INTEGRATED MASTER IN ENVIRONMENTAL ENGINEERING 2019/2020

# ORGANIC WASTE IN SELECTED LOCATIONS IN NORWAY AND PORTUGAL – HANDLING AND TREATMENT

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*“A sorte existe, tem é de nos encontrar a trabalhar”*
*- Ditado Popular*

# Abstract

With the stress that the world is being submitted due to the population growth, a circular economy model must be achieved, reducing the need for unsustainable raw materials exploitation. Circular economy is accomplished when the used materials, energy and water are efficiently managed, namely through effective interconnections within the value chain. Therefore, waste generation must be prevented and whenever unavoidable, wastes should be valued as secondary raw materials. One example of circular economy promotion is the conversion of wastes into biomethane (to be used as a fuel), or into electricity. Among various technologies, this can be performed through Anaerobic Digestion and Hydrothermal Liquefaction.

The main focus of the present work was to present a comparison between Portugal and Norway, since the obtained product from the Anaerobic Digestion is different: the selected Norwegian plants - Romerike Biogas Plant (RBA) and Grenland Vestfold Biogas Plant (Greve) upgrade the biogas into biomethane and the selected Portuguese locations (Valorsul, Suldouro and Tratolixo) transform it into electricity. The Norwegian locations receive wet organic waste whilst in the Portuguese ones the input varies, being both from selective an unsorted collection. Additionally, since the Hydrothermal Liquefaction is still being developed, the obtained values were compared with those presented in the literature.

The comparison was performed considering different aspects: the waste handling & collection, the type of treatment that the waste is submitted to (presenting the respective process schemes) and the amounts of biogas produced and upgraded/transformed. In addition, an energy balance considering Valorsul and Greve plants was also performed. The analysed years were 2016, 2017, 2018 and, when applicable, 2019. Additionally, RBA's last four years of collection where evaluated in more detail.

The main differences between the Portuguese and the Norwegian plants was related to the characteristics of the waste streams (wet organic waste is selectively collected in 72% of Norway in 2019, contrary to Portugal) and the types of products obtained from the Anaerobic Digestion: whilst the Norwegian plants upgrade the biogas into biomethane, Portugal's transform it into electricity. Regarding biogas production, the highest absolute value was obtained at the Norwegian Romerike Biogas Plant (162.3 $Nm^3$/tonne), whereas mean values were higher from the Portuguese plant Tratolixo (131.8 $Nm^3$/tonne). In terms of electricity, Valorsul achieved the highest mean values concerning electricity production per treated waste (267.6 kWh/tonne). In what concerns the production of fertilizers, between the Norwegian's entities (producing liquid fertilizer) RBA produced the highest amount per treated waste (1.5, mass basis), and in the Portuguese locations, Tratolixo achieved the highest value (0.16, mass basis). The obtained energy efficiencies for the Valorsul and Greve were considered to be comparable (77% and 67%).

**Keywords:** Bio-waste, Biofuel, Anaerobic Digestion, Hydrothermal Liquefaction, Biogas, Compost

# Resumo

Com o *stress* a que o mundo está exposto devido ao crescimento populacional, é necessária a implementação do modelo de economia circular, reduzindo a necessidade de exploração insustentável das matérias-primas. Uma economia circular é alcançada quando os materiais, energia e água introduzidos são geridos de forma eficiente, nomeadamente através de interligações entre as diferentes fases da cadeia de valor. Desta forma, a produção de resíduos deve ser evitada e, sempre que inevitável, estes devem ser valorizados como matéria-prima secundária. Um exemplo da promoção de economia circular é a conversão de resíduos em biometano (posteriormente utilizado como combustível), ou em eletricidade. Tal pode ser efetuado através de tecnologias como Digestão Anaeróbica e a Liquefação Hidrotérmica.

O principal foco deste trabalho foi a comparação entre Portugal e Noruega, uma vez que o produto obtido da Digestão Anaeróbica é diferente: os sistemas Noruegueses selecionados - Romerike Biogas Plant (RBA) e Grenland Vestfold Biogas Plant (Greve) transformam o biogás em biometano e as entidades Portuguesas selecionadas (Valorsul, Suldouro e Tratolixo) transformam o biogás em eletricidade. Os sistemas Noruegueses recebem resíduos orgânicos húmidos, enquanto nas entidades portugueses depende, recebendo resíduos tanto de recolha seletiva como de indiferenciada. Além do mais, como a Liquefação Hidrotérmica ainda está em desenvolvimento, os valores obtidos foram comparados com valores da literatura.

Foram analisados diferentes aspetos: a recolha de resíduos, o tipo de tratamento a que estão submetidos (apresentando os respetivos esquemas de processo) e a quantidade de biogás produzido e convertido/transformado. Também foi realizado um balanço energético relativamente às instalações da Valorsul e de Greve. Os anos analisados foram 2016, 2017, 2018 e, quando aplicável, 2019. Adicionalmente, avaliou-se mais aprofundadamente os últimos quatro anos de recolha de resíduos da instalação RBA.

As principais diferenças entre as instalações estudadas foram em relação às características dos resíduos rececionados (resíduos orgânicos húmidos são recolhidos de forma seletiva em 72% da Noruega em 2019, antagonicamente a Portugal) e relativamente ao tipo de produto obtido pela Digestão Anaeróbica: enquanto que as plantas Norueguesas convertem o biogás em biometano, as Portuguesas transformam-no em eletricidade. Em relação à produção de biogás, em termos absolutos o valor mais alto foi alcançado pela entidade Norueguesa, Romerike Biogas Plant (162,3 Nm$^3$/tonelada), enquanto que em termos médios a Tratolixo obteve o valor mais alto (131,8 Nm$^3$/tonelada). Face à eletricidade, a Valorsul alcançou o valor médio mais elevado por resíduo tratado (267,6 kWh/tonelada). Relativamente à produção de adubos/matérias fertilizantes, entre as entidades Norueguesas (que produzem adubo líquido), a RBA obteve a quantidade mais elevada por resíduo tratado (1,5, base mássica) e, nas localidades Portuguesas, a Tratolixo alcançou o maior resultado (0,16, base mássica). As eficiências energéticas obtidas para Valorsul e Greve foram consideradas comparáveis (77% e 67%).

**Palavras-chave:** Biorresíduos, Biocombustível, Digestão Anaeróbica, Liquefação Hidrotérmica, Biogás, Composto

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# Preface

This thesis is part of the WASTE2ROAD project, an EU funded project whose purpose is the development of cost-effective advanced biofuels from feedstocks like municipal waste, pulp from the paper industry and contaminated wood.

The aim of this work, as part of the project, is to analyse the data of three years of collection, sorting and treatment of biological waste, from the city of Oslo – data from EGE (Waste Management Agency in Oslo Municipality in Norway). With this, and other general conclusions, it will be possible to understand Norway's position towards bio-waste, how it is being handled. Therefore, EGE was included in one of the comparing entities on this document.

More information about the project is available on its website [1].

