposende	0.301	Santo Tirso	0.163
Fafe	0.118	Trofa	0.311
Felgueiras	0.130	Valença	0.038
Gondomar	0.051	Valongo	0.077
Guimarães	0.263	Viana do Castelo	0.241
Lousada	0.117	Vila do Conde	1.762
Maia	0.288	Vila Nova de Cerveira	0.034
Matosinhos	0.217	Vila Nova de Famalicão	0.823
Paços de Ferreira	0.077	Vila Nova de Gaia	0.033
Paredes	0.110	Vila Verde	0.230
Paredes de Coura	0.126	Vizela	0.015
Penafiel	0.102	**Total**	**9.479**

2.3.2 Pigs potential results

Figure 29 shows the dispersion of biomethane potential from pig waste per Portuguese municipality. Observing the figure we can notice that the majority of the municipalities in the higher ranges of BMP are located in the center-western region of the nation, as well as the Alentejo region of the country. However, unlike BMP from cattle waste, BMP from pig waste is considerably low in the northern region of the country.

Additionally, we can also notice from the legend in Figure 29, that the biomethane potential from pig varies for all mainland municipalities from a minimum value of 0.000 Mm^3/a to roughly 0.400 Mm^3/a. It is important to note that this is considerably smaller than the BMP available from cattle waste in fact the highest range of BMP from pig waste would corresponds to the lowest range of BMP from cattle waste.

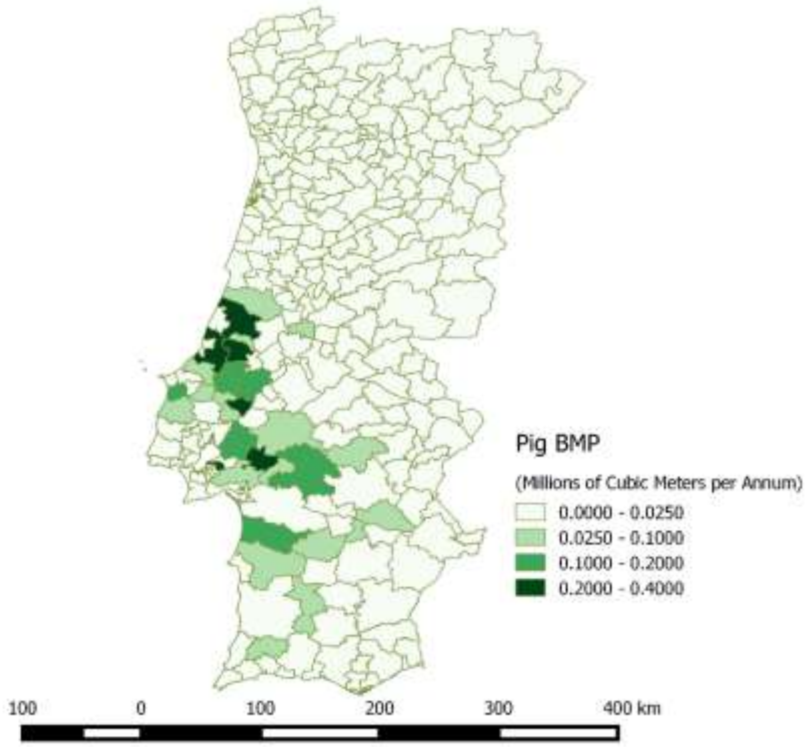

Figure 29. Biomethane potential from pig waste in the Portuguese mainland

Table 13 shows the BMP from pig waste available in each of the municipalities where Portgás owns assets. From this table we can notice that the total BMP of the region of interest is around 0.077 Mm^3/a. This represents around 1.7% of the total BMP available from pig waste in the nation. All the municipalities where Portgás owns assets have low BMPs from pig waste. The only exception being the municipality of Vila Nova de Famalicão that has the highest out all of the 29 municipalities of interest.

Table 13. Biomethane potential from pig waste in Portgás municipalities[(A)]

Municipality	BMP [Mm^3/a]	Municipality	BMP [Mm^3/a]
Barcelos	0.002	Ponte de Lima	0.003
Braga	0.002	Porto	0.000
Caminha	0.000	Póvoa de Varzim	0.008
Esposende	0.001	Santo Tirso	0.002
Fafe	0.002	Trofa	0.000
Felgueiras	0.015	Valença	0.003
Gondomar	0.000	Valongo	0.000
Guimarães	0.002	Viana do Castelo	0.002
Lousada	0.001	Vila do Conde	0.001
Maia	0.000	Vila Nova de Cerveira	0.000
Matosinhos	0.000	Vila Nova de Famalicão	0.026
Paços de Ferreira	0.000	Vila Nova de Gaia	0.001
Paredes	0.001	Vila Verde	0.003
Paredes de Coura	0.001	Vizela	0.000
Penafiel	0.002	**Total**	**0.077**

A) Note that all values are rounded to the third digit, hence values with 0.000 do not necesaraly mean 0 potential. Exact values can be found in the Excel files of the support material

2.3.3 Poultry potential results

Figure 30 shows the dispersion of biomethane potential from poultry waste per Portuguese municipality. Observing the figure we can notice that the majority of the municipalities in the higher ranges of BMP are located in the center-western region, center-north region. On the other hand, we can also notice that the northern region of the country has an aggregate of municipalities with BMPs in the upper-lower and mid-ranges.

In addition, we can also notice from the legend in Figure 30, that the biomethane potential from poultry varies for all mainland municipalities from a minimum value of 0.000 Mm^3/a to roughly 0.800 Mm^3/a. While this range is double that of the BMP range for pig waste, it still considerably smaller than the range used for BMP from cattle waste.

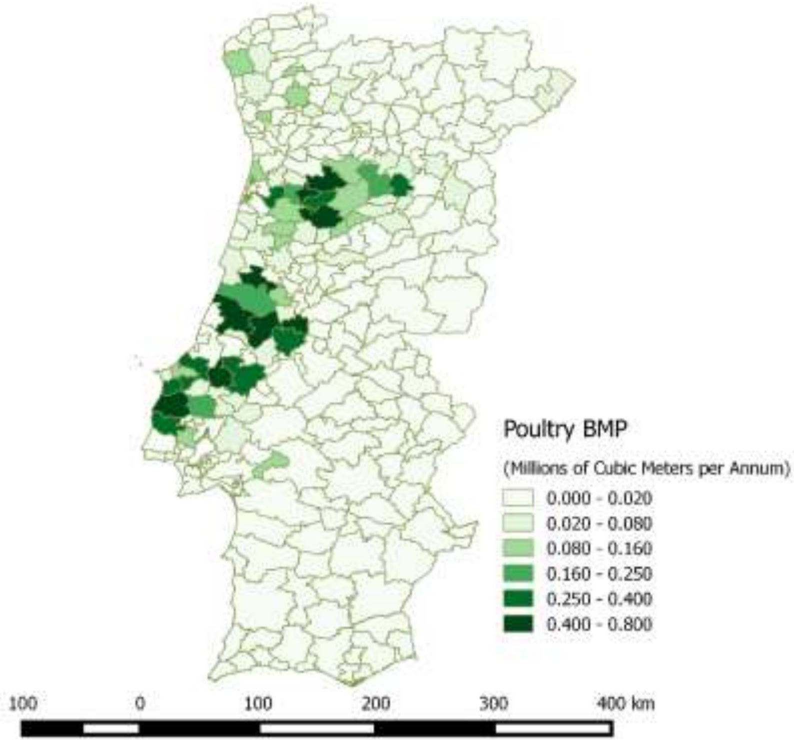

Figure 30. Biomethane Potential from poultry waste in the Portuguese mainland

Table 14 shows the BMP from poultry waste available in each of the municipalities where Portgás owns assets. From this table we can notice that the total BMP of the region of interest is around 0.698 Mm^3/a. This represents around 4.9% of the total BMP available from poultry waste in the nation. Moreover, from the 29 municipalities where Portgás owns assets the municipalities of Santo Tirso and Guimarães stand out for having higher BMPs compared to the rest.

Table 14. Biomethane potential from poultry waste in Portgás municipalities

Municipality	BMP [Mm^3/a]	Municipality	BMP [Mm^3/a]
Barcelos	0.045	Ponte de Lima	0.024
Braga	0.012	Porto	0.000
Caminha	0.008	Póvoa de Varzim	0.012
Esposende	0.009	Santo Tirso	0.008
Fafe	0.008	Trofa	0.135
Felgueiras	0.025	Valença	0.014
Gondomar	0.003	Valongo	0.021
Guimarães	0.142	Viana do Castelo	0.118
Lousada	0.010	Vila do Conde	0.016
Maia	0.018	Vila Nova de Cerveira	0.002
Matosinhos	0.002	Vila Nova de Famalicão	0.019
Paços de Ferreira	0.007	Vila Nova de Gaia	0.003
Paredes	0.005	Vila Verde	0.020
Paredes de Coura	0.004	Vizela	0.001
Penafiel	0.006	**Total**	**0.698**

2.3.4 Sheep potential results

Figure 31 shows the dispersion of biomethane potential from sheep waste per Portuguese municipality. Observing the figure we can notice that the BMP available from sheep waste is spread out more or less evenly throughout the eastern part of the nation. In particular, the northern-east region, center-east region and in the Alentejo region have the municipalities with the highest BMP available from sheep waste in the nation. On the other hand, the western part of the nation has municipalities mostly in the lower and upper lower ranges of sheep waste BMP.

Furthermore, we can also notice from the legend in Figure 31, that the biomethane potential from poultry varies for all mainland municipalities from a minimum value of 0.000 Mm^3/a to roughly 0.180 Mm^3/a. This range is half of that available for pig waste, and considerably smaller than that of poultry and cattle waste.

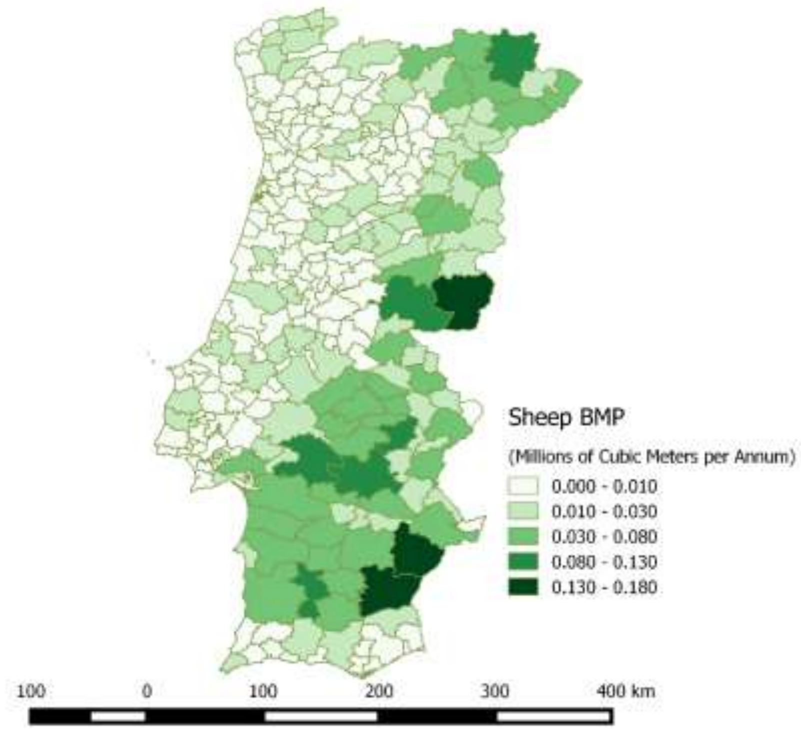

Figure 31. Biomethane potential from sheep waste in the Portuguese mainland

Table 15 shows the BMP from sheep waste available in each of the municipalities where Portgás owns assets. From this table we can notice that the total BMP of the region of interest is around 0.112 Mm^3/a. This represents around 2.5% of the total BMP available from sheep waste in the nation. Moreover, from the 29 municipalities where Portgás owns assets the municipalities of Paredes de Coura, Ponte de Lima and Vila Verde are of interest since they are all adjacent to each other and have the highest BMP from sheep waste.

Table 15. Biomethane potential from sheep waste in Portgás municipalities

Municipality	BMP [Mm^3/a]	Municipality	BMP [Mm^3/a]
Barcelos	0.005	Ponte de Lima	0.015
Braga	0.004	Porto	0.000
Caminha	0.004	Póvoa de Varzim	0.000
Esposende	0.001	Santo Tirso	0.004
Fafe	0.007	Trofa	0.001
Felgueiras	0.001	Valença	0.007
Gondomar	0.003	Valongo	0.001
Guimarães	0.002	Viana do Castelo	0.006
Lousada	0.002	Vila do Conde	0.001
Maia	0.001	Vila Nova de Cerveira	0.004
Matosinhos	0.001	Vila Nova de Famalicão	0.002
Paços de Ferreira	0.003	Vila Nova de Gaia	0.002
Paredes	0.004	Vila Verde	0.013
Paredes de Coura	0.014	Vizela	0.000
Penafiel	0.004	**Total**	0.112

2.3.5 Urban waste potential results

Figure 32 shows the dispersion of biomethane potential from urban solid residues per Portuguese municipality. As expected, the majority of the biomethane potential is located in the metropolitan area of Lisbon and the metropolitan area of Porto.

Moreover, we can also notice from the legend in Figure 32, that the biomethane potential from urban waste varies for all mainland municipalities from a minimum value of 0.000 Mm^3/a to roughly 24.00 Mm^3/a. This range is considerably higher than all of the previous ranges used for livestock, in fact it is roughly ten times higher the highest livestock range (cattle).

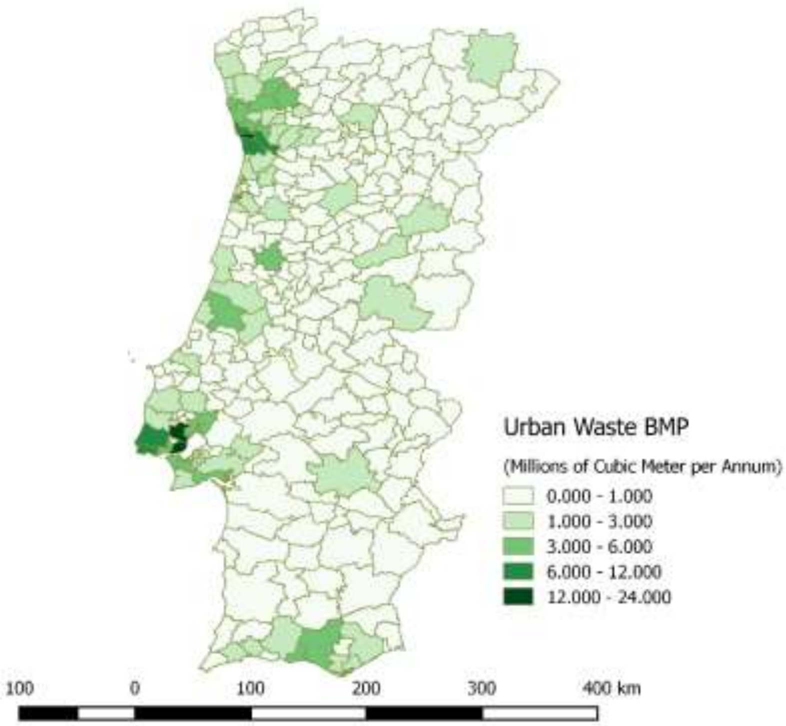

Figure 32. Biomethane potential from urban waste in the Portuguese mainland

On the other hand, Table 16 shows the BMP from urban solid waste in each of the municipalities where Portgás owns assets. From this table we can notice that the total BMP of the region of interest is around 88.695 Mm^3/a. This represents around 27.5% of the total BMP available from urban solid waste in the nation. Moreover, most of the 29 municipalities where Portgás owns assets are in the higher ranges of BMP. However, the municipalities of Porto, Gondomar, Vila Nova de Gaia and Matosinhos stand out since they have high BMP values (for national levels) and are all located adjacently.