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# List of Abbreviations

AD - Anaerobic Digestion

APA - *Agência Portuguesa do Ambiente* | Portuguese Environmental Agency

BM - Biomethane

CBG - Compressed Biogas

DCO – Decarboxylation

EC – Energy Content

EEA – European Economic Area

EGE - *Energigjenvinningsetaten* | Oslo Municipal Waste-to-Energy Agency

EGF - Environment Global Facilities

ER – Energy Recovery

EU27 – European Union without United Kingdom (Brexit)

FAME - Fatty Acid Methyl Esters

FCC - Fluid catalytic cracking

GHG - Greenhouse Gas Emission

HC – Unburnt Hydrocarbons

HEFA - Hydrotreated Esters and Fatty Acids

HHV - Higher Heating Value

HPO - Hydrotreated Pyrolysis Oil

HRT - Hydraulic Retention Time

HTL - Hydrothermal Liquefaction

HVO - Hydrotreated Vegetable Oil

ILUC – Indirect Land Use Change

LBG - Liquid Biogas

MBT – Mechanical Biological Treatment

NGV – Natural Gas Vehicle

ORS - Organic Recovery Station

PM – Particulate Matter

POSEUR - *Programa Operacional Sustentabilidade e Eficiência no Uso de Recursos* | Operational Programme for Sustainability and Efficient Use of Resources

RBA – Romerike Biogas Plant

RED - Renewable Energy Directive

RES – Renewable Energy Share

RES-E – Renewable Energy Share, Electricity sector

RES-T – Renewable Energy Share, Transportation sector

RIG – Renovasjon in Grenland

TOC – Total Organic Carbon

TS - Total Solids

UW - Unsorted Waste

VFA - Volatile Fatty Acid

WWT – Wastewater Treatment

WWTP – Wastewater Treatment Plant

# Chapter 1. Introduction

In this chapter the relevance and motivation as well as the objectives established for this dissertation will be presented in order to give the reader a better understanding of the work developed. It will also tackle the document structure to make it easier to follow its content.

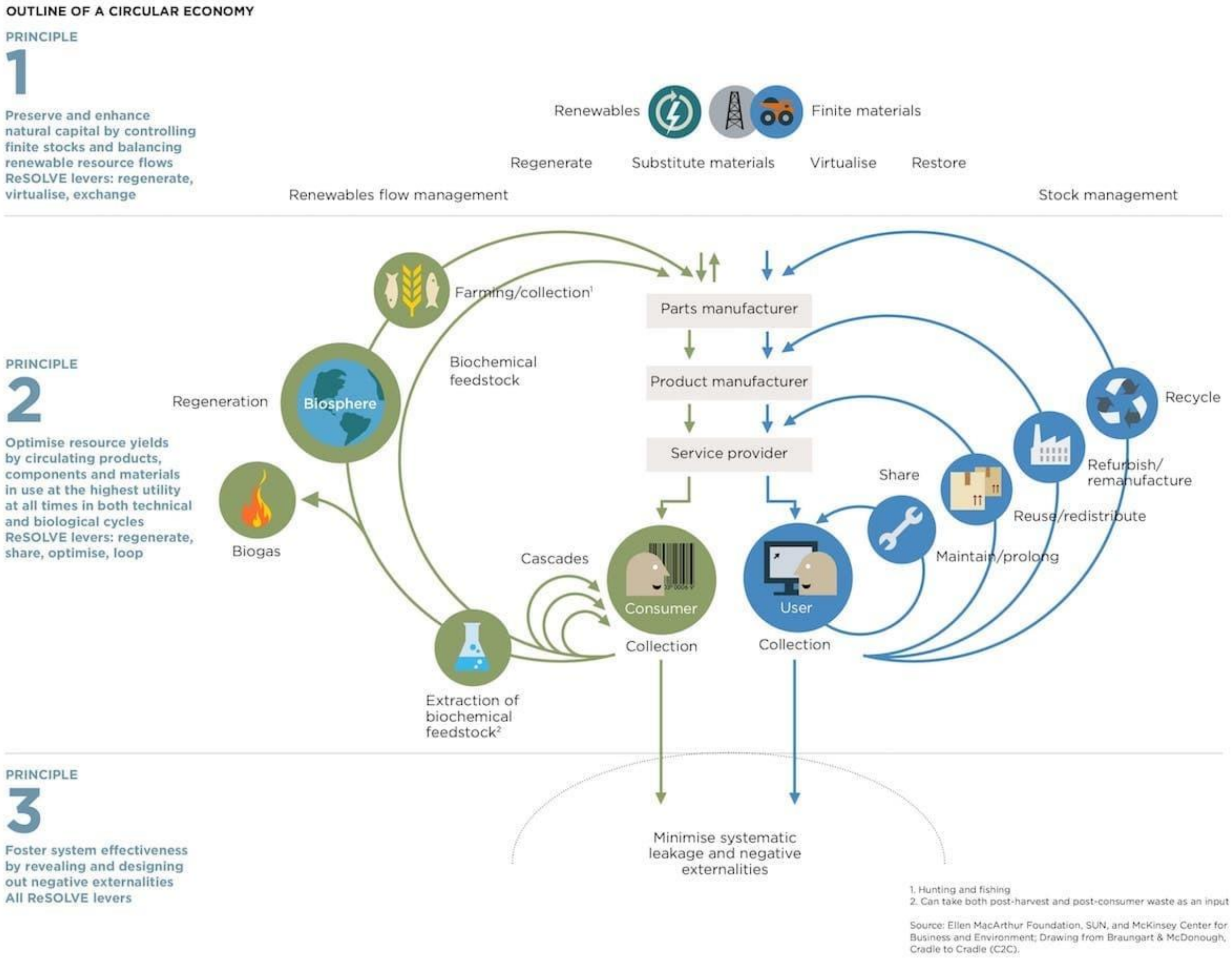
## 1.1. Relevance and Motivation

Society's economy is still mostly based on a *linear model*. With the world's population growth, both the environment and human health are submitted to stress. Thus, raw materials exploitation and use, once considered to be unlimited, leading to unlimited waste, needs urgent intervention. To ensure the basic needs for future generations, with enough resources like food and water and an overall well-being, a shift to a *circular economy* must take place.

The first step to reach it is an evolution to a *reuse economy*, that keeps the products in use at their highest value and utility and avoids their unnecessary discard. In such a model, the recycling takes place for some used products which cannot be further used. After including a wide range of possibilities and interconnections in the value chain, a *circular economy* can be achieved. The final goal is therefore the closure of the cycle, with an efficient reuse, recycle and other forms of recovery, with the optimum use of the materials, energy and water. This can be enabled by business models of recovery and recycling , boosted for instances by industrial symbiosis, that allows sharing both energy, water and materials, attributing value to other industries' waste, and thus reintegrating them in their production chain in a sustainable way. In both economies (*reuse & circular*) waste obtains a status of a product – or a secondary raw material. In the European Union, this is defined as the «End-of-Waste» criteria. In Figure 1-1, an example of a circular economy model is presented [2, 3].

To help this shift, the EU compiled the Circular Economy Package, that tackles all phases of the lifecycle of a product, from cradle-to-grave. Among others, food waste and biomass and bio-based products are highlighted, with some actions being proposed to promote the circularity [4].

As the years go by, an interest for 'cleaner' resources has increased, largely due to the stress to which the Earth has been exposed to, manifesting itself mainly in Climate Change.



1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

FIGURE 1-1 – OUTLINE OF A CIRCULAR ECONOMY, ADAPTED FROM THE ELLEN MACARTHUR FOUNDATION [5]

According to the International Energy Agency (IEA), in 2018, the share of fossil fuels (Coal, Oil & Natural Gas) accounted for 81% of World Primary Energy Demand, totalizing 11 595 Mtoe – meaning that 33.2 Gt of CO2 were released. In order to achieve the ideal sustainable development, IEA proposes a 9% decrease in demand for fossil fuel energy in 2030 (totalizing 72%) and a reduction in fossil fuel demand to 58% in 2040. At the same time, according to Eurostat, in the European Union[1], about 250 474 thousand tonnes of municipal waste were produced in 2018, with 98% of it being treated (the remaining 2%, includes rejects). From the treated waste, 42 506 thousand tonnes of both sorted and unsorted waste, were estimated to be sent to composting and anaerobic digestion (AD), corresponding to about 17.3% [6, 7].

IEA states that over one billion tonnes of organic based products per year are not correctly handled, being just thrown away or abandoned. It should be noted that the methane which bio-waste releases is more harmful for the environment than $CO_2$ – besides the well-known global warming effect, $CH_4$ also contaminates land and groundwater. Additionally, according to Renewable Energy

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[1] Statistics include the UK

Directive (RED), the effect of methane is 25 times that of $CO_2$, on a weight basis [8]. If bio-waste was managed in an appropriate way, not only it would tone down the environmental pressures but would also provide renewable sources of energy: biogas or biofuels.

EU is aware of this and thus, by December 2023, it established that bio-waste must be sorted and recycled at source or collected separately and not mixed with other waste types, although, if any constraints regarding environmental impacts, technical or economic issues arise, member states may be allowed derogations. With the creation of a specific flux of bio-waste[2] – as it is imposed by Directive 2018/851/EU (amending Directive 2008/98/EC), the tonnes of waste sent to composting and to AD (traditional end-use solution) could be higher and it would avoid the harmful discard of organic waste and so, the energy harnessed from bio-waste could reach higher numbers [8].

Biogas has a number of uses in different areas like heating, electricity and recently in the transportation, as biomethane, an advanced biofuel (i.e. if produced from feedstocks listed in part A of annex IX of RED such as manure or waste), being some of its advantages the reduction of $CO_2$ emissions since it's a "clean-burning fuel". Greve's Sustainable Biogas project concluded that biogas is one of the most 'environmental friendly' fuels available by calculating the environmental impact per kilometre of bus transportation in the market when compared to natural gas, electricity from hydroelectricity, electricity from coal power, biodiesel and fossil fuels [10].

In 2017, around 30 Mtoe of biogas were produced in the world, being 90% of this produced in Europe, China and United States. About 60% of the biogas production was used for electricity and heating, and only 8% was upgraded to biomethane, with a very small amount used for transportation. There is however a potential of over 570 Mtoe of biogas that could be produced in a sustainable way, therefore, with the evolution of technologies, biogas can be a great renewable source and in 2040, this value could increase to 880 Mtoe. These numbers take into account crop residues, animal manure, municipal solid organic waste and wastewater. In IEA's Stated Policies Scenarios, biogas production would grow 7% each year and so, by 2040, over 70 Mtoe of biogas would be consumed directly as power, with 80 Mtoe being upgraded to biomethane. In the Sustainable Development Scenario, in 2040 nearly 120 Mtoe could be directly consumed as power with 200 Mtoe being upgraded. If supportive policies were enforced, biogas & biomethane could be great products with various advantages; however, for now, the production cost can be slightly more expensive, with the average cost being about 0.04$/kWh, while fossil fuels are about 0.03 $/kWh [6]. According to Witcover and Williams, the cheapest biofuel would be obtained through pyrolysis and could reach an average cost of 0.14$/kWh [11, 12].

The newest policy that also enhances not only the biogas production but also the biofuel production is the Renewable Energy Directive II (2018/2001/EU) [8] that entered into force in December of 2018. This Directive defines goals to be achieved by the member states, regarding shares of renewable energy, divided into generated electricity, use in transports, and consumed for heating

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[2] Includes «biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises and comparable waste from food processing plants» [9]

& cooling. By the year 2020, 20% of EU's energy must come from renewable sources, whilst a 10% share of renewables must be associated to the transport sector.

Therefore, in order to give a possible answer to the presented problems, the Waste2Road EU funded project, summarized in Figure 1-2, aims to achieve circular economy by transforming waste (household, paper industry pulp & contaminated wood streams) into advanced biofuels. This is obtained through primary conversion of the waste (Pyrolysis & Hydrothermal Liquefaction (HTL) technologies) in which the bio-liquids will be submitted to intermediate refinery processes in an already existent infrastructure, with co-processing technologies (Co-Fluid Catalytic Cracking (FCC) & Co-Hydrotreating) [1].

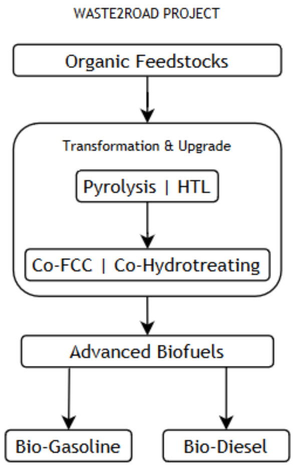

FIGURE 1-2 -SIMPLE SCHEME OF THE WASTE2ROAD PROJECT, ADAPTED FROM [1]

## 1.2. Objectives

An overview of the present status in specific countries such as Norway and Portugal regarding collection & treatment of municipal organic waste was conducted, in order to pinpoint the differences and draw conclusions, that could lead to a better handling and optimization on the use of this resource.

In a more specific scope, the objective was to evaluate two current technologies available to transform & upgrade waste to biofuels and biogas (biogas production and HTL), through household bio-waste recovery, having the Waste Management Agency in Oslo Municipality (EGE) and Grenland Vestfold Biogas (Greve) from Norway and from Portugal, Valorsul, Suldouro and Tratolixo as three main examples. It will be shown and evaluated the waste handling, treatment schemes and transformation of waste (into biomethane for the Norwegian locations and electricity for the Portuguese ones). There will also be presented a simple energy balance between Valorsul and Greve, a brief summary of the mentioned technologies along with the comparison between them and their established conditions. A discussion about the nutrient cycle will also take place.

This thesis is expected to provide future perspectives in this field in order to achieve national targets and circular economy in the waste treatment field, by using waste as a secondary feedstock.

## 1.3. Document Structure

The present document is organized into 6 main chapters, being presented below a brief description of each one.

The document starts with chapter 1, named “Introduction” which aims to present to the reader the relevance and motivation behind this work and the respective objectives.

It is followed by chapter 2, named “State of Art”, which tackles relevant knowledge about the addressed theme, such as the classification and understanding of biofuels and ‘drop-in’ biofuels, renewables in the European Union context and an overall introduction to the pertinent technologies – the Anaerobic Digestion and Hydrothermal Liquefaction.

In chapter 3, named “Methodology”, the 5 study locations are introduced with a short description of each (EGE, Greve, Valorsul, Suldouro and Tratolixo) and it is explained how the data about the systems was collected.

In the following chapter 4, named “Data & Interpretation”, all the gathered information about the 5 systems is presented, regarding its waste and biogas & compost data, followed by the respective interpretation of the shown tables and figures.