Table 16. Biomethane potential from urban waste in Portgás municipalities

Municipality	BMP [Mm^3/a]	Municipality	BMP [Mm^3/a]
Barcelos	2.549	Ponte de Lima	0.676
Braga	4.961	Porto	12.727
Caminha	0.563	Póvoa de Varzim	3.191
Esposende	1.114	Santo Tirso	2.681
Fafe	0.977	Trofa	1.580
Felgueiras	1.261	Valença	0.455
Gondomar	6.657	Valongo	3.664
Guimarães	5.577	Viana do Castelo	1.975
Lousada	0.994	Vila do Conde	3.887
Maia	4.798	Vila Nova de Cerveira	0.234
Matosinhos	8.144	Vila Nova de Famalicão	4.116
Paços de Ferreira	1.225	Vila Nova de Gaia	9.253
Paredes	1.884	Vila Verde	1.103
Paredes de Coura	0.152	Vizela	0.853
Penafiel	1.442	**Total**	**88.695**

2.3.6 Overall biomethane potential results

The results in this section represent the sum of all the biomethane potential determined from the different substrates of the previous sections. In other words, it is the simple sum of each of the substrate potentials (cattle, pigs, urban, etc) determined for each municipalities. The overall result of this sum per municipality is shown in Figure 33.

Observing Figure 33, we can notices that the majority of municipalities within the higher ranges of BMP are located in the Lisbon metropolitan area and the Porto metropolitan area. This is to be expected, since the results presented in the previous sections show that urban waste has considerably more biomethane potential than livestock waste.

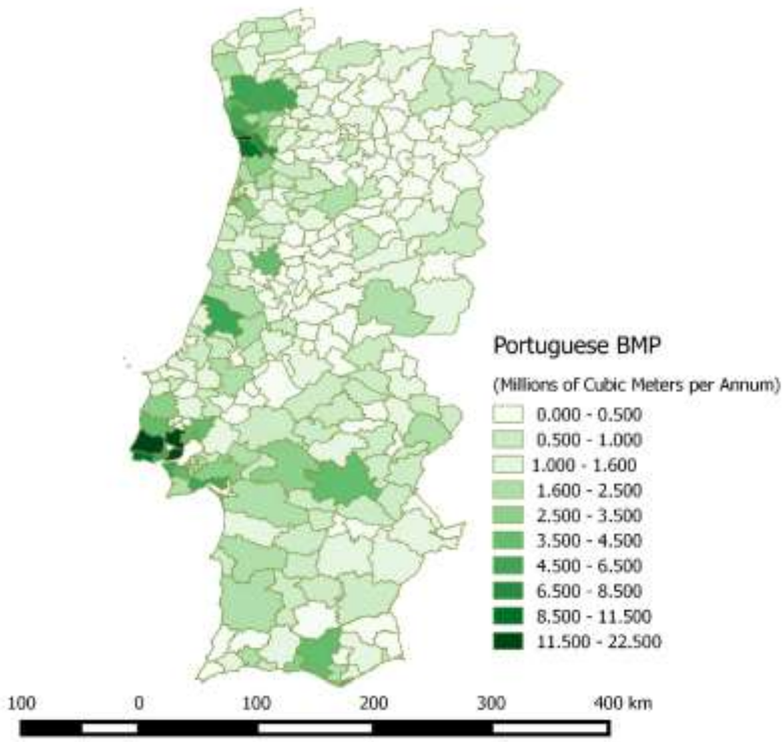

Figure 33. Biomethane potential from all waste in the Portuguese mainland

On the other hand, observing Table 17 we can notice that the total biomethane potential available in the municipalities where Portgás owns assets is around 99.062 Mm^3/a. This represents around 24.1% of the total national potential.

Similarly to the urban waste case, the municipalities of greatest interest for Portgás are Porto, Gondomar, Vila Nova de Gaia and Matosinhos due to their proximity and high potential. However, it is worth noting that municipalities adjacent to these main ones, also have BMPs in the higher national ranges. Hence, it is possible to state that the municipalities where Portgás owns assets, comprise one of the areas in the country which is preliminary more favorable for producing biomethane.

Table 17. Biomethane potential in Portgás municipalities

Municipality	BMP [Mm^3/a]	Municipality	BMP [Mm^3/a]
Barcelos	4.939	Ponte de Lima	1.020
Braga	5.336	Porto	12.730
Caminha	0.599	Póvoa de Varzim	4.043
Esposende	1.425	Santo Tirso	2.858
Fafe	1.112	Trofa	2.027
Felgueiras	1.431	Valença	0.517
Gondomar	6.714	Valongo	3.764
Guimarães	5.986	Viana do Castelo	2.342
Lousada	1.123	Vila do Conde	5.667
Maia	5.107	Vila Nova de Cerveira	0.274
Matosinhos	8.364	Vila Nova de Famalicão	4.985
Paços de Ferreira	1.313	Vila Nova de Gaia	9.291
Paredes	2.004	Vila Verde	1.369
Paredes de Coura	0.297	Vizela	0.870
Penafiel	1.556	**Total**	99.062

2.4 Portuguese Landscape: Conclusions

After observing an analyzing the results presented in the previous sections 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 99.062 Mm^3/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.

Chapter 3: Locating Biomethane Plants Across The Portgás Concession Area

This chapter 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.

Lastly, the work presented in this chapter is largely based on the model proposed by Richard O'Shea [44]. Moreover, the data used for assessing the feedstock and biomethane resource in the region was previously determine by the author in chapter #2: "Portugal Landscape".

3.1 Model Characteristics

3.1.1 Feedstock and biomethane resource assessment

An analysis on the location of waste streams used for biomethane productions in the region was previously assed by the author in the Chapter 2 : "Portugal Landscape". Furthermore, the total theoretical potential of biomethane for each waste stream was also previously estimated in the same document. However, that estimate represents an ideal scenario in which biochemical conversions are assumed completely efficient. Since this is not the case for real world applications, an estimate on how much of that theoretical resource can actually be used must be made.

Therefore, in order to estimate the real amount of methane that can be obtained from a specific feedstock processed in a digestion plant, the assumption made by Richard O'Shea is used [44]. Namely, it is assumed that any waste stream, regardless of its origin, is digested with an 80% efficiency of its biochemical methane potential. In other words, the real specific methane yield per ton of waste processed is assumed to be 80% the theoretical specific yield.

Bearing the previous assumption in mind, and considering the theoretical yields presented in Chapter 2, a simple transformation is done to determine the real specific yield of each of the waste streams considered in the area. Such yields can be observed Table 18.

Table 18. Real specific methane yields from different waste streams in different units

Waste type	Biomethane yield [m^3/ ton_{vs}]	Biomethane yield [m^3/ ton]	Biomethane yield [MWh/ ton]
Cattle waste	110.4	7.2	0.07
Pigs waste	172.8	8.1	0.08
Poultry waste	144.0	21.3	0.21
Sheep waste	82.1	18.5	0.18
Urban Solid Residues	274.1	82.2	0.83

Note: The assumptions made in this subsection do not include methane losses due to upgrading efficiency, as well as other characteristics related to the load factor of the plant which lower total biomethane production in a plant. These assumptions, are considered latter on in the subsequent subsections.

3.1.2 Transport of biomass

Biomass transportation is modeled assuming that all biomass available in a municipality is collected in a single point; which corresponds to the centroid of the municipality. This assumption is done since there is no information available on the exact coordinates of each of the feedstock sources.

On the other hand, it is also assumed that all feedstock is received in a single point within a chosen municipality. This location corresponds to the site where the biomethane processing plant will be built. Similarly, to the collection point, it is assumed that the plant site is located the centroid of the municipality. Moreover, this assumption is also done since there is no information available on the exact coordinate locations a plant can be built within each municipality. In this sense, the model allows for an estimate of biomethane plant location only at the municipal level.

Furthermore, biomass transport is assumed to be done via roads a using Heavy Duty Vehicles (HDVs) fueled by diesel. The distance traveled by HDVs from one centroid of a municipality and another is determined based on actual road distances. These real distances are determined with the Bing Maps Application Program Interface (API) coupled with Microsoft EXCEL as proposed by Purna Duggirala [45]. However, since there are many routes, distance from “A” to “B” might slightly different from distance from “B” to “A”, hence the average value was taken. Moreover, In order to use the Bing Maps API, coordinates of the centroids need to be determine beforehand; these calculations were done previously using the inbuilt centroid function of QGIS.

For modelling purposes, two main variables were considered when analyzing biomass transportation using HDVs between municipalities. Namely, the annual transport cost, and the annual emissions incurred during transport. In order to determine the annual transport, a modified version the methodology proposed by Richard O’Shea was used [44].

O'Shea assumes that the energy used by a vehicle to transport one ton of material over one kilometer (referred to as the specific energy consumption) is 2.66 MJ/(ton*km). This assumption can be used in Portugal since HDV technology is pretty much standard. Moreover, for this model price of diesel is considered to be 1.414€/L. This value is based on the average price in Portugal from August 12 to November 18 of 2019 as reported by the Portuguese Direção-Geral de Energia e Geologia [46]. In this sense, we can determine that the specific transport cost of biomass in Portugal associated to fuel is 0.10446 €/(ton*km)

Furthermore, O'Shea considers that digestate from agricultural waste must be delivered back fully to the farmers. This is done so that farmers do not lose the fertilizer value of their waste. Therefore, transporting agricultural waste is accounted for twice, by using a Return Trip Multiplier of 2. On the other hand, urban waste transport returns empty. To account for this empty return trip, O´Shea uses a return trip multiplier of 1.62.

Additionally, in order to consider the cost of loading and unloading the biomass, as well as "other costs" related the vehicle use; the assumptions made by Taede Weidenaar are considered [32]. Weidenaar assumes that the loading/unloading costs are equal to 0.66€/ton, while the "other costs" can be summed in a flat kilometer cost equal to 0.05€/€/(ton*km). This flat cost is added to the specific transport cost of biomass in Portugal associated to fuel which leads to a final specific transport cost of 0.15446 €/(ton*km).

Bearing the previous in mind, the total transport cost of biomass from one municipality to a processing plant using a HDV is determined by the following equation:

$$TC_t = \sum_i^n \sum_j^m x_{i,j} * M_{i,j} * (RTP_{i,j} * D_{i,j} * STC + LC) \quad (6)$$

In terms of estimating transport emissions it is assumed that diesel emits around 93.95 gCO2eq/MJ [47]. Hence, the Specific Transport Emissions (STE) can be calculated by multiplying the diesel emissions (in tons) with the specific energy consumption (2.66 MJ/ton*km) of diesel reported by O'Shea. This multiplication yields a STE of 0.00025 tonCO2eq/(ton*km). Hence the total transport emissions can be calculated similarly to the total transport cost according to the following equation:

$$TE_t = \sum_i^n \sum_j^m x_{i,j} * RTP_{i,j} * M_{i,j} * D_{i,j} * STE \quad (7)$$

Where the variables in equations (6) and (7) are:

- $D_{i,j}$: Distance of transporting feedstock of type "j" from location "i" to a specific plant [km]
- LC: Loading costs [€/ton]
- $M_{i,j}$: Tonnage of feedstock "j" collected in location "i" [ton/a]
- m: number of feedstock [#]
- n: number of locations [#]
- $RTP_{i,j}$: Return trip multiplier of a type "j" feedstock to location "i".

- STC: Specific Transport Cost [€/(ton*km)]
- STE: Specific Transport Emissions [tonCO2eq/(ton*km)]
- TC_t: Total transport cost for a given plant [€/a]
- TE_t: Total transport emissions for a given plant [tonCO2eq /a]
- $x_{i,j}$: Decision variable to take feedstock "j" from location "i" [-] (Value 0 if no 1 if yes).

3.1.3 Feedstock cash flows

Similarly to O'Shea, it is assumed that the feedstock's are procured at no cost. In this sense the suppliers of different feedstock's are not remunerated for the material they provide, and therefore the biomethane plant does not incurred any cost for acquiring said material other than the transport cost. On the other hand, when dealing with organic landfill waste, a gate fee can be charge for the acceptance of said waste. In this sense, the biomethane plant can will be remunerated per ton of organic landfill waste received [44].

For the purpose of this model, a gate fee of 11€/ton for organic landfill waste is used. This value corresponds to the target set by Portugal for 2020 as reported by Confederation of European Waste-to-Energy Plants (cewep) [48].

In to make the model as general as possible, and allow further sensitivity analysis when considering cost of different types of feedstocks, we can consider that the revenue of acquiring feedstock for biomethane plant is given by:

$$FR_t = \sum_i^n \sum_j^m x_{i,j} * M_{i,j} * FF_{i,j} \quad (8)$$

Where:

- $FFi_{,j}$: Fee of feedstock "j" in location "i" [€/ton]
- FR_t: Annual feedstock revenue for a processing plant [M€/a]
- $M_{i,j}$: Tonnage of feedstock "j" collected in location "i" [ton/a]
- $x_{i,j}$: Decision variable to take feedstock "j" from location "i" [-] (Value 0 if no 1 if yes).

It is important to note that both the feedstock fee (FF) and the feedstock revenue can take either positive or negative values. A positive value for FF implies that there is a gate fee, while a negative value implies that the feedstock must be bought. Moreover, a positive value for the annual feedstock revenue (FR) implies that the processing plant earns money for receiving all the feedstock while a negative money implies that the processing plant incurs a cost for receiving the feedstock.

3.1.4 Plant capacity

Plant capacity is measure in terms of the annual energy output of each upgrading site. Furthermore, the annual energy output is represented in terms of MWh of biomethane injected annually into the grid. On the other hand, in order to have a more realistic estimate of the amount of biomethane that can be produced and injected into the grid by given plant, a Load Factor (LF) of 84% is assumed. This assumption is in accordance to that made by O'Shea in order to account for methane losses during the upgrading process, as well as electric and thermal parasitic demand [44]. Lastly, it is also assumed that the biomethane is produced with an energy content (E) of 36.65 MJ/m^3 or 0.01018 MWh/m^3. With the previous in mind, the annual energy output of a given plant is given by the following equation:

$$P_t = \sum_i^n \sum_j^m x_{i,j} * RMY_j * M_{i,j} * LF * E \quad (9)$$

Where:

- E: Energy content of biomethane [MWh/m3]
- LF: Plant load factor [-]
- Mi,j: Tonnage of feedstock “j” collected in location “i” [ton/a]
- RMYj: Real methane yield of a type “j” feedstock table [m3/tonvs]
- Pt: Plant annual energy output [MWh/a]
- xi,j: Decision variable to take feedstock “j” from location “i” [-] (Value 0 if no 1 if yes).

Note that the real methane yield (RMY) corresponds to the specific methane yield of a given feedstock multiplied by digestion efficiency. Moreover, the values for each feedstock can be found in Table 18.