In the penultimate chapter, chapter 5, named “Discussion”, the information introduced in the previous chapter is discussed, presenting a simple energy balance between Valorsul and Greve, comparing the different products of the Anaerobic Digestion (biogas upgraded to biomethane and biogas transformed into electricity) and an overall comparation between both technologies: Anaerobic Digestion and Hydrothermal Liquefaction.

Finally, in chapter 6, named “Conclusions”, the most significant conclusions of this work are presented, along with the limiting aspects to it and possible future studies.

# Chapter 2. State of the Art

In this chapter, relevant knowledge about the addressed theme, such as the classification and understanding of biofuels and ‘drop-in’ biofuels, renewables in the European Union context and an overall introduction to the pertinent technologies – the Anaerobic Digestion and Hydrothermal Liquefaction will be presented.

## 2.1. Biofuels Classifications and Definitions

As it is known, fossil fuels are a non-renewable source, mainly composed of carbon, hydrogen, nitrogen, and sulphur, which are generated from geological processes evolving long dead organisms (about hundreds of millions of years old). It is considered to be a store of solar power since its energy is stocked mainly from the sun, and its biggest issue nowadays relates to its burning, resulting in a noxious amount of GHG [13].

On the other hand, biofuels' feedstock is biomass, mainly plant matter and 'food-based' products. This product is a renewable source of energy since plant crops can be reproduced at the current rate of consumption (although full compensation considering the whole life cycle of the biofuels production is not achieved). According to Directive 2018/2001, biofuels are liquid fuels for transport produced from biomass. The main environmental difference between biofuels and fossil fuels is related to the released $CO_2$ through combustion. Both of these products release $CO_2$, however, the mass balance differs. As biofuels use recent crops as feedstock, the released $CO_2$ is balanced by the $CO_2$ uptake during the feedstock growth, thereby not contributing to additional amounts of long saved $CO_2$ being released into the atmosphere as the fossil fuels do. Nevertheless, life cycle analyses are still needed in order to have a more detailed assessment of the environmental impact – although it is possible to find typical values of greenhouse emissions and thus savings in the RED. As it was mentioned, the feedstock used is distinct from fossil fuels, thus this product cannot be efficiently used in the already existent petroleum infrastructure, unless modified engines are used. If not, they can only be exploited in low blends (ethanol maximum 15% and biodiesel 20%) [8, 14, 15].

Biofuels can be split into two categories: conventional (first generation) biofuels and advanced biofuels. The first generation of biofuels refers to biofuels that are produced from food crops, like sugar, starch, and vegetable oils. The main controversy about these fuels is that they use feedstock which can be also used for food and feed, questioning its ethics and sustainability. On the other hand, advanced biofuels do not compete directly with food and feed crops. Advanced bioenergy uses advanced biofuels (also known as second and third generation biofuels) to produce energy with high GHG reduction reaching zero or low ILUC impact[3]. After a pre-treatment of the biomass, these biofuels are mostly produced through physical, thermochemical (e.g. pyrolysis, gasification, liquefactions, and direct combustion) and biochemical processes. A low ILUC impact means that there will not be an imperative necessity of transforming land use (for example a forest into an agricultural land) since there is no competition between the crops' usage. In the conventional biofuels' case, the usage of feedstock that is also utilized as a food or feed, results in a need to create additional food crops, because the demand is still there [17, 18].

According to the Directive 2018/2001 [8], the advanced biofuels are biofuels which are produced from the feedstock list present in the annex IX of the Directive. In other words, produced from lignocellulosic feedstocks, non-food crops, industrial waste, and residue streams. Some worthy of mention are algae if cultivated on land or ponds in photobioreactors, biomass fraction of mixed municipal waste, biowaste fraction from private households with separate collection and from industrial waste which do not fit for use in the food or feed chain, animal manure and sewage sludge, biomass fraction of wastes and residues from forestry and forest-based industries, among others. The minimum shares in the transport sector originated from the contribution of the advanced biofuels and biogas used in transportation which uses the stated feedstocks (14% in the transport section and 3,5% of advanced biofuels' use for the EU27 by 2030) can be considered twice the amount of their energy content.

## 2.2. Renewables in EU's Transportations & National Targets

In 2018, the Directive 2018/2001 [8] emerged to clarify all the emends that were made throughout the years to the Directive 2009/28 [19]. It establishes mandatory goals regarding the use of renewable energy in different sectors such as electricity (RES-E), transport (RES-T) and heating and cooling (RES-H&C). Together, these three sectors, are the total renewable energy share (RES). It also distinguishes important concepts such as 'bioliquids', 'biofuels' and 'advanced biofuels', and presents a list of what feedstocks are acceptable to produce biogas for transport and advanced biofuels (annex IX of the Directive 2018/2001).

The national overall renewable energy targets are presented in Annex I of the directive, and in Table A-1 of the present document. As it can be seen, Norway is not stated in the document (due to not being a member of European Union), however the country decided to establish its own goals (as other non-member states, yet part of the EEA, did). The comparison between Norway and Portugal's status and their respective goals are presented in Table 2-1.

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[3] «ILUC (Indirect Land Use Change) can occur when pasture or agricultural land previously destined for food and feed markets is diverted to biofuel production» [16]

TABLE 2-1 - RENEWABLE ENERGY TARGETS FOR THE EU AND SPECIFICALLY PORTUGAL AND NORWAY, ADAPTED FROM [8, 20-22]

| | | Value 2018 [%] | Target 2020 [%] | Target 2030 [%] |
|---|---|---|---|---|
| RES | EU27 | 18.88 | 20.0 | 32.0 |
| | PT | 30.32 | 31.0 | 47.0 |
| | NO | 72.75 | 67.5 | - |
| RES-T | EU27 | 8.26 | 10.0 | 14.0 |
| | PT | 9.04 | 10.0 | 20.0 |
| | NO | 1995 | 10.0 | - |

Regarding the specified countries, Norway showcases a very positive development, achieving their proposed target already in 2014, with a percentage of 69.19 of renewable energy. The value further increased in the following years, achieving an overall share of 72.8% in 2018. In the transportation sector, the country exceeded the 10% target in 2016 with 13.72% of renewables, increasing its value 6.23% in 2 years. Norway has a join cooperation with Sweden, since 2012, sharing the costs and benefits 50-50 (for additional information on this cooperation see section 2.3.1 of [23]). As for the 2030 target, up until now (2020) Norway has not defined/made public its goals. Opposite to Norway, Portugal in 2018 did not meet its 2020 target – however it was close, with a small gap of 0.68%. Similarly, in the transportation sector, its 2018 was only about 1% away from its desired value.

Among all the member states, 12 already reached its target: Bulgaria, Czechia, Denmark, Estonia, Greece, Croatia, Italy, Latvia, Lithuania, Cyprus, Finland, and Sweden – with the highest share (54.6%). From the non-member states, Iceland, Norway, and Montenegro also overcame their target, with the highest value being achieved in Norway [21].

## 2.3. Biogas Technologies

### 2.3.1. Anaerobic Digestion

The anaerobic digestion of food waste is very attractive due to its high degradability and quick hydrolysis (the first step). The chemical reactions inside the reactor can be divided into 4 main stages (see Figure 2-1) [24, 25]:

- Hydrolysis – where biopolymers are broken into monomers, e.g. fatty acids, glucose, amino acids.
- Acidogenesis – where the monomers are fermented, creating mainly volatile fatty acids, pyruvic acid, acetic acid, formic acid.
- Acetogenesis – where transformation of the last step's product into $CO_2$, $H_2$ and acetic acid takes place.
- Methanogenesis – where $H_2$ and acetic acids are converted to $CH_4$ and $CO_2$ in the end.

It should be noted that hydrolysis can be considered the rate-limiting step due to its tendency to also produce toxic by-products and non-desirable VFA. However, a common conclusion is that an efficient pre-treatment (e.g. particle size reduction and heating) can overturn a poor hydrolysis [25].

A lot of different factors influence the production of biogas, such as temperature, pH, C:N ratio, %TS, HRT, among others. It should also be noted that these parameters differ among hydrolysis/acidogenesis and methanogenesis phases. However, the main obstacles in this process is the inhibition by ammonia and VFA [24, 25].

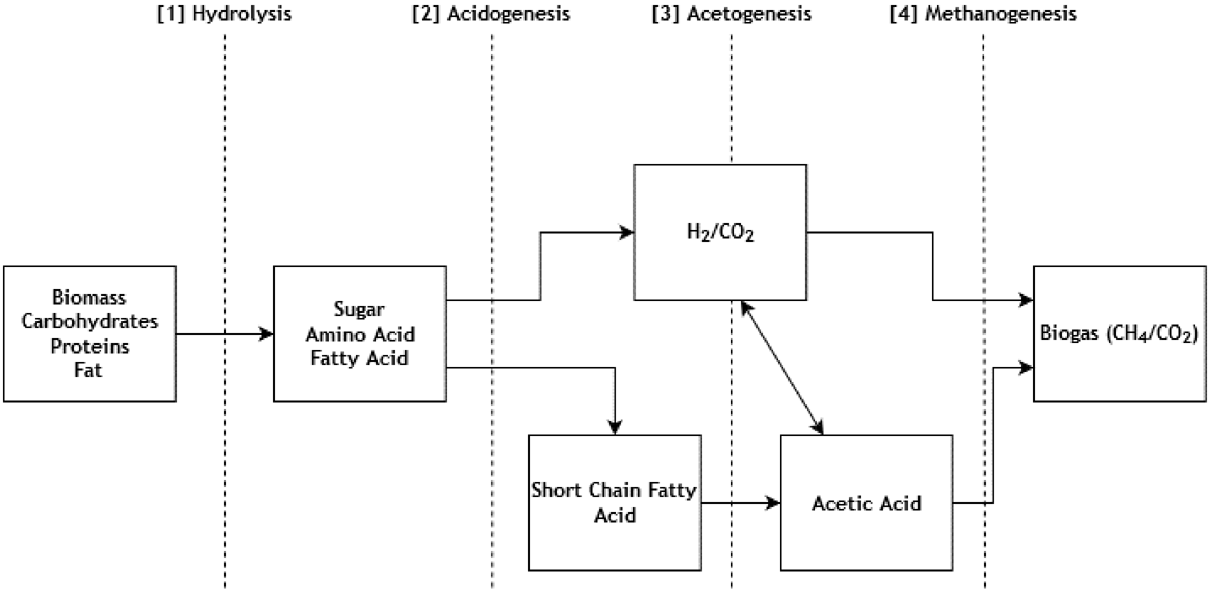

FIGURE 2-1 - STAGES OF ORGANIC MATERIAL DEGRADATION BY MICROORGANISMS UNDER ANAEROBIC CONDITIONS, ADAPTED FROM [26]

Due to food waste's low C:N ratio (high nitrogen content), not only excessive ammonia will be produced[4] - increasing the pH of the mixture - but it will also enhance rapid acidification, making the system unstable. The excessive ammonia causes deterioration and inhibitory effects to the bacterium, such as the increase of maintenance energy requirements and inhibiting specific enzyme responses. To avoid this, there are both physical and chemical options. With air stripping, as ammonia is partially present as a dissolved gas, some of it will be transferred to the air, keeping the equilibrium. In some systems this air stripping are small concentrations of biogas. The removed ammonia can be recycled and used in products such as a nitrogenous fertilizer. Precipitation reactions are also used to partially remove this substance [24, 25].

The mentioned rapid acidification means that there is a high growing rate of acid-producing bacteria which slows the methanogenic bacteria and results in an excessive presence of VFAs. This accumulation decreases the pH. Electrodialysis and ion exchange prevent the proliferation of VFAs -

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[4] $NH_3 + H^+ \rightarrow NH_4{}^+$

which react with the free $NH_4^+$ and provide a weak buffering system. To avoid this, the alkalinity of the medium must be considered [25].

The low C:N ratio can be improved by mixing the entering feedstock with another of low nitrogen content, like cardboard waste - studied by Capson-Tojo et al [27]. In other words, co-digestion of different substrates can help to avoid the above-mentioned problems and can be a more economic route. Other substrates with positive outcomes in co-digestion include seaweed waste [25].

Even though there is a lot of discussion about what the ideal temperature for methanogenic bacteria is, it is widely accepted that it is within the mesophilic range, between approximately 30ºC and 38ºC, and in the thermophilic range, between 47ºC and 49ºC. It was verified that under thermophilic conditions (50-60ºC) there is more inhibition by ammonia accumulation and a better hygienization [24, 28]. The hydraulic retention time varies with the used technologies, temperatures and, of course, waste composition – for vegetable residues the HRT needs to be higher. It can vary from 10 days up until 40 days. According to a literature review performed by Mao et al in 2015 [29], the ideal parameters were an HRT of 15-30 days to treat waste under mesophilic conditions – between 30ºC and 38ºC [25, 29, 30].

To enhance the biogas production yield, there is a need for both physical and biological pre-treatments. The physical treatment involves mechanical and heating processes. The mechanical processing of the feedstock is mainly to decrease the particle size so that the surface area increases, positively affecting the performance of the degrading bacterium (resulting in a better contact). However, undersize particle will influence the VFA excessive presence. On the other hand, the heating treatment is used to promote the hydrolysis process. Regarding the biological treatment, its studies and implementation at an industrial scale are recent and being continuously improved regarding food waste treatment. The addition of ethanol on a pre-fermentation stage has been proved to control the VFA concentration, propionic acid, and acetic acid, preventing acidification. In a study by Zhao et al [31], ethanol was introduced in a pre-treatment stage (that lasted 2,5 days) and its effects evaluated, at 37ºC and 60rpm, collecting samples every 12 hours. The methane yields were 49.6% higher when compared to the control group, also lowering the population of unwanted pathogens like *E.coli* [25].

In traditional reactors, the process can happen in a single-phase, where all reactions take place or in a two-phase system, where hydrolysis and acidogenesis occurs in the first reactor and the other two take place in the second one. The singe-phase is usually chosen due to its design simplicity. On the other hand, a two-phase system has been proved to be more efficient due to its more controlled nature [25].

In Europe, most of the waste management systems have mechanical biological treatments (MBT), which treats not only household waste but also industrial and commercial waste. Due to its different natures, a pre-treatment is required to enhance its homogeneity. In Portugal, the present MBT plants only treat municipal waste. Such process also requires a digestate treatment (so it can be stabilized) among other necessities, which increases the processing costs, limiting the capacity of the plant. It was concluded in a study done by Di Maria et al [32] that the addition of a solid state anaerobic digestion step (where TS% content is superior to 25%) can help tackle this economic issues. This biogas can be upgraded to biomethane through technologies such as absorption, adsorption, membrane separation and cryogenic separation [33].