3.1.5 Plant Capital and Operational Expenditures (CAPEX and OPEX)

The CAPEX and OPEX for any given plant are determined using a linear regression on the actual performance data of biomethane plants (with injection to the distribution grid) reported by the UK’s Department of Energy and Climate Change [49]. In this sense, the equations calculate the CAPEX and OPEX as a function of the annual MWh of biomethane injected to the grid using a conversion factor of 1.17€ per 1£. Moreover, the range of injection data used is roughly around 7,000 to 250,000 MWh/a. For this range, the UK’s Department of Energy and Climate Change consider unit cost to increase proportionally with scale as shown in Figure 34 and Figure 35[49].

Furthermore, the CAPEX data that was regressed comprises of 7 elements namely: (i) Development costs, (ii) Civil works, (iii) Waste pre-treatment, (iv) Digester Waste, (v) Boiler, (vi) Upgrading, (vii) Injection and (vii) Gas grid connection. On the other hand, OPEX is divided into two categories: “Maintenance OPEX” and “Other OPEX”. The former encompasses maintenance cost of the same 7 aforementioned components listed for the CAPEX, and as so, are calculated as a percentage (%) of their respective CAPEX.

The “Other OPEX” comprises of: (i) Electricity, (ii) Propane, (iii) Labor, (iv) Insurance, (v) Landfill costs (vi) Landfill taxes and (vii) Digestate. However, for the regression digestate OPEX is excluded since the manner in which transport cost is modeled (as discussed in section 2.3) already accounts for the disposal of such. Additionally, each of the components of the “Other OPEX” are reported in conjunction with their respective assumed prices in the UK, hence in order to better adjust it to the Portuguese scenario a linear relationship between the assumed price in the UK and the current equivalent price in Portugal was used. In order words, the OPEX values reported are multiplied by a factor given by the ratio of the Portuguese price divided by the UK price, these values are as follows:

i. **Electricity**: it is calculated assuming an electricity price of 159.1 €/MWh (£136/MWh [49]), which for Portugal corresponds to a value of 118.6 €/MWh according to Eurostat [50]

ii. **Propane**: it is determined assuming a price of 70.2 €/MWh (£60/MWh [49]), which for Portugal corresponds to a value of 145.56 €/MWh according to values reported in Portgás internal documentation [51].

iii. **Labor cost**: it is calculated assuming that the average wage is 36,270 € per year (31,000 £ per year [49]), which for Portugal corresponds to a value of 11,644.8 € per year according to PORDATA [52]

iv. **Insurance**: There is no ratio, since the OPEX associated to this parameter is assumed to be 1% of CAPEX [49].

v. **Landfill cost**: it is determined assuming that feedstock rejected by the plant must pay a gate fee of 29.25€/ton (25£/ton), which for Portugal corresponds to a value of 11€/ton [5], as previously mentioned in section 3.1.3.

vi. **Landfill tax**: it is based on the assumption that rejected feedstock must pay a tax of 93.6 €/ton (80£/ton) to be disposed in a landfill, this corresponds to a value of 3.5 €/ton for Portugal according to the European Environmental Agency [53].

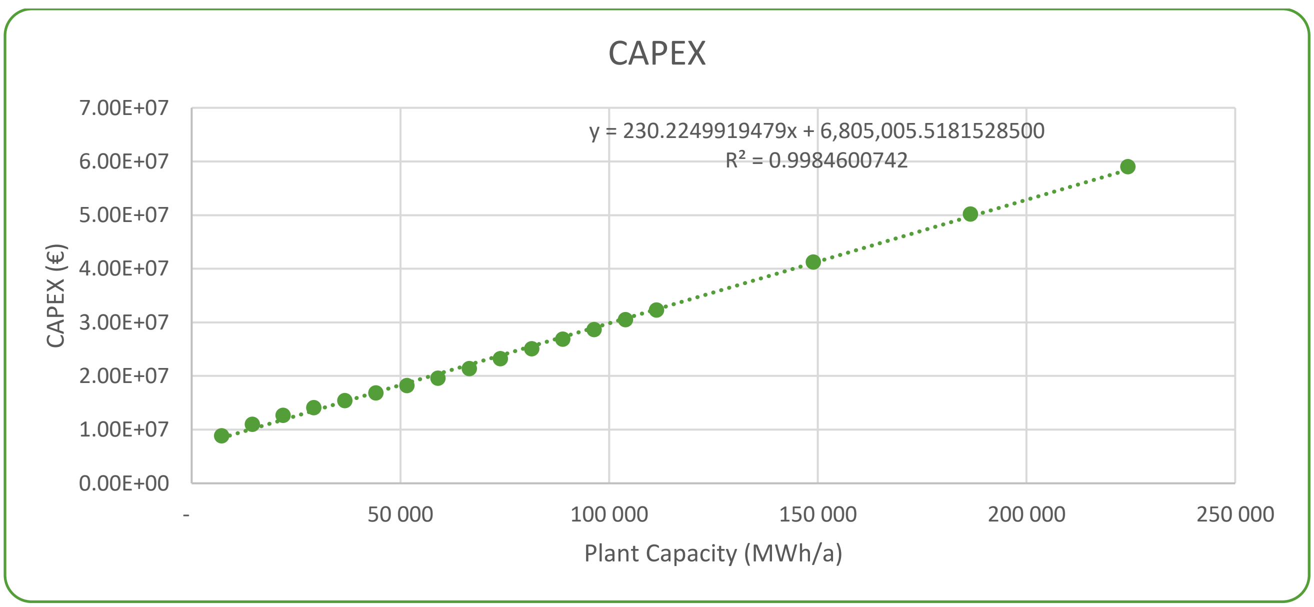

Figure 34. CAPEX curve for AD plants processing waste with biomethane injection

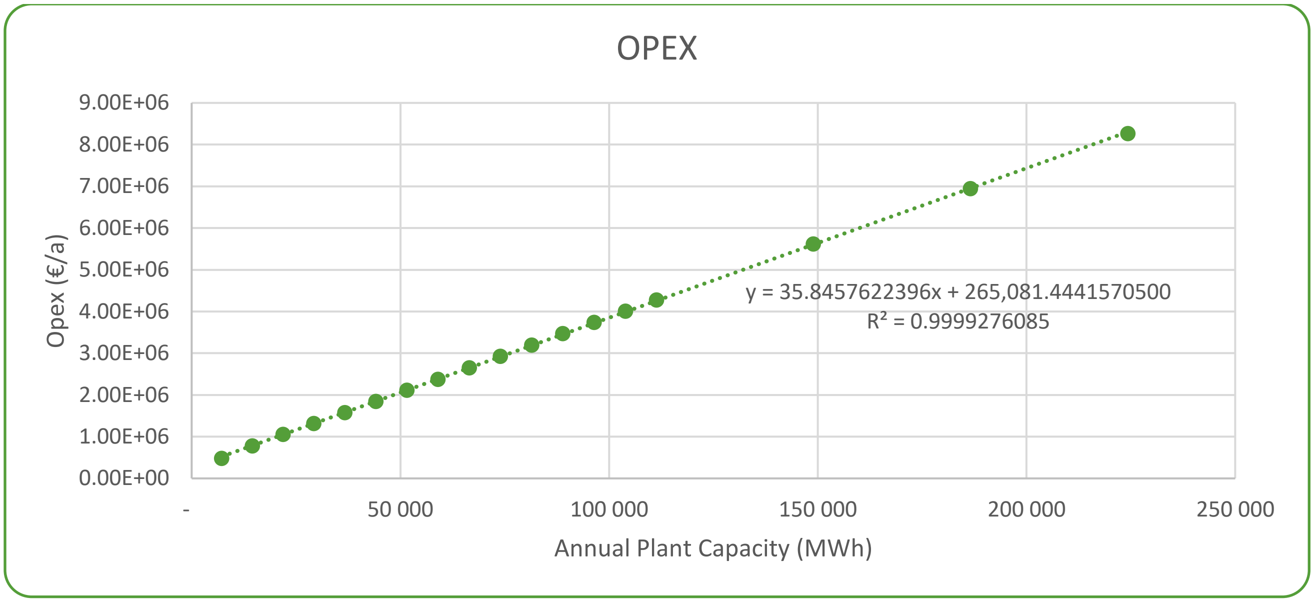

Figure 35. OPEX curve for AD plants processing waste with biomethane injection

Furthermore, the linear constants for each of the equations shown in the previous figures are presented as model parameters in Table 19.

Table 19. Linear constant parameters for equations (10) and (11)

Equation	Linear Constants	Unit	Value
(10) CAPEX	Cc	[€]	6805005.5181528500
	Sc	[€/(MWh/a]	230.2249919479
(11) OPEX	Co	[€/a]	265081.4441570500
	So	[€]	35.8457622396

Bearing the previous in mind, the equations used in this model for actually estimating CAPEX and OPEX of each plant based on the feedstock are the following:

$$CAPEX = Cc + \sum_i^n \sum_j^m x_{i,j} * RMY_j * M_{i,j} * LF * E * Sc \quad (10)$$

$$OPEX = Co + \sum_i^n \sum_j^m x_{i,j} * RMY_j * M_{i,j} * LF * E * So \quad (11)$$

Where the variables in equations (10) and (11) are:

- C_c: CAPEX linear intersection constant [€]
- C_o: OPEX linear intersection constant [€/a]
- E: Energy content of biomethane [MWh/m^3]
- LF: Plant load factor [-]
- $M_{i,j}$: Tonnage of feedstock “j” collected in location “i” [ton/a]

- S_c: CAPEX linear slope constant [€/(ton*km)]
- S_o: OPEX linear slope constant [€]
- RMY_j: Real methane yield of feedstock “j” [m^3/ton]
- $x_{i,j}$: Decision variable to take feedstock “j” from location “i” [-] (Value 0 if no 1 if yes).

3.1.6 Revenue streams

For the purpose of this model, revenue streams for a processing plant stem from either selling the biomethane produced or from any type of incentive policy which accounts for the “green value” of the gas. Moreover, while it is true that gate fees for handling certain types of waste are a form of revenue, they are considered apart as discussed in the previous subsections.

Biomethane produced from a processing plant is assumed to be sold at a wholesale price of 32.5€/MWh. This value corresponds to the average price of natural gas for non-household consumers in Portugal during the first half of 2019 as reported by Eurotostat [54]. Non-household consumer prices was chosen since the majority of Portgás supply is destined to this market. Moreover, it is assumed that this selling price is held constant during the lifetime of the given plant i.e. constant for 20 years.

For this model an incentive policy is any policy that allows a plant to generate additional revenue per MWh of biomethane injected into the grid. These types of policies were presented in document #1 for different EU nations; with the most common being either feed-in-tariffs or feed-in-premiums. However, in 2012 Portugal approved the “Decreto-Lei n.º 215-B/2012” which stopped all feed-in-tariffs for any new renewable installations and his held to this day [55]. Therefore, for a base case scenario it is assumed that this type of incentives are equal to zero.

On the other hand, generating and selling Guarantees of Origin (GoOs) could be an alternative and applicable policy in Portugal that would allow for processing plants to generate an extra revenue stream. As previously mentioned, in chapter #1, countries such as France allow biomethane producers and distributers to generate GoOs per each MWh of biomethane injected in the natural gas grid. These GoOs can later be transferred and sold between distributers, which can later be used by end consumers for the purpose of meeting environmental targets. Additionally, this policy makes sense in Portugal, since it has already set a carbon tax and is part of the EU Emissions Trading System (ETS).

The pricing of GoOs will depend on the type of market. For this model a forward market will be considered in which long-term contracts are established. Additionally, it is assumed that the price of a GoO is tied to the price of CO_2 emissions. In this sense, it is assumed that one GoO can be used to abate the equivalent amount of CO_2 produced from burning 1 MWh of natural gas. Therefore, if 1MWh of natural gas emits 0,258 tons of CO_2 [47], and the carbon tax in Portugal is 12.75€/ton [56], then the price of one GoO in Portugal should be at least 3.29€/MWh. However, it is important to note that 1MWh of biomethane will not completely abate the same emissions of 1MWh of natural gas; since GHGs emissions are incurred when producing biomethane. Hence, the price of GoOs will likely be lower, and the previous value will be lower. Therefore, in order to consider a more precise green value the transport emissions incurred are discounted for this extra source of revenue.

Lastly, some nations do provide tariff bonus for digesting certain types of waste. However, other than fees per tones, these types of incentives are not explicit in the model. Nonetheless, the user in the GUI interface can include them as euros per ton processed; in case of euros per MWh the user can refer to Table 18 for conversion purposes.

Bearing the previous in mind, the annual revenue of a given plant can be determine based on the amount of biomethane produced using the following equation:

$$R_t = \left((NGP + Itax + I) * \sum_i^n \sum_j^m x_{i,j} * RMY_j * M_{i,j} * LF * E\right) - TEt * CO_{2_{tax}} \qquad (12)$$

Where:

- E: Energy content of biomethane [MWh/m^3]
- CO_{2tax}: Carbon tax [€/ton]
- I: Incentive policy [€/MWh]
- I_{tax}: Carbon tax incentive [€/MWh]
- LF: Plant load factor [-]
- $M_{i,j}$: Tonnage of feedstock "j" collected in location "i" [ton/a]
- NGP: Natural Gas Price [€/MWh]
- P_t: Plant annual energy output [MWh/a]
- R_t: Annual revenue [€/a]
- RMY_j: Real methane yield of a type "j" feedstock table [m^3/ton_{vs}]
- TE_t: Transport emissions [ton/a]
- $x_{i,j}$: Decision variable to take feedstock "j" from location "i" [-] (Value 0 if no 1 if yes).

3.1.7 NPV optimization function

The model optimizes the Net Present Value (NPV) at each injection point by determining: (i) Which feedstock to use, (ii) The location from where to source the feedstock and (iii) The plant size. Moreover, the NPV represents the sum of the total discounted cash flows (both incoming and outgoing) of given plant during its lifetime [44]. Additionally, for this model, depreciation, financing and taxes are not considered. With this in mind the NPV is given by the following equation:

$$NPV = \left(\sum_{k=1}^{L}\left(Cash_k^{in} - Cash_k^{out}\right) * \left(\frac{1}{(1+dr)^k}\right)\right) - CAPEX_0 \qquad (13.1)$$

Where:

- $Cash_{kin}$: Incoming cash flows in year "k" [€]
- $Cash_{kout}$: Outgoing cash flows in a year "k" [€]
- $CAPEX_0$: Initial Capital Expenditure [€]

- dr: discount rate [-]
- k: year [-]
- L: Total number of years [-]
- NPV: Net Present Value [€]

However, the previous equation can be rearranged in a manner that is easier to handle by converting the future cash flows to their present-day value. This is done by separating the values dependent from the summation and solving the summation in a manner similar manner to O'Shea [44]. Hence, equation (8) can be converted to in terms of the parameters define in the previous subsection as:

$$NPV = DF * (R_t + FR_t - OPEX_t - TC_t) - CAPEX \quad (13.2)$$

Where discount factor DF is given by:

$$DF = \frac{(1+dr)^L - 1}{dr * (1+dr)^L} \quad (14)$$

Moreover, similarly to O'Shea it is assumed that the lifetime of a given plant ("L) is 20 years and that the discounted rate (dr) is set at 8%. However, the GUI interface allows the user to change these parameters based on his or her discretion.