Recirculation of the biogas and the digestate can also help the efficiency of the plant. The recirculation of biogas promotes its purification and the transformation of $CO_2$ into $CH_4$. On the other hand, by recirculating the digestate it lowers its emissions, also helping the dilution of organic loading and the increase of pH buffering capacity [25].

Lately, there has been studies, performed by Venkata Mohan et al and Uçkun Kiran et al. [34, 35] on how to combine the anaerobic digestion of food waste in a biorefinery processing model.

## 2.4. Drop-In Biofuels Technologies

First, it is important to understand what really are 'drop-in' biofuels and what is their difference when compared to regular biofuels and fossil fuels.

'Drop-in' biofuels refer to biofuels whose properties are equivalent to the petroleum derived ones and can indeed use fossil fuels designed engines and infrastructures. While conventional biofuels refer to specific functional groups, like bioethanol or biodiesel (FAME), among others, with distinctive chemical compositions, 'drop-in' biofuels are a mixture of hydrocarbons - therefore, they are specified by their properties and not composition - which need to be oxygen-free in order to be functionally equivalent to petroleum-derived fuels [15, 36, 37]. In this sense, additional purification is needed. Some examples are HVO and HPO, being HVO descripted in the section 2.4.1.1.

As so, in order to show similar properties as conventional biofuels, there are some requirements that need to be checked like the hydrogen to carbon (H/C) ratio and the oxygen content.

The reason why oxygen must be removed from drop-in biofuels is because this element, present in groups such as esters, ethers, and hydroxyl groups, is not compatible with the petroleum infrastructure leading to corrosion problems. The presence of oxygen can also lead to the creation of gums and acids (among others) degrading the storability and stability of biofuels. Additionally, the existence of oxygen reduces the biofuels' energy density - the lower the energy density, less is the amount of energy stored in its mass, meaning that a bigger storage tank would be needed, affecting among others the traveling range. In other words, its provides undesirable qualities such as low heating value, incompatibility with conventional fuels, higher viscosity, incomplete volatility and chemical instability [15, 38, 39].

The mentioned deoxygenation can be achieved through three ways: decarbonylation, decarboxylation (DCO) and hydrodeoxygenation. The important distinction between them is the products they form (CO+H2O; CO2; H2O). A general scheme is presented in the Figure 2-2 below.

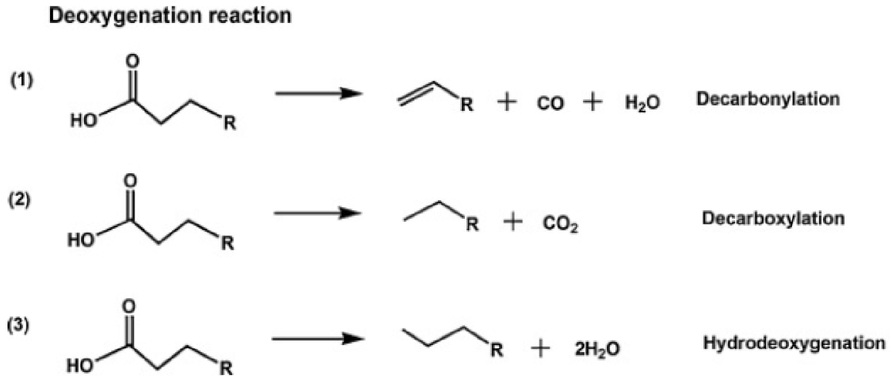

FIGURE 2-2 - THREE MAIN DEOXYGENATION REACTIONS, TAKEN FROM IEA BIOENERGY [15]

While in (3) the $H_2$ is oxidized with oxygen (and therefore removed as $H_2O$), in (1) and (2), oxygen is removed as CO or $CO_2$, reducing the yield of hydrocarbons, which is undesirable. In Hydrodeoxygenation a better efficiency is achieved with external input of $H_2$, but this translates in higher associated costs. Plus, it may not be environmentally sustainable if fossil hydrogen has to be used. DCO is then preferable when there is no external source of hydrogen. Finally, there has to be additional care regarding the products: in most cases CO and $CO_2$ have to be removed in order to avoid chemical and physical problems [15].

The hydrocarbon fuels are composed mainly of three compounds: paraffins, naphthenes and aromatics. Each class ends up having different hydrogen to carbon ratio (H/C). Low H/C ratios occur in intermediates such as sugar and cellulosic biomass (with high oxygen content and low hydrogen) and high H/C ratios occur for lipids and diesel. Therefore, this parameter ends up being a more easy and direct way of describing the fuel's chemical properties. The ideal H/C for 'drop-in' biofuels is near 2, so that it falls on the same range as diesel (as mentioned), jet and gasoline. This means that in order to reach that level, $H_2$ must be injected, the quantity depending on how far away it is from the desirable value [15, 40].

As 'drop-in' biofuels are meant to be a better yet equivalent petroleum alternative, it's only natural that its production will take place in already existent processes and infrastructures in refineries, making use of methods such as hydroprocessing (combination of hydrotreatment – removal of the oxygen and other heteroatoms with the injection of $H_2$ at high pressures - and hydrocracking – a cracking process executed with $H_2$ at high pressures, breaking high molecular weight substances into lower molecular weight ones). In that sense, it is necessary to know in which is the best insertion point: in distillation, in the Fluid catalytic cracking (FCC), in the hydrotreater or in the hydrocracking. All of the mentioned have both advantages and disadvantages which must be evaluated [15].

### 2.4.1. Oleochemical Platforms

The oleochemical platform uses lipids as feedstock (derived from vegetable oils, animal fats or algae). As it was stated before, its H/C ratio is high (about 1.8) and its oxygen content is low (about

11%), making it a very good substitute to petroleum-based fuels. The most common biodiesel that uses this technology is FAME (Fatty Acid Methyl Esters); however, in order to be considered a 'drop-in' biofuel it must pass through deoxygenation steps. Products from deoxygenation might be "Hydrotreated Esters and Fatty Acids" (HEFA) or Hydrotreated Vegetable Oils (HVO), depending on the initial type of processing of the lipids [15].

#### 2.4.1.1. Hydrotreated Vegetable Oils

Hydrotreated Vegetable Oils, or HVO, are a diesel substitute obtained using lipid sources as feedstock. Most of them are derived from vegetable oils which results in a long fatty acid chain equivalent to diesel ($C_{16}$-$C_{22}$). Up until now, these are the only 'drop-in' biofuels whose quantity is stable enough to be commercialized. Even though this process is very attractive, it still has some significant costs associated, like the hydrogen input in the hydrotreatment. As it would be expected, the $H_2$ quantity depends on the feedstock used, if it has a high number of double bonds, more hydrogen is needed to saturate them. Tallow and palm oil's levels of saturated hydrocarbons is high, making them a more accessible feedstock to upgrade. In Figure 2-3, the simplified process is shown.