Lastly, knowing the net cashflows and the CAPEX it is possible to determine the discounted payback period as follows:

$$DPP = \frac{\ln\left(\frac{1}{1-(CAPEX * \frac{dr}{CF})}\right)}{\ln(1+dr)} \quad (15)$$

Where discount factor CF is given by:

$$CF = (R_t + FR_t - OPEX_t - TC_t) \quad (16)$$

3.1.8 Model summary

The previous equations are summarized for practical use in this section as follows:

Equation 6*:* 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 7: 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 8: Feedstock Revenue

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

Equation 9: Plant Annual Energy Output

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

Equation 10: CAPEX

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

Equation 11: OPEX

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

Equation 12: Revenue streams

$$R_t = \left((NGP + Itax + I) * \sum_{i}^{n}\sum_{j}^{m} x_{i,j} * RMY_j * M_{i,j} * LF * E \right) - TEt * CO_{2_{tax}}$$

Equation 13: Net Present Value

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

Equation 14: Discount factor

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

Equation 15: Discounted Payback Period

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

Constrains

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

3.1.9 Solving algorithm

The full algorithm can be seen in Figure 36. Moreover, observing the figure we can notice that the algorithm 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.

The first block can be further broken down in:

- **User Input Data**: This data refers to any data that can be added by the user in the Graphical User Interface (GUI). The main purpose of this data is to allow the user to conduct sensitivity analysis.
- **CSV Loaded Data**: This refers to all data loaded as CSV files, and it solely corresponds to big data related to each of the municipalities (i.e. types of waste, distances between municipalities, capacity of each municipality)
- **Intrinsic Model Data**: This data corresponds to underlying constants used in the model that cannot be change by the user. Mostly it is the values aforementioned presented in the previous subsections.

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 [57] [58].

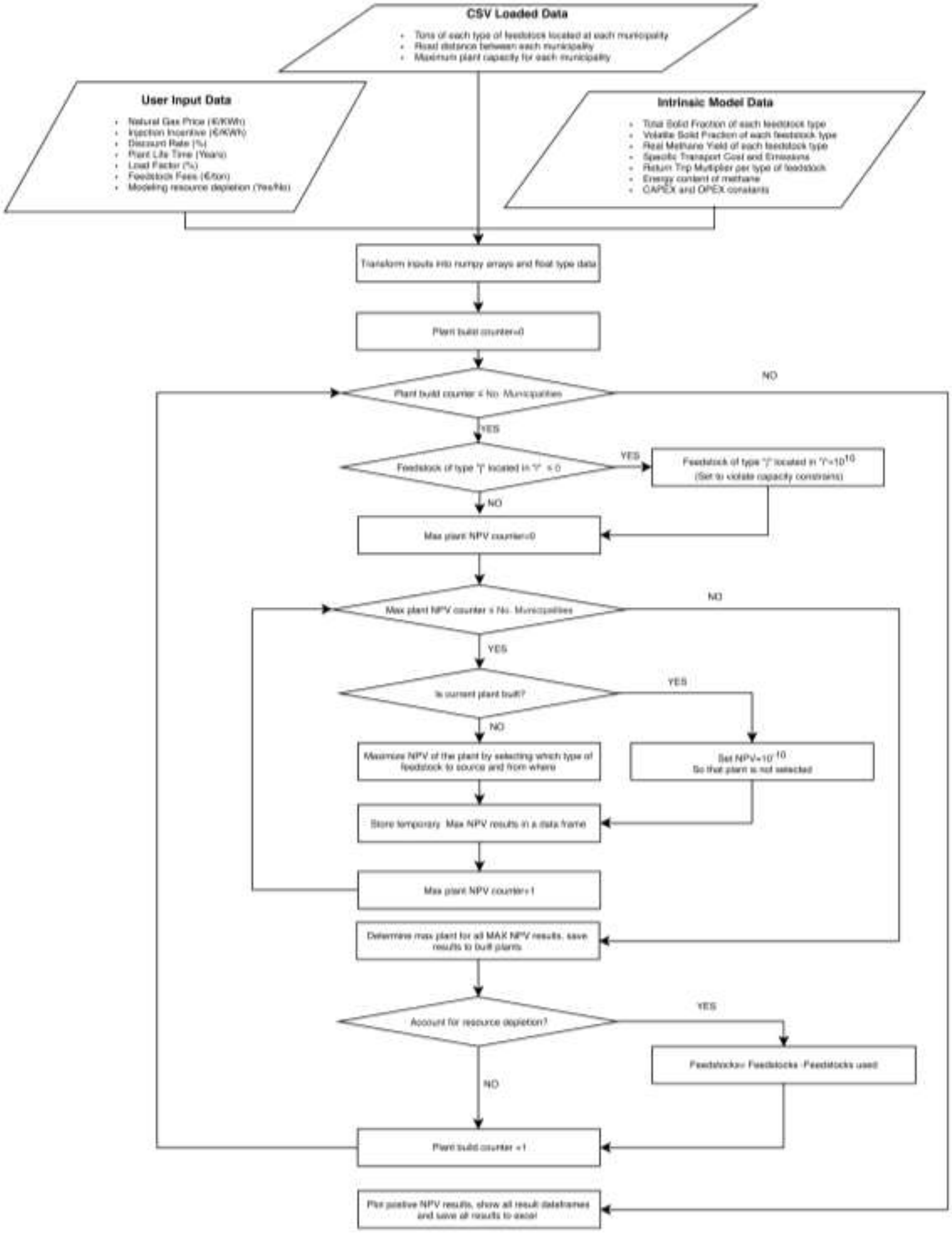

Figure 36. Green Gas Planner optimization flowchart

3.2 Case Studies

The purpose of this work is to provide insight on the best locations for building biomethane plants within the concession area of Portgás in terms of Net Present Value of an investment. However, as is with most renewable energies, policymaking will influence the value and feasibility of any investment. Therefore, to understand the extent of this influence a set of case studies considering different policy scenarios from the leading EU nations in biomethane are proposed.

Moreover, since Portgás is a natural gas distribution company, the policies consider are those that promote biomethane injection into the gas grid. In this sense, 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.

Furthermore, it is important to note that while Germany has the most biomethane plants, current German policies do not promote biomethane injection into the grid and therefore it is discarded as a case study for the General Policy Scenarios.

On the other hand, it is important to note that the current waste management concessions in Portugal may limit how biomass is transported within the country; particularly urban solid residues. As it stands today, there are 23 different waste management concession areas in mainland Portugal as seen in figure 4. Therefore, it is likely that under current Portuguese legislation transporting one type of waste from one concession are to another is prohibited.

Figure 37. SGRU distribution map in mainland Portugal [59]

In order to account for these limits in biomass transportation another set of case studies is proposed. In these set of case studies, referred to from now on as "Waste Concession Scenarios", biomethane plants can only be built in municipalities where the concession of Portgás and a concession of waste management company overlap. Moreover, for these plants, waste can only be sourced from municipalities where the given waste management company holds a concession. In this sense, a total of seven cases studies are proposed, since out of the 23 waste management concessions shown in figure 4, only the first 7 companies share municipalities with Portgás.

On the other hand, it is important to note that there is an inherent different between the nature of the "General Policy Scenarios" and the "Waste Concession Scenarios". The former implies changes in incentives such as the carbon tax, injection incentive, incentive for processing a certain waste and so on. The latter on the other hand, implies limits in where plants can be built and where biomass can be sourced. Therefore it is obvious that the assumptions of one of the set scenario can be easily applied to the other set and vice versa. Hence, in order to limit the scope of the study, the General Policy Scenario shall be conducted first. Afterwards the assumptions of the "best case" of the General Policy Scenario shall be applied to all the Waste Concession Scenario; with "best case" implying the highest cumulative NPV when resources depletion is accounted for. In other words, the policies for the case in which the sum all of the

NPVs of all plants built is the highest are selected. The highest is selected in other to run a optimistic analysis seeing that the current European scenario is heading towards an increase in sustainability direction.

Lastly, for all case scenarios the capacity constrain is set to 60 MWh per annum for all municipalities with the exception of Porto and Vila Nova de Gaia. This assumption was set after internal deliberation in which it is considered that grid of Portgás has no limitation when injecting 60MWh in most municipalities. However, the two municipalities previously mention have higher biomethane potential than 60 MWh based on biomethane potential determined in Chapter 2. Hence, in order to consider them in the study the capacity of those municipalities was chosen as to cover their potential rounded to the nearest multiple of ten. These capacities are 90MWh for Porto and 70 MWh for Vila Nova de Gaia.

3.2.1 Portuguese current policy scenario

The current policies in Portugal correspond to the base assumptions describe in section 3.1. As previously mentioned, the country does not have any scheme that supports biomethane injection nor biomethane GoOs. However, since there is a carbon tax in Portugal, it will be assumed that in case of building a biomethane plant the gas produced can be used to avoid paying CO_2 tax. In this sense, the assumptions related to this case study are summarized as follows:

- **Carbon Tax**: 12.8 € per ton of CO_2
- **Injection Incentive**: 0 € per MWh
- **Livestock Waste**: No cost or incentive

3.2.2 United Kingdom policy scenario

As mentioned in chapter 1, the United Kingdom has several policies in play that incentives biomethane use. However, for the purpose of this study only the Non-Domestic Renewable Heat Incentive policy will be considered since it is the main policy that directly promotes biomethane injection into the gas grid. Additionally, more broad aspects such as the UK's national carbon tax and national gate fees will also be considered. In this sense, the assumptions related to this case study are summarized as follows:

- **Carbon Tax**: 20.3 € per ton of CO_2 [56]
- **Tier Injection Incentive**:
  - **Tier 1** (40000 MWh): 54€/MWh
  - **Tier 2** (80000 MWh): 32 €/MWh
  - **Tier 3** (Remaining): 24€/MWh
- **Livestock Waste**: No cost or incentive

3.2.3 Sweden policy scenario

Similarly, to the UK, chapter #1 shows that Sweden also has several incentives that promote the use of biomethane. The main incentives are feed-in-tariff for injecting gas into the grid and special tariff when processing manure. The incentive for processing manure is expressed in terms of MWh, however in order to use the values in the Green Gas Planner the units must be in tons. Hence, the values presented in Table 18 are used as a converter to tons for each type livestock waste.

Additionally, both carbon taxes and municipal gate feed are also considered. Therefore, bearing the previous in mind we can summarized the assumptions of this case scenario as follows:

- Carbon tax: 148.6 € per ton of CO_2 [56]
- Injection Incentive: 0 € per MWh
- Livestock Waste: 39€ per MWh of biomethane produced from that waste. This is equivalent to the following incentive as processing per tonnage of each of the livestock's waste:
  - Cattle: 2.86 € per ton
  - Pigs: 3.21 € per ton
  - Poultry: 8.46 € per ton
  - Sheep: 7.34 € per ton

3.2.4 France policy scenario

As discussed in chapter #1 the main incentive for promoting biomethane plants in France is related to a feed-in-tariff which varies with plant capacities lower than 350 m^3/h or 25GWh/a. However, since all plants consider in our studies tend to have capacities higher than this the flat tariff for plants larger than the aforementioned value is used. Additionally, all waste is assumed to be non-hazardous and therefore the tariff that applies to that type of waste is used. Moreover, France also implements substrate premiums, which similarly to the previous case are presented in MWh and must be converted to tons. Lastly, similar to the previous cases both carbon tax and gate fees are considered. Hence, the assumptions are as follows:

- **Carbon tax**: 45 € per ton of CO_2 [56].
- **Injection Incentive**: 45€ per MWh
- **Urban Solid Residues**: 5/MWh (4.2€/ton) substrate premium leading to a total 15.2 € per ton when considering the Portuguese gate fee.
- **Livestock Waste**: 20€ per MWh of biomethane produced from that waste. This is equivalent to the following incentive as processing per tonnage of each of the livestock's waste:
  - **Cattle**: 1.47 € per ton
  - **Pigs**: 1.65 € per ton
  - **Poultry**: 4.34 € per ton
  - **Sheep**: 3.77 € per ton

3.2.5 VALORMINHO

The VALORMINHO concession encompasses a total of 6 municipalities from which biomass may source these are [60]:

- Caminha
- Melgaço
- Monção
- Paredes de Coura
- Valença
- Vila Nova de Cerveira

Out of the previous municipalities only four of them are within the concession are of Portgás, and hence only four biomethane plants may be built. These are:

- Caminha
- Paredes de Coura
- Valença
- Vila Nova de Cerveira

3.2.6 RESULIMA

The RESULIMA concession area encompasses a total of six municipalities from which biomass may source these are [61]:

- Arcos de Valdevez
- Barcelos
- Esposende
- Ponte da Barca
- Ponte de Lima
- Viana do Castelo

Out of the previous municipalities only four of them are within the concession are of Portgás, and hence only four biomethane plants may be built. These are:

- Barcelos
- Esposende
- Ponte de Lima
- Viana do Castelo

3.2.7 BRAVAL

The BRAVAL concession area encompasses a total of six municipalities from which biomass may source these are [62]:

- Amares
- Braga   Povoa de Lanhoso
- Terras de Bouro

- Vieira do Minho
- Vila Verde

Out of the previous municipalities only two of them are within the concession are of Portgás, and hence only two biomethane plants may be built. These are:

- Braga
- Vila Verde

3.2.8 RESINORTE

The RESINORTE concession area encompasses a total of 35 municipalities from which biomass may source these are [63]:

- Alijo
- Amarante
- Armamar
- Baião
- Boticas
- Cabeceiras de Basto
- Celorico de Basto
- Chaves
- Cinfães
- Fafe
- Guimarães
- Lamego
- Marco de Canaveses
- Mesão Frio
- Moimenta da Beira
- Mondim de Basto
- Montalegre
- Murça
- Penedono
- Peso da Régua
- Resende
- Ribeira de Pena
- Sabrosa
- Santa Marta de Penaguião
- Santo Tirso
- São João da Pesqueira

- Sernancelhe
- Tabuaço
- Tarouca
- Trofa
- Valpaços
- Vila Nova de Famalicão
- Vila Pouca de Aguiar
- Vila Real
- Vizela

Out of the previous municipalities only six of them are within the concession are of Portgás, and hence only six biomethane plants may be built. These are:

- Fafe
- Guimarães
- Santo Tirso
- Trofa
- Vila Nova de Famalicão
- Vizela

3.2.9 Lipor

The Lipor concession area encompasses a total of eight municipalities from which biomass may source these are [64]:

- Espinho
- Gondomar
- Maia
- Matosinhos
- Porto
- Póvoa de Varzim
- Valongo
- Vila do Conde

Out of the previous municipalities only seven of them are within the concession are of Portgás, and hence only seven biomethane plants may be built. These are:

- Gondomar
- Maia
- Matosinhos
- Porto

- Póvoa de Varzim
- Valongo
- Vila do Conde

3.2.10 Ambisousa

The Ambisousa concession area encompasses a total of six municipalities from which biomass may source these are [65]:

- Castelo de Paiva
- Felgueiras
- Lousada
- Paços de Ferreira
- Paredes
- Penafiel

Out of the previous municipalities only five of them are within the concession are of Portgás, and hence only five biomethane plants may be built. These are:

- Felgueiras
- Lousada
- Paços de Ferreira
- Paredes
- Penafiel

3.2.11 SULDOURO

The SULDOURO concession area encompasses a total of two municipalities from which biomass may source these are [66]:

- Santa Maria da Feira
- Vila Nova de Gaia

Out of these two only Vila Nova de Gaia is within the Portgás concession are, and hence a biomethane plant can only be built there.

3.3 Results for Locating Biomethane Plants Across The Portgás Concession Area

This section presents the results from the case studies. An overview of the results from subsections 3.3.2 through 3.3.4 (Table 20, Table 21and Table 22) show 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. Therefore, since the analysis to be done for the waste concession is an optimistic scenario the French policies are applied to all the waste concession case (results from subsection 3.3.5 and onwards). Moreover, since the locations for the case studies of sections

3.3.5 and onwards are small, only analysis without resource depletions was considered. On the other hand, the tool developed can be seen in Annex A.1. The decisions to source waste for each plant is an extensive list results and can be seen in supporting excel file, nonetheless and example of this output is shown in Annex A.2.

3.3.1 Portuguese scenario 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.

3.3.2 United Kingdom scenario results

Analyzing the concession area with the UK policies it was found that modeling with the Green Gas Planner yielded 11 biomethane plants with an NPV higher than 0 as seen in Table 20 and Figure 38. Moreover, when resource depletion is not accounted for it is shown that all 29 municipalities could be feasible for an investment as seen in Figure 39.

Table 20. Plant built results for the UK policy scenario accounting for resource depletion

Municipality	NPV [M€]	Transport Cost [k€]	Transport Emissions [ton/a]	Feedstock Revenue [M€]	Capacity [GWh/a]	CAPEX [M€]	OPEX [M€/a]	Revenue [M€/a]	Payback [Years]	LCOE [€/MWh]
Porto	20.2	81.7	0.0	1.4	87.0	26.9	3.4	6.9	8	71.2
Vila Nova de Gaia	14.9	59.4	0.0	1.0	63.3	21.4	2.5	5.3	8	75.4
Matosinhos	13.0	52.3	0.0	0.9	55.7	19.6	2.3	4.8	8	77.4
Gondomar	12.4	175	194.5	0.9	58.4	20.3	2.4	5	9	78.7
Maia	12.4	166.6	182.7	0.9	57.9	20.1	2.3	4.9	9	78.7
Guimarães	12.2	225.9	276.5	0.9	59.3	20.5	2.4	5.0	9	79.3
Vila do Conde	11.8	255.5	323.5	0.9	59.2	20.4	2.4	5.0	9	79.8
Braga	11.6	269.2	346.2	0.9	58.9	20.4	2.4	5.0	9	80.1
Vila Nova de Famalicão	10.3	296.0	395.7	0.9	54.9	19.4	2.2	4.7	9	82.1
Viana do Castelo	5.0	243.6	345.3	0.5	32.3	14.2	1.4	3.1	11	96.6
Penafiel	2.7	74.9	95.9	0.3	16.7	10.6	0.9	2.0	13	121.3

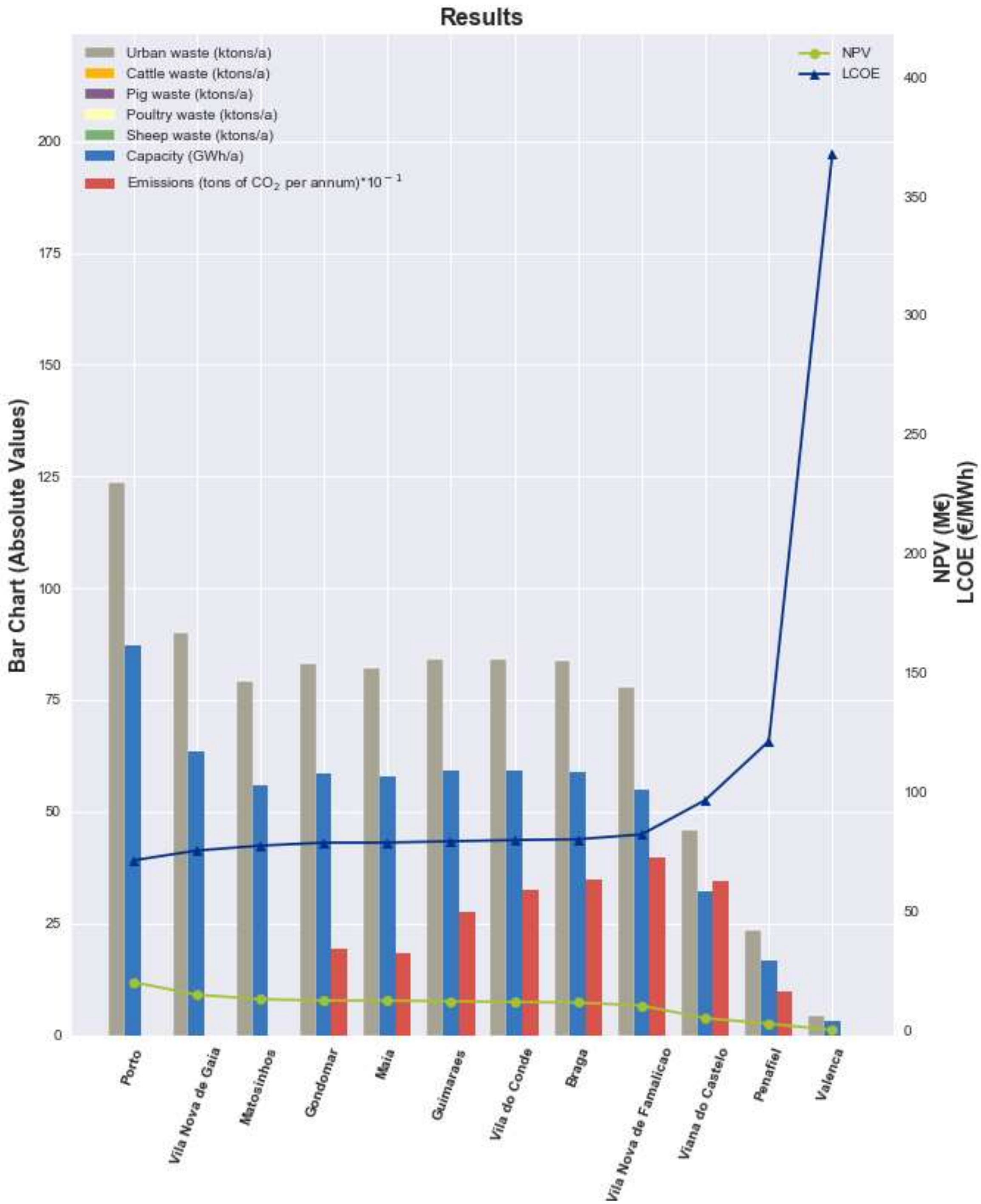

Figure 38. Results of the UK policy scenario with resource depletion

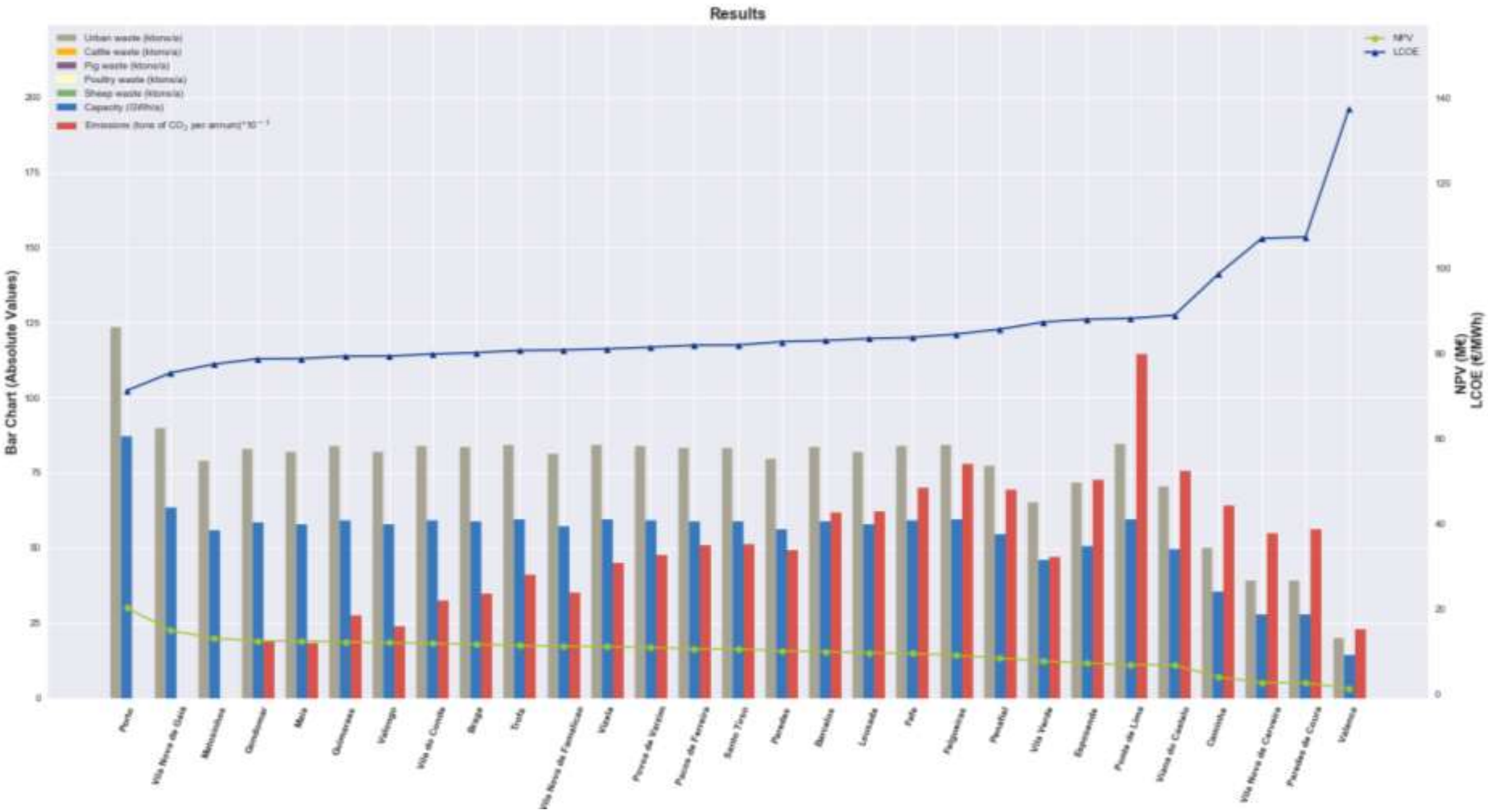

Figure 39. Results of the UK policy scenario without resource depletion

3.3.3 Sweden scenario results

Analyzing the Swedish policies applied in Portugal it was found that 10 biomethane plants with an NPV higher than 0 can be built in the concession area. However, unlike the case in the UK we can notice more plants that utilize livestock as feedstock. These results are shown in Table 21 and Figure 40. Moreover, when resource depletion is not accounted for it is shown that only 19 municipalities could be feasible for an investment as seen in Figure 41.

Table 21. Plant built results for the Sweden policy scenario accounting for resource depletion

Municipality	NPV [M€]	Transport Cost [k€]	Transport Emissions [ton/a]	Feedstock Revenue [M€]	Capacity [GWh/a]	CAPEX [M€]	OPEX [M€/a]	Revenue [M€/a]	Payback [Years]	LCOE [€/MWh]
Porto	13.1	141.3	87.8	1.4	88.5	27.2	3.4	6.3	10	71.7
Vila Nova de Gaia	7.0	61.9	0.0	1.0	63.532	21.4	2.5	4.5	12	75.4
Vila do Conde	5.8	342.8	275.90	1.3	57.184	20	2.3	4.1	12	82
Matosinhos	5.6	68.3	0.0	0.9	57.204	20	2.3	4.1	12	77.2
Barcelos	5.5	533.9	517.6	1.4	59.555	20.5	2.4	4.2	13	84.3
Maia	5.1	190.2	185.2	1.0	59.923	20.6	2.4	4.2	13	78.5
Guimarães	4.4	234.7	260.3	1.0	59.418	20.5	2.4	4.2	14	79.4
Gondomar	4.3	178.7	194.5	0.9	58.78	20.3	2.4	4.2	14	78.6
Vila Nova de Famalicão	4.0	387.6	443.7	1.1	59.996	20.6	2.4	4.3	14	81.7
Braga	1.7	492.3	662.4	1.0	59.249	20.4	2.4	4.2	17	83.8