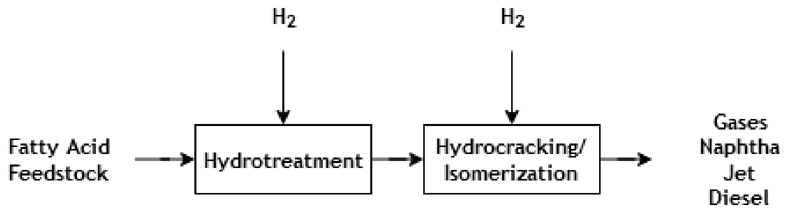

FIGURE 2-3 - SIMPLIFIED SCHEME OF THE PRODUCTION OF HVO, ADAPTED FROM IEA BIOENERGY [15]

As it can be seen, both in the hydrotreatment process and hydrocracking a hydrogen stream input is needed. In the first stage, alkanes are created through the deoxygenation. First the carbon-carbon double bonds within the triacylglyceride (TAG) are saturated and next, propane is removed. After that, the fatty acids pass through the three chemical reactions of the deoxygenation (Figure 2-2). A balance of these reactions must take place to avoid poor outcomes such as the carbon loss as $CO_2$. After this, HVO can be directly blended with petroleum diesel.

The second stage is optional, only used in facilities whose product is biojet fuel. The cracking/isomerisation is used to improve the cold properties of the fuel since the branching of the carbon chains reduces the freezing point, making it suitable for cold climates.

This process has a very good mass yield, rounding the 80% of liquid fuel and 20% of light gases and oxygenated gases. Outside of the $CO_2$ generated, the other gases can be used as power through combustion or used to generate hydrogen. As it can be observed in Figure 2-3, the liquid part of the process consists in Naphtha, Jet and Diesel, being the latter the most relevant quantity. Naphtha is a lightweight petrochemical feedstock that can be used as a solvent, diluent, or raw material for gasoline conversion. It is a volatile, flammable mixture of liquid hydrocarbons. The process conditions can be adapted to the desirable quantity of the three products. Both the diesel and the jet fuel do not have significant sulphur content and aromatics which is an advantage when comparing to the petroleum based ones [15, 41].

Even though it is a very attractive alternative to the petroleum-based fuels, the main obstacles are the cost, availability, and sustainability – as stated by IEA [15]. Regarding sustainability, a circular economy can take place by using waste feedstocks such as tall oils and cooking oils, however, even though the carbon footprint is lower, their quantity is limited. More sustainable feedstocks such as algae and non-food crops are still under research and development. The most used feedstock is vegetable oil; however, its price is often higher than diesel price. Being the same feedstock for both FAME and HVO, it also creates competition and FAME is cheaper to produce. The oleochemical route will continue to be the predominant one, for the short-to-midterm due to the low oxygen and high H/C ratio of the products[15].

## 2.4.2. Thermochemical Platforms

The thermochemical route uses biomass as its feedstock, relying on high temperatures (>500ºC) and catalysts to obtain the desired renewable fuel. In this process, carbonaceous gases, liquids, and char solids are formed. This platform has two main routes: the gasification (the biomass is converted to syngas) and the liquefaction (where the main product of the process is in the liquid phase, also known as pyrolysis oil or bio-oil). In both, these are intermediates and need to have further upgrading in order to be considered a 'drop-in' biofuel. In gasification, syngas can be upgraded through the Fischer-Tropsch process while in the liquefaction processes biocrudes are upgraded using catalysts and hydrogen. However, if they are not upgraded, they can be used as combustion fuels for infrastructures such as burners, boilers, among others [15]. In this document Gasification will not be covered, and in the liquefaction route only Fast Pyrolysis and HTL will be explored [14].

### 2.4.2.1. Fast Pyrolysis

Fast Pyrolysis is a form of the pyrolytic process which operates without oxygen in high temperatures (about 500ºC) with a residence time of a couple of seconds. After a quick heating, the biomass passes through rapid cooling resulting in vapours at room temperature. This method must be very controlled in order to maximize the bio-oil production. The ideal is that the heat (about 1000ºC/s) passes through all the biomass particles in one second. High liquid yield conversion rates, about 75%, have been achieved in reactors such as: bubbling fluidized bed (BFB), circulating fluidized bed (CFB) and in the rotating cone reactors. Still, its oxygen content is high: about 40% or more, being more demanding on the hydrogen quantity in the posterior stages [15].

### 2.4.2.2. HTL

As mentioned, the product of hydrothermal liquefaction is still an intermediate in the light of biofuels, needing further upgrade. When compared to Pyrolysis, HTL's oxygen content is lower: from 5-25%, depending on the process conditions. A lower oxygen level is obviously more attractive because it means that less hydrogen is needed in the hydrotreatment process [15].

This process aims to mimic the natural geologic process that formed fossil fuels, however instead of millions of years it can be achieved in 20-60 minutes. The solvent of this process is commonly water, avoiding the need to dry the feedstock – contrary to fast pyrolysis. The water is put under high pressures (50-250 bar or more) and moderate temperatures (250-550ºC), where the liquid product formation is favoured) reaching the sub/super-critical state. In this state, this solvent becomes a weak polar substance, gaining the lipophilic characteristic – making it a good solvent for nonpolar substances like oils, fats, greases [14, 42].

Inside the reactor, high efficiencies can be achieved because the water is not evaporated. Under these conditions, reactions such as hydrolysis and/or hydrocracking take place. After the oxidization or mineralization of the biomass $CO_2$ and $H_2O$ are formed and the desirable bio-oil product is formed after the quick repolymerization of the highly reactive hydrolysed molecules. The oxygen is removed through dehydration or decarboxylation. In Figure 2-4, a simple scheme of the process is shown. The solid phase includes minerals, nutrients and metals, the liquid phase contains the bio-oil, water and low amounts of soluble organics and the gas phase mainly $CO_2$ [15, 42].

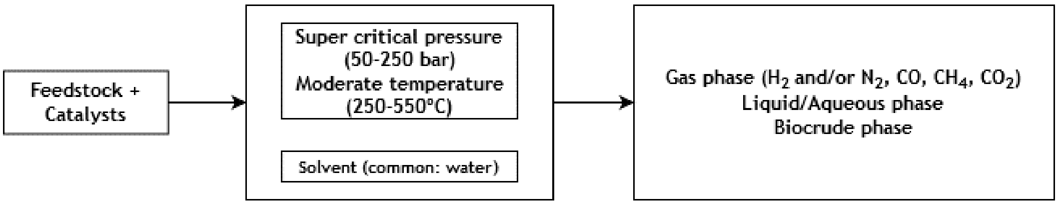

Figure 2-4 - Simplified scheme of the HTL process, adapted from IEA bioenergy and Dimitriadis and Bezergianni [15, 43]

Since no drying is needed and the solvent is in a non-polar state, this technology makes a good use of feedstocks such as lignocellulosic biomass, organic waste, sludge, manure, peat, algae, among others. To make the operation more stable, catalysts and anti-coking additives are added together with the reaction medium (water). Comparing to Pyrolysis, a complete carbon content utilization takes place. Being a low-oxygen content bio-oil, there is no need for a pre-treatment and drying translating it into energetic advantages[15].

Regarding the reactor, there are several ways of operating: batch, semi batch and continuous. With such high temperatures some corrosion is expected. Since metal ions get dissolved in critical water, having a role as catalysts, stainless steel reactors have been used. However, further investigation is needed [42].