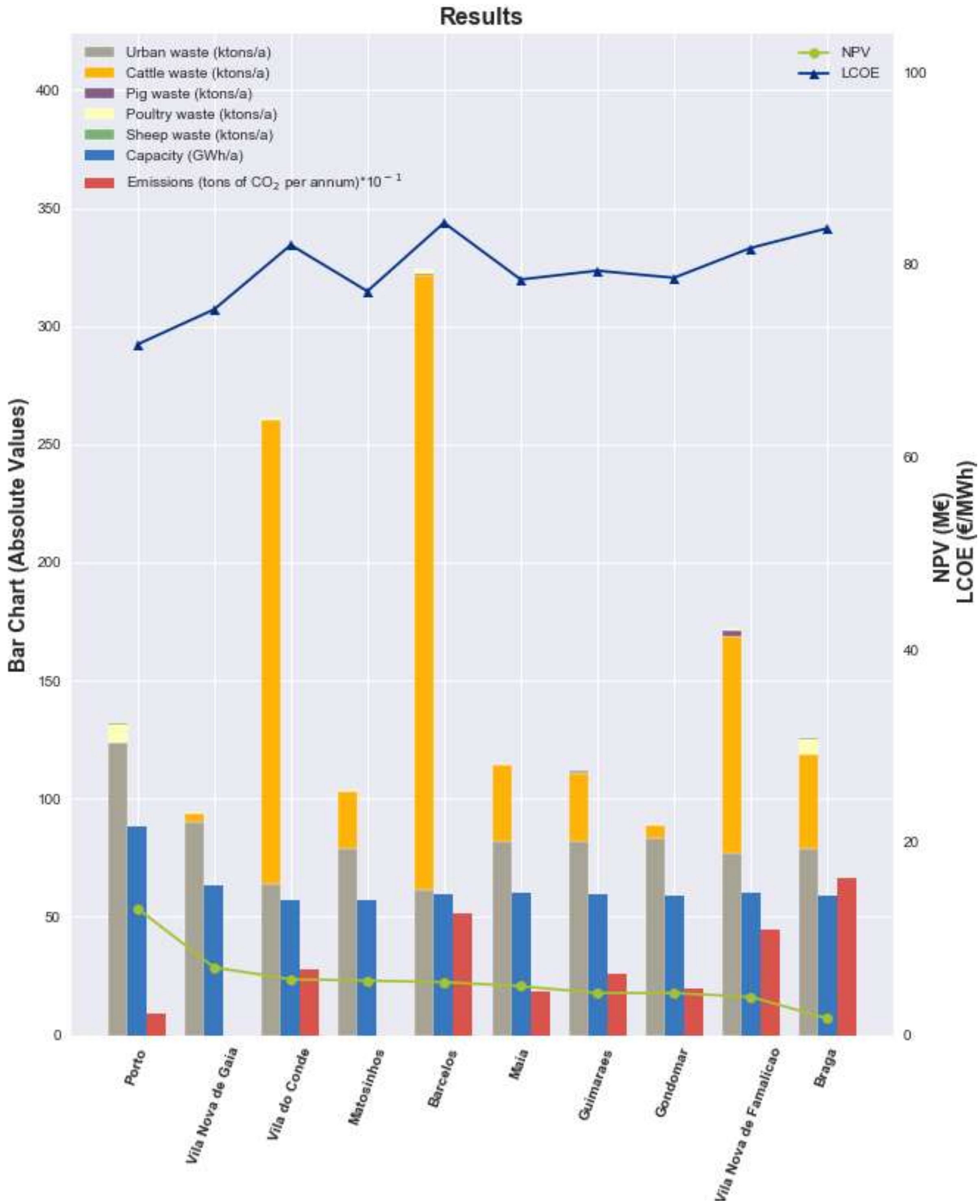

Figure 40. Results of the Sweden policy scenario with resource depletion

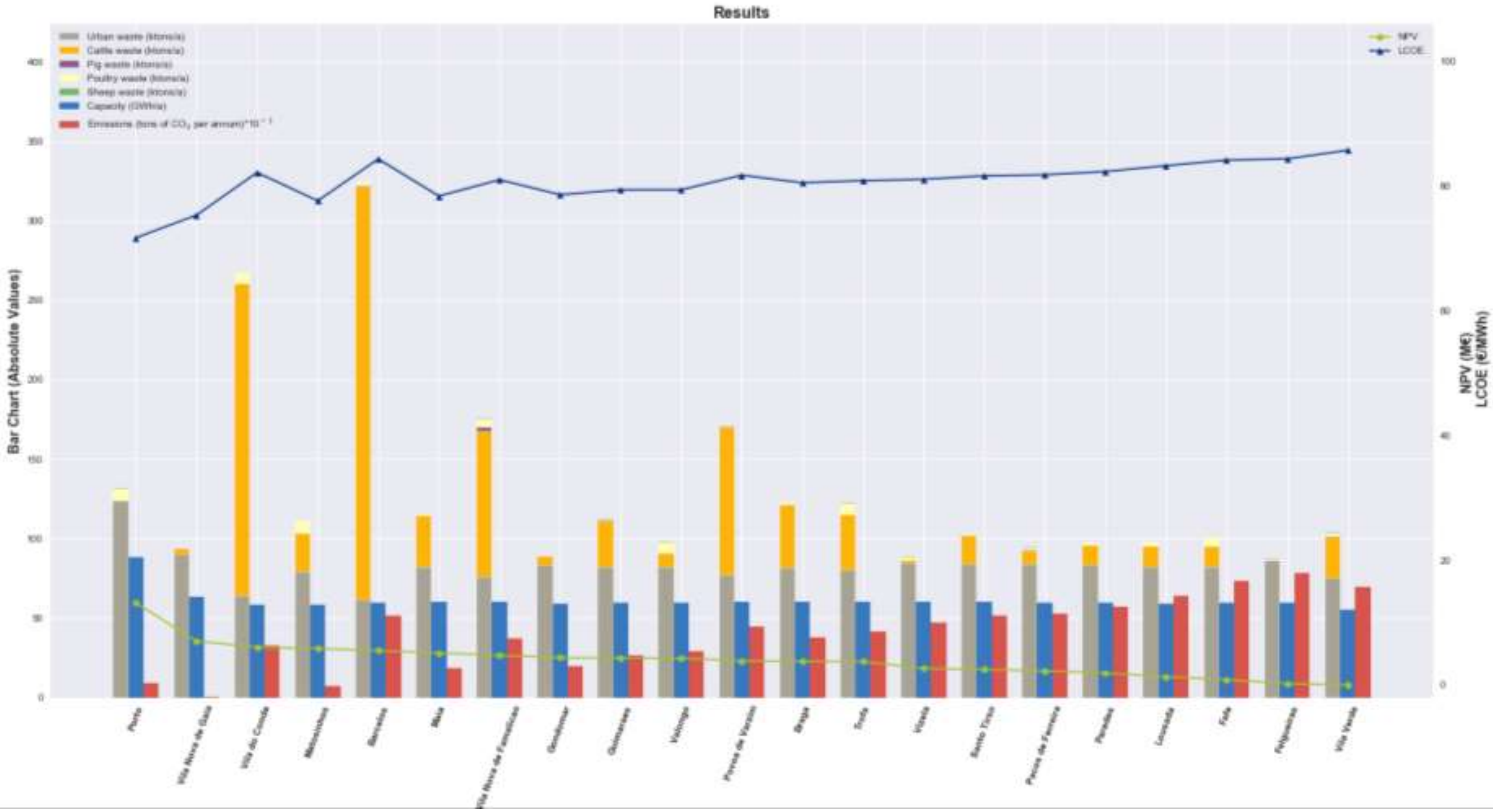

Figure 41. Results of the Sweden policy scenario without resource depletion

3.3.4 France scenario results

Analyzing the French policies applied in Portugal it was found that similarly to the Swedish case scenario, only 10 biomethane plants with an NPV higher than 0 can be built in the concession area. Furthermore, just like the Swedish case more utilization of livestock waste can be notice when compared to the UK case scenario. These results are shown in Table 22 and Figure 42. Moreover, when resource depletion is not accounted for it was found that all 29 municipalities could be feasible for an investment as seen in Figure 43.

Table 22. Plant built results for the France policy scenario accounting for resource depletion

Municipality	NPV [M€]	Transport Cost [k€]	Transport Emissions [ton/a]	Feedstock Revenue [M€]	Capacity [GWh/a]	CAPEX [M€]	OPEX [M€/a]	Revenue [M€/a]	Payback [Years]	LCOE [€/MWh]
Porto	34.0	197.9	182.1	1.9	90.000	27.5	3.5	8	6	72.1
Vila Nova de Gaia	23.4	221.9	249.8	1.5	69.417	22.8	2.8	6.2	6	76.3
Matosinhos	19.0	107.4	57.1	1.3	58.274	20.2	2.4	5.2	7	77.6
Maia	18.9	193.1	189.6	1.3	59.983	20.6	2.4	5.3	7	78.5
Gondomar	18.5	180.6	197.0	1.3	58.857	20.4	2.4	5.2	7	78.6
Vila do Conde	17.9	258.5	327.8	1.3	59.324	20.5	2.4	5.3	7	79.8
Guimarães	17.7	315.8	390.9	1.3	59.987	20.6	2.4	5.3	7	80.5
Braga	17.7	299.1	389.9	1.3	59.71	20.6	2.4	5.3	7	80.4
Vila Nova de Famalicão	16.7	419.7	496.3	1.3	59.937	20.6	2.4	5.3	7	82.3
Barcelos	8.6	1137.5	1497.8	1.3	58.445	20.3	2.4	5.2	10	95.2

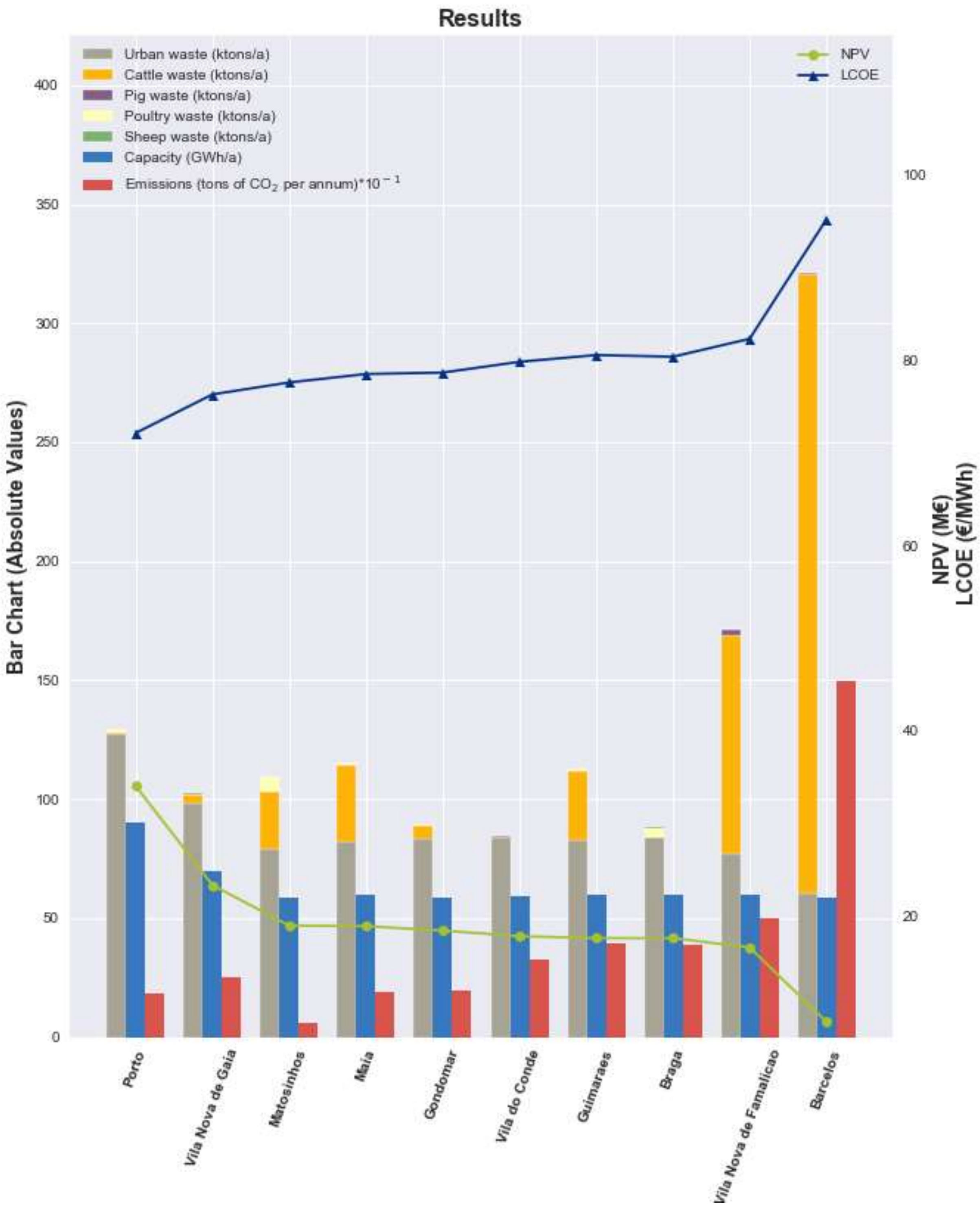

Figure 42. Results of the France policy scenario with resource depletion

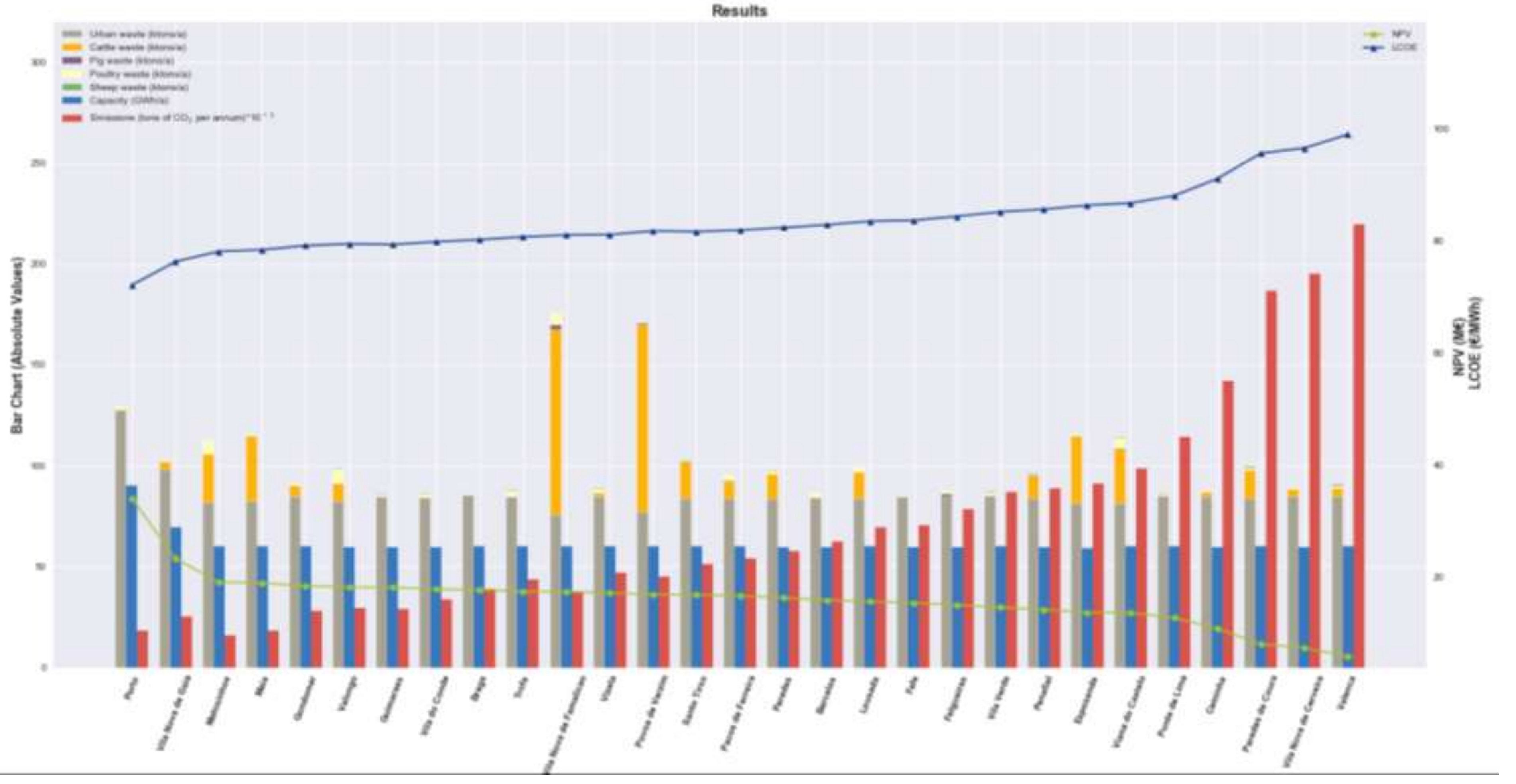

Figure 43. Results of the France policy scenario without resource depletion

3.3.5 VALORMINHO results

When analyzing the feasibility of building biomethane plant with a joint Portgás and VALORMINHO partnership it was found that no plant with a positive NPV can be built. Hence, under current French policies no plants should be built since the investment will result in a net loss for the company.

3.3.6 RESULIMA results

When analyzing the feasibility of building biomethane plant with a joint Portgás and RESULIMA concession it was found that all shared concessions have and NPV greater than zero as seen in Table 23 and Figure 44.

Table 23. Plant built results for the RESULIMA-Portgás joint concession

Municipality	NPV [M€]	Transport Cost [k€]	Transport Emissions [ton/a]	Feedstock Revenue [M€]	Capacity [GWh/a]	CAPEX [M€]	OPEX [M€/a]	Revenue [M€/a]	Payback [Years]	LCOE [€/MWh]
Barcelos	15.2	570.9	577.9	1.3	59.546	20.5	2.4	5.3	8	85.0
Viana do Castelo	10.3	537.7	763.5	1.1	50.086	18.3	2.1	4.5	9	89.2
Esposende	9.4	601.9	865.8	1.1	49.546	18.2	2.0	4.4	10	90.8
Ponte de Lima	8.6	726.6	1061.4	1.1	50.577	18.4	2.1	4.5	10	92.6

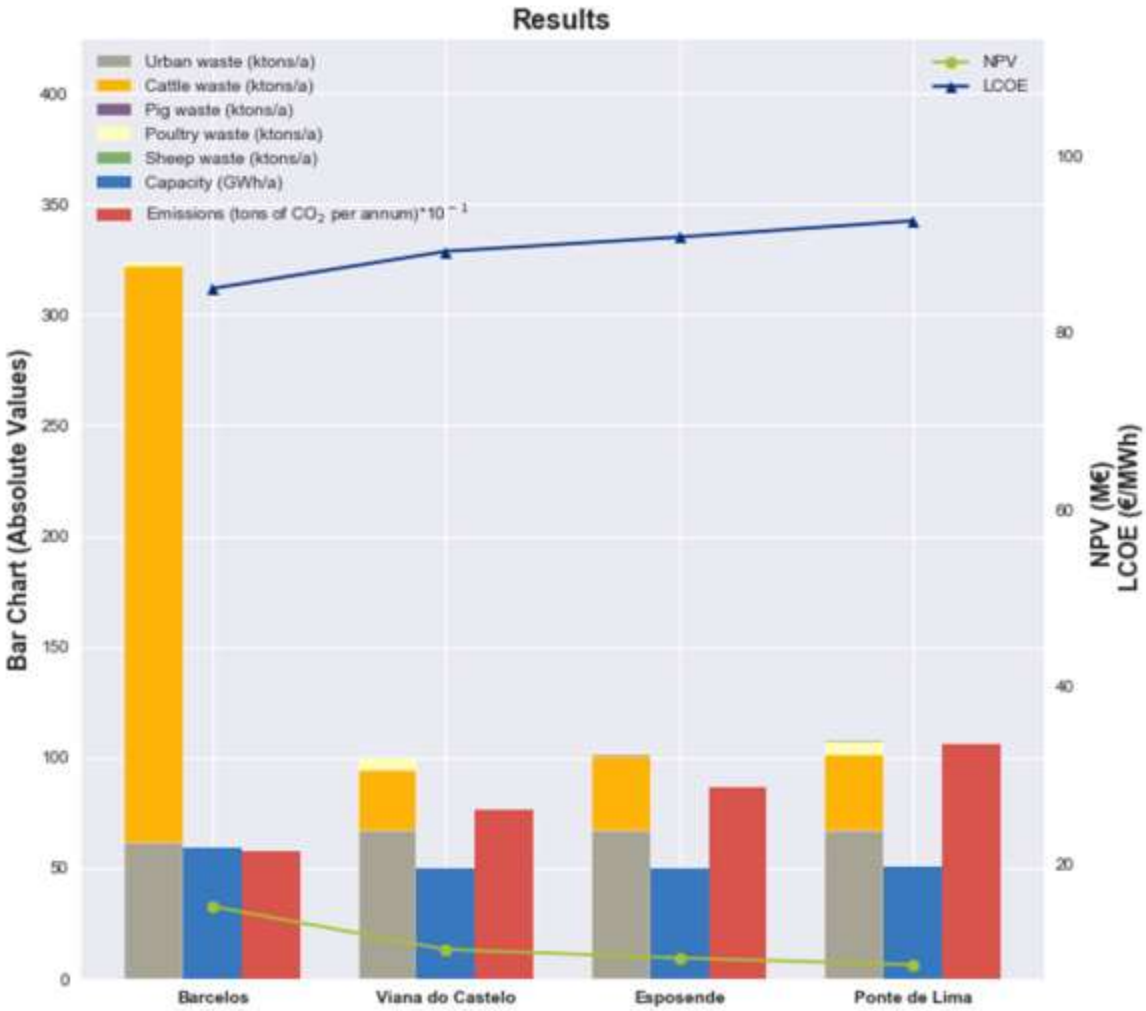

Figure 44. Results for the RESULIMA-Portgás joint concession

3.3.7 BRAVAL results

When analyzing the feasibility of building biomethane plant with a joint Portgás and BRAVAL concession it was found that the two municipalities shared in the concessions have and NPV greater than zero as shown in Table 24 and Figure 45.

Table 24. Plant built results for the BRAVAL-Portgás joint concession

Municipality	NPV [M€]	Transport Cost [k€]	Transport Emissions [ton/a]	Feedstock Revenue [M€]	Capacity [GWh/a]	CAPEX [M€]	OPEX [M€/a]	Revenue [M€/a]	Payback [Years]	LCOE [€/MWh]
Braga	15.8	283.3	329.8	1.2	55.565	19.6	2.3	5.0	7	81.6
Vila Verde	13.5	454.2	621.2	1.2	54.606	19.4	2.2	4.9	8	85.2

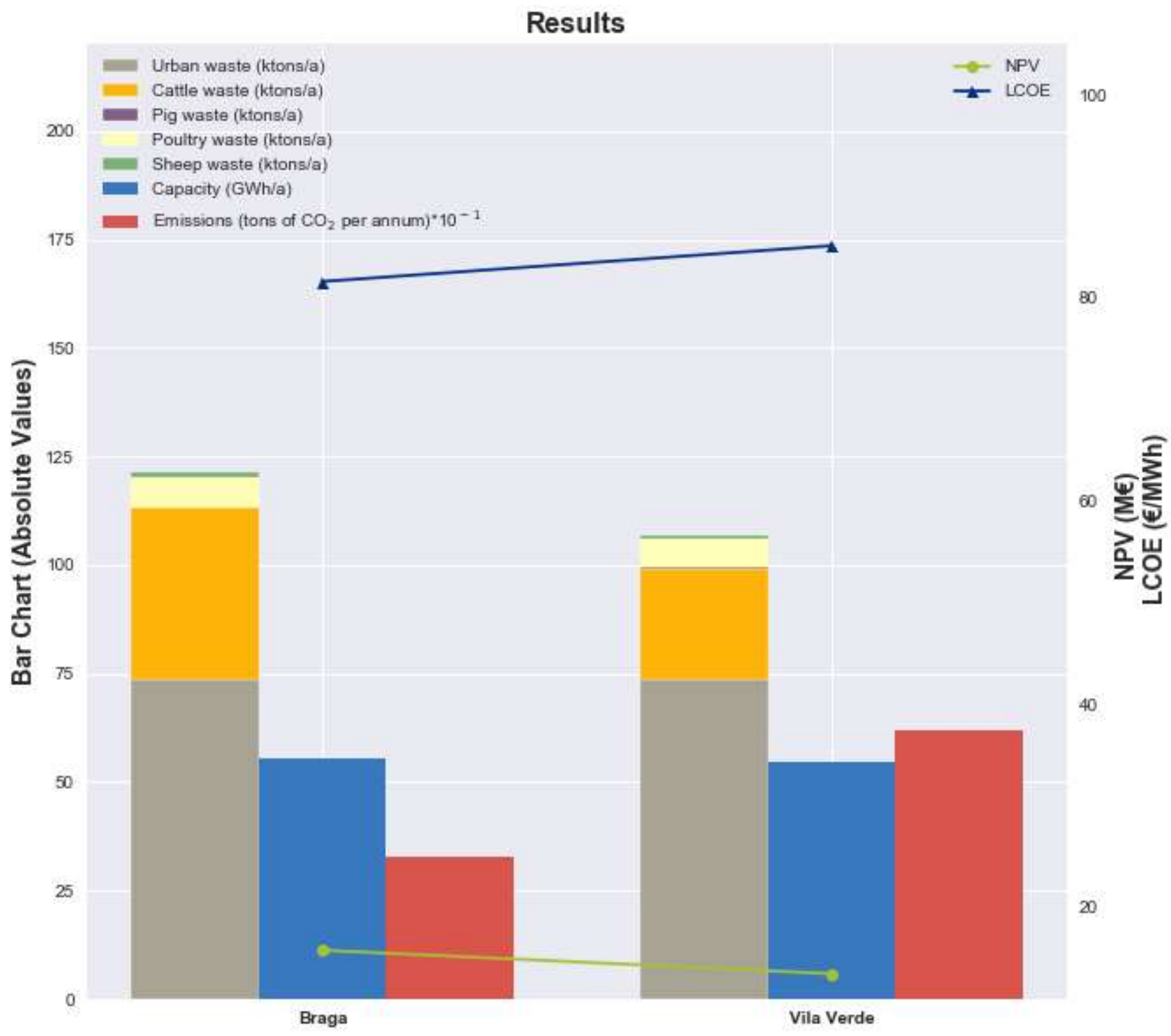

Figure 45. Results for the BRAVAL-Portgás joint concession

3.3.8 RESINORTE results

When analyzing the feasibility of building biomethane plant with a joint Portgás and RESINORTE concession it was found that the six municipalities shared in the concessions have and NPV greater than zero as shown in Table 25 and Figure 46.

Table 25. Plant built results for the RESINORTE-Portgás joint concession

Municipality	NPV [M€]	Transport Cost [k€]	Transport Emissions [ton/a]	Feedstock Revenue [M€]	Capacity [GWh/a]	CAPEX [M€]	OPEX [M€/a]	Revenue [M€/a]	LCOE [€/MWh]
Guimarães	17.9	295.3	353.5457	1.3	59.992	20.6	2.4	5.3	80.2
Vila Nova de Famalicão	17.4	333.2	447.5824	1.3	59.998	20.6	2.4	5.3	80.8
Trofa	16.9	373.9	479.7718	1.3	59.668	20.5	2.4	5.3	81.6
Santo Tirso	16.4	433.5	592.1848	1.3	59.978	20.6	2.4	5.3	82.5
Vizela	16.3	437.9	615.5344	1.3	59.933	20.6	2.4	5.3	82.6
Fafe	15.2	549.7	785.415	1.3	59.993	20.6	2.4	5.3	84.4

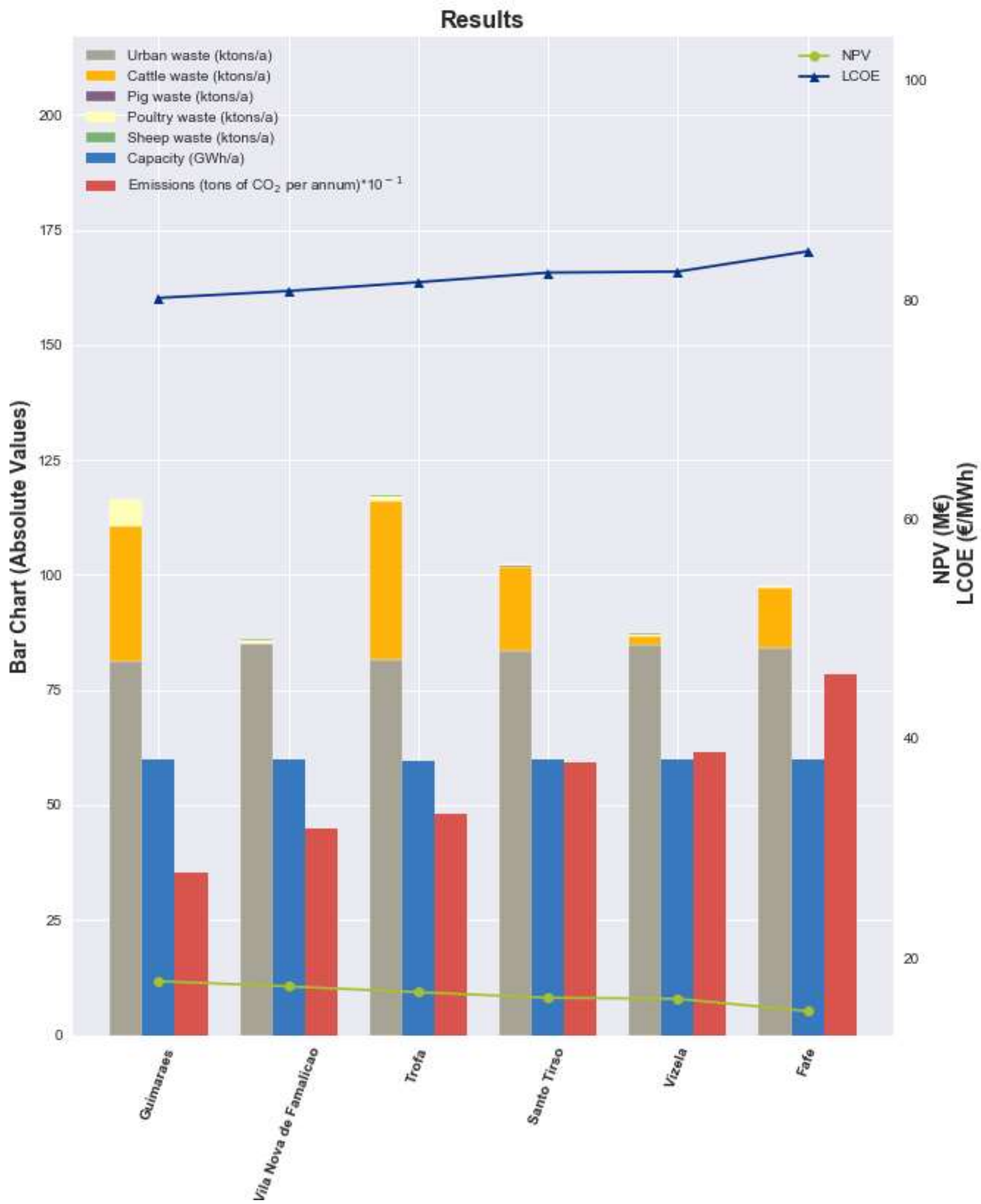

Figure 46. Results for the RESINORTE -Portgás joint concession

3.3.9 Lipor results

When analyzing the feasibility of building biomethane plant with a joint Portgás and Lipor concession it was found that the six municipalities shared in the concessions have and NPV greater than zero as shown in Table 26 and Figure 47.

Table 26. Plant built results for the Lipor-Portgás joint concession

Municipality	NPV [M€]	Transport Cost [k€]	Transport Emissions [ton/a]	Feedstock Revenue [M€]	Capacity [GWh/a]	CAPEX [M€]	OPEX [M€/a]	Revenue [M€/a]	Payback [Years]	LCOE [€/MWh]
Porto	33.8	98.5	24.1	1.9	87.546	27.0	3.4	7.8	6	71.4
Maia	19.0	189.6	183.9	1.3	60	20.6	2.4	5.3	7	78.4
Matosinhos	18.9	81.9	19.5	1.3	57.628	20.1	2.3	5.1	7	77.3
Valongo	18.1	214.6	248.3	1.3	58.754	20.3	2.4	5.2	7	79.3
Gondomar	17.7	176.7	192.8	1.2	57.207	20.0	2.3	5.1	7	79.1
Vila do Conde	17.0	360.2	490.6	1.3	59.774	20.6	2.4	5.3	7	81.4
Povoa de Varzim	16.0	455.1	644.1	1.3	59.815	20.6	2.4	5.3	8	82.9