There are several parameters influencing the overall yield of the bio-oil such as biomass feedstock type, particle size, and biomass concentration, temperature, heating rate, residence time, pressure, solvent, biomass to solvent ratio and catalysts [42].

Regarding the biomass type and composition, it has been studied that the ratio of protein, lipid and carbohydrate fractions influences the outcome of the process. More heterogenous biomass leads to a higher oxygen content and reduced viscosity in the bio-oil. Higher bio-oil yields are typically achieved through biomass with high cellulose and hemicellulose content. The particle size does not seem to affect the outcome very significantly, discarding the need of a meticulous pre-treatment. Water ends up acting as both heat medium and extractant overcoming these difficulties [42].

In this process, there is competition between three reactions: hydrolysis, fragmentation and repolymerization. The temperature ends up being the most important parameter since it is the most controllable one, also favouring one of the reactions. With the increasing of temperature there has been observed an increase in bio-oil yield up until a certain value: after that, the yield decreases because it promotes repolymerization (with the condensation and cyclization reactions of the liquid products and the cracking reactions of the hydrocarbon gases), which transforms into non wanted products like char, a heavier molecular compound. This parameter will also depend on the biomass type. The heat transfer rate must be as homogeneous as possible to avoid areas with poor heat distribution which may favour the char formation. Slow heating also favours the creation of bio-oil along with secondary reactions, yet, with very high heat transfer, high gas yields take place. Close to the reactor wall, high local temperatures can be found which leads to dehydration reaction and thus char formation. However, this effect can be exploited if the desired product is the solid carbonaceous material [42, 43].

Similarly, the residence time also increases the bio-oil yield until certain values – named the critical residence time – and the gas and the bio-oil yield increase up until the saturation point. This parameter depends mostly on the temperature and feedstock type. Short residence times are expected to be positive since hydrolysis and decomposition are very quick in supercritical processes. It has been observed that longer residence times have a negative effect on bio-oil yield except for processes with a high biomass to water ratio [42, 43].

Pressure helps the solvent to stay in one phase. Once supercritical conditions are achieved, there is no gain in continuously increasing the pressure, however, it should be favourable to keep the pressure above the critical conditions so that the rate of hydrolysis and biomass disassociation can be controlled. With this, the solvent's density increases, which means that the extraction of bio-oil increases as well [42, 43].

The most used solvent is indeed water, being environmental benign and with low associated costs, acting as a solvent, reactant, and catalyst. Nevertheless, other alcoholic solvents like ethanol and methanol have been studied due to being more accessible to achieve the supercritical state (low temperatures and low pressures needed when compared to water) and their ability to more easily dissolve high molecular weight products derived from cellulose, hemicellulose and lignin – since they have lower dielectric constants than water. In literature [43], good results have been achieved with incorporation of these solvents, as it is an effective way of removing oxygen and produce hydrocarbons with high value through the carbon and hydrogen present in the feedstock. There is also the option to combine more than one solvent: with a 50/50 mix of water and alcohol. Good bio-oil yields were reported. Specifically, in waste biomass, alcohols are proven to be much more efficient than water [43]. At higher temperatures, alcohol may disintegrate and produce hydrogen, which helps with the deoxygenation. Ethanol has been studied as a promising solvent for biomass liquefaction due to its positive results and its renewable trait: it can be produced through the bioconversion of lignocellulosic biomass. However, as it can be too costly, using co-solvents can be more economical [42, 43].

The higher bio-oil yields were obtained with a high water-to-biomass ratio since it promotes dehydration of the aqueous intermediates. A well achieved dilution of the feedstock minimizes cross reactions between the different compounds in the mix. However, if the water-to-biomass ratio value is very high, it becomes costly (with more wastewater to treat and more solvent use). It has been concluded that there is an optimal value of this parameter, same as for temperature and residence time [42, 43].

The use of catalyst is proven to be important. It is used mainly to avoid the creation of char, by reducing the reactions of repolymerization and/or condensation. Overall, these substances are homogenous, like mineral acids, organic acids, bases and as heterogenous zirconium dioxide, anatase, among others. It depends on the type of feedstock used, and, for waste biomass, there has been positive studies on $BaOH_2$ and $Rb_2CO_3$, $CaOH_2$ and $BaOH_2$, $AlCl_3$ and $Na_2CO_3$ [42, 43].

Overall, even though it is a very promising technology, with a promising calorific value (about 35MJ/kg for food waste), it is not yet very commercialized due to its specific high temperature and pressures, needing special reactors and plants – therefore with high capital costs associated. Even the management of the system's pressure tends to be a very minacious task, especially for small-scale plants. It is wise to recover the used homogenous catalysts at the end of the process and reuse them. Additionally, lab-scale projects and industrial scale ones are very different regarding the heat and mass transfer effects. These phenomena must be well understood in order to avoid complications with the wall effect [15, 39, 42-50].

Below, a summary table (Table 2-2) concerning the HTL technology is presented.

TABLE 2-2 - SUMMARY OF THE PARAMETERS THAT INFLUENCE THE HTL PROCESS

| Parameters | Conditions' Summary |
|---|---|
| Biomass Feedstock Type | The best conditions are achieved with a homogeneous biomass, avoiding lower viscosities and high oxygen content. Particle size does not have a significant influence. |
| Temperature | Temperature increase is favourable until a certain point. Further increase of the temperature promotes repolymerization which is undesirable. |
| Heating Rate | As homogeneous as possible in order to avoid char formation. |
| Residence Time | Increasing residence time is favourable until a certain point – the so-called critical residence time. |
| Pressure | Better to keep pressure above critical conditions for better management. There is no need to increase it further. |
| Solvent | Water is the most common solvent, however alcohols like ethanol and methanol have better qualities, like a lower critical point and can dissolve nonpolar organic compounds. Those can be used as co-solvents together with water. |
| Water-to-biomass | An optimal value needs to be achieved. A higher ratio is positive, however costly. |
| Catalyst | Use of catalysts is very important to avoid char formation. Type of catalyst depends on the feedstock used. |

## 2.5. HTL Reported Data

According to [51], that performed HTL on food waste with a TS% content of 15%, the highest HHV was 31.9 MJ/kg, obtained at 240°C in 30 mins, which was translated in 46.46% of bio-crude oil energy recovery (ER) and 32.26 char ER. In another study [52], food waste (33% dry basis) was submitted to a temperature of 300°C for 1 hour, using as a catalyst 5% $CeZrO_x$ (heterogenous), the highest value of HHV was 31.2 MJ/Kg with an ER of 38.8%, which proved to be higher than without using a catalyst (27.6% of energy recovery). According to both studies, the obtained values were comparable to HTL performed on algae – a feedstock with higher energy density than food waste – yet lower than HTL on vegetable oil, with 77.4% of ER, in 350°C for 1 hour, using H-ZSM5 as catalyst [53]. In [54], by submitting food waste to a pre-treatment with 5wt% of $K_2CO_3$ at 100°C for 1 hour and then perform HTL at 320°C for 30 minutes, the higher HHV was 34.8 MJ/kg with an ER of 50.3%. The obtained bio-oil had a low water content (0.3 wt%) and the H/C was within the desired range (1.61).

# Chapter 3. Methodology

In this chapter, the 5 study locations are introduced with a short description of each (EGE, Greve, Valorsul, Suldouro and Tratolixo) and it is explained how the data about the systems