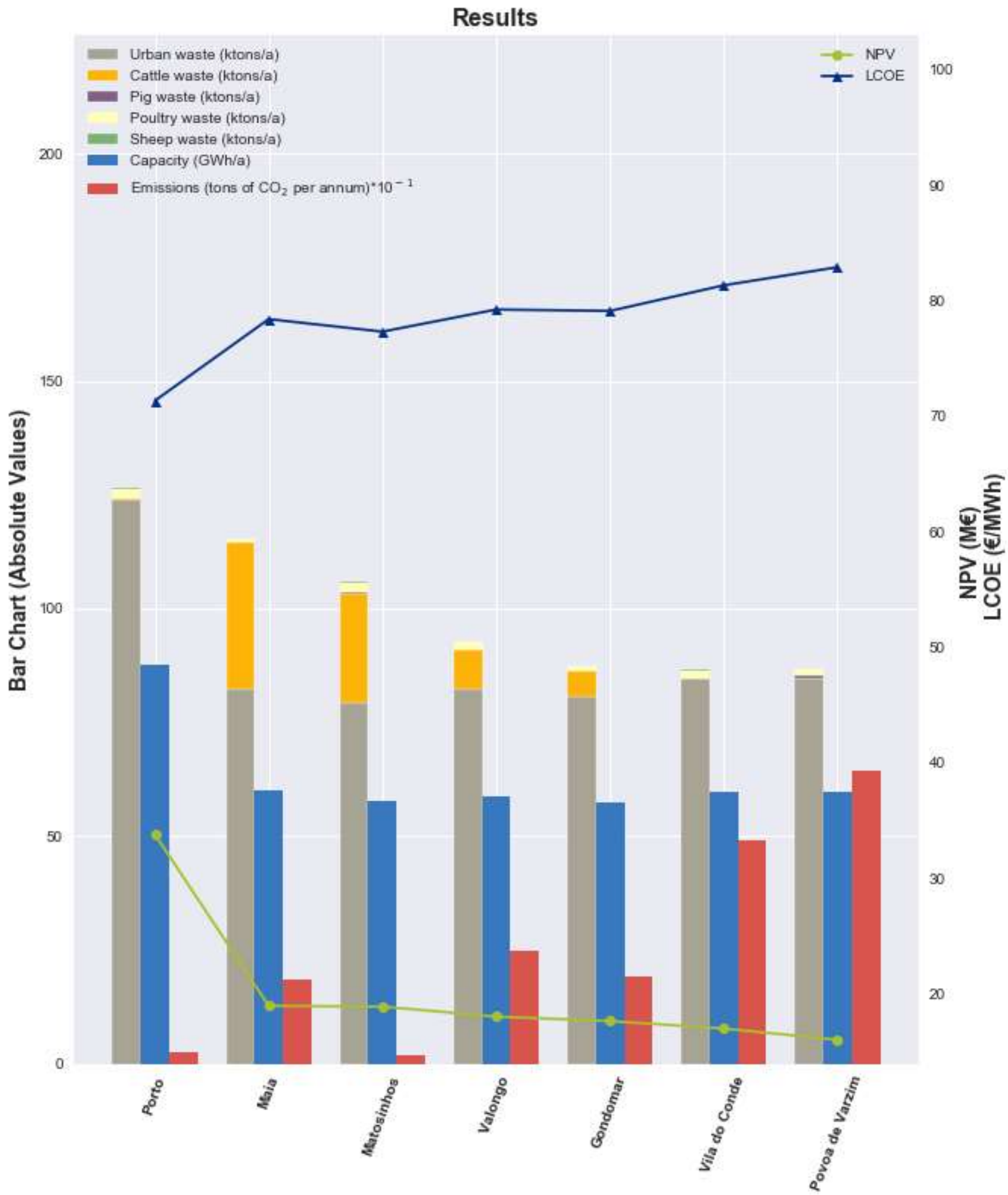

Figure 47. Results for the Lipor -Portgás joint concession

3.3.10 Ambisousa results

When analyzing the feasibility of building biomethane plant with a joint Portgás and Ambisousa concession it was found that the five municipalities shared in the concessions have and NPV greater than zero as shown in Table 27 and Figure 48.

Table 27. Plant built results for the Ambisousa-Portgás joint concession

Municipality	NPV [M€]	Transport Cost [k€]	Transport Emissions [ton/a]	Feedstock Revenue [M€]	Capacity [GWh/a]	CAPEX [M€]	OPEX [M€/a]	Revenue [M€/a]	Payback [Years]	LCOE [€/MWh]
Lousada	11.3	419.3	588.9	1.1	49.664	18.2	2	4.4	9	87
Penafiel	11.1	430.9	609.6	1.1	49.475	18.2	2	4.4	9	87.4
Paredes	10.9	444.5	631.4	1.1	49.432	18.2	2	4.4	9	87.7
Pacos de Ferreira	10.8	456.2	653.3	1.1	49.377	18.2	2	4.4	9	87.9
Felgueiras	10.1	538.0	778.3	1.1	49.782	18.3	2	4.4	9	89.3

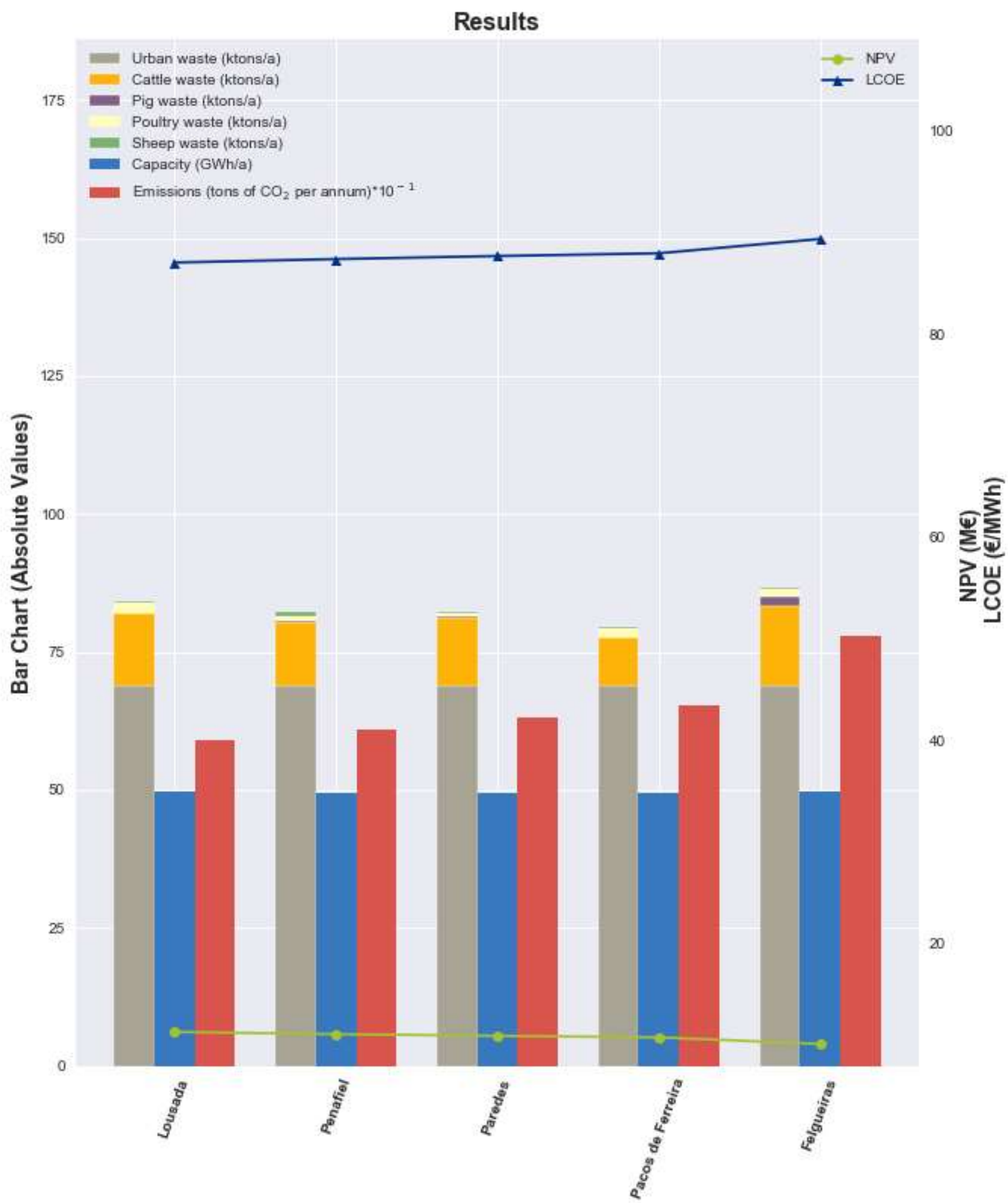

Figure 48. Results for the Ambisousa -Portgás joint concession

3.3.11 SULDOURO results

When analyzing the feasibility of building biomethane plant with a joint Portgás and SULDOURO concession it was found that Vila Nova de Gaia, the only shared municipality in the concessions, has an NPV greater than zero as shown in Table 28 and Figure 49.

Table 28. Plant built results for the SOLDOURO-Portgás joint concession

Municipality	NPV [M€]	Transport Cost [M€]	Transport Emissions [ton/a]	Feedstock Revenue [M€]	Capacity [GWh/a]	CAPEX [M€]	OPEX [M€/a]	Revenue [M€/a]	Payback [Years]	LCOE [€/MWh]
Vila Nova de Gaia	22.1	63.5	2.2	1.4	63.607	21.4	2.5	5.7	6	75.4

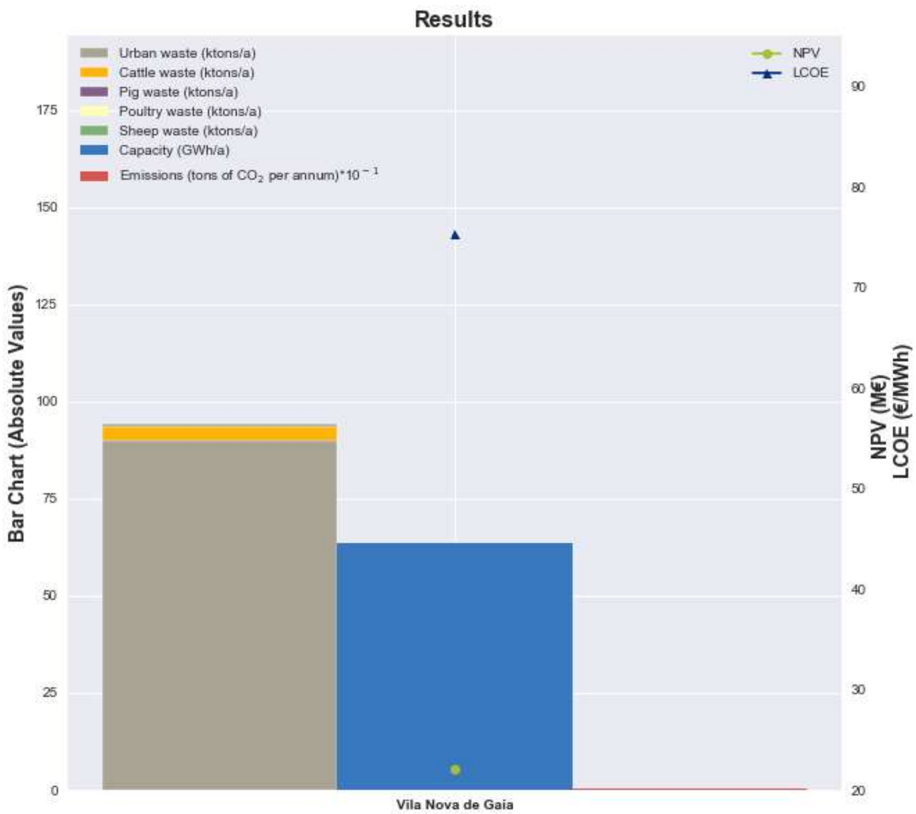

Figure 49. Results for the SULDOURO-Portgás joint concession

3.4 Conclusions of Locating Biomethane Plants Across The Portgás Concession Area

After observing an analyzing the results presented in the previous sections we can make the following conclusions and recommendations 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 since it will result in a loss for a company.

- Implementing the policies of the UK in Portugal leads to 10 out of the 29 municipalities in Portgás to have Positive NPV when considering resource depletion. Moreover, the top three investments (in order) under these conditions should be biomethane a plant in Porto, Vila de Nova Gaia and Matosinhos which have an NPV of 20.2, 14.9 and 13 M€ respectively.

- Implementing the policies of the UK in Portugal without resource depletion leads to all 29 municipalities in Portgás to have Positive NPV. Meaning that if a municipality of the preferred choices is not a feasible location due to external consideration, other municipalities could receive their waste in a model which results in a positive investment for the company.

- Considering Portugal under Swedish policy results in to 9 out of the 29 municipalities in Portgás to have Positive NPV when considering resource depletion. Moreover, the top three investments (in order) under these conditions should be biomethane a plant in Porto, Vila de Nova Gaia and Vila do Conde which have an NPV of 13.1, 7.0 and 5.8 M€ respectively.

- Considering Portugal under Swedish policy without resource depletion results in only 19 out of all 29 municipalities in Portgás to have Positive NPV. Meaning that if a municipality of the preferred choices is not a feasible location due to external consideration, other municipalities, but not all of them may receive the waste of the preferred ones leading to a feasible business model.

- Portugal under French policies leads to 9 out of the 29 municipalities in Portgás to have Positive NPV when considering resource depletion. Moreover, the top three investments (in order) under these conditions should be biomethane a plant in Porto, Vila de Nova Gaia and Matosinhos which have an NPV of 34.0, 23.4 and 19 M€ respectively.

- Considering Portugal under French policies without resource depletion results in all 29 municipalities in Portgás to have Positive NPV. Meaning that if a municipality of the preferred choices is not a feasible location due to external consideration, every other municipality may receive the waste of the preferred ones leading to a feasible business model.

- 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€.

- Under French policy conditions building biomethane plants limited only to joint concession partnership between VALORMINHO and Portgás is not feasible.

- Under French policy conditions building biomethane plants limited only to joint concession partnership between all other six wax management companies and Portgás results in feasible plants with NPV higher than zero.

3.5 Recommendations for future studies

To improve the work done and the tool developed the following recommendations are proposed:

- Further incorporate and regress data regarding CAPEX and OPEX of newer plants developed for higher capacities as means to account more accurately economies of scale as well as recent developments in biomethane production technology that lower overall costs.

- Incorporate salaries of heavy-duty vehicle drives into the transportation cost of biomass in order to account more accurately the transportation costs.

- Further consider actual plant build sites within a municipality as well as possible injection points as means to account more accurately the cost of transports and pipe length cost for injection.

- Add a capacity depletion feature in order to account for the capacity serviced when building a biomethane plant that cannot be covered by another plant built that share the same gas grid.

- Incorporated a transient cash flow feature into the algorithm that allows for change in natural gas price through the years as well as digression of incentives.

  IV.

- Incorporate a transient gas demand feature that accounts for changes in gas demand thought the year with possible solutions such as backhauling, pipeline flexibility and storage tanks.

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Annexes

A.1 Green Gas Planner

A.2 Example of decision output for sourcing waste streams

Table 29. Plant output example for sourcing waste

Plant Location: Porto Scenario: France	Cattle	Pig	Sheep	Poultry	Urban
Barcelos	0	0	0	0	0
Braga	0	0	0	0	0
Caminha	0	0	0	0	0
Esposende	0	0	0	0	0
Fafe	0	0	0	0	0
Felgueiras	0	0	0	0	0
Gondomar	0	0	0	0	0
Guimaraes	0	0	0	0	0
Lousada	0	0	0	0	0
Maia	0	0	0	692.67	0
Matosinhos	0	0	0	0	0
Pacos de Ferreira	0	0	0	0	0
Paredes	0	0	0	0	0
Paredes de Coura	0	0	0	0	1474.55
Penafiel	0	0	0	0	0
Ponte de Lima	0	0	0	0	0
Porto	254.5	0.46	2.552	0	123830.6
Povoa de Varzim	0	0	0	0	0
Santo Tirso	0	0	0	0	0
Trofa	0	0	0	0	0
Valenca	0	0	0	0	0
Valongo	0	0	0	783.66	0
Viana do Castelo	0	0	0	0	0
Vila do Conde	0	0	0	0	0
Vila Nova de Cerveira	0	0	0	0	2280.85
Vila Nova de Famalicao	0	0	0	0	0
Vila Nova de Gaia	0	0	0	0	0
Vila Verde	0	0	0	0	0
Vizela	0	0	0	0	0
Total	254.5	0.46	2.552	1476.33	127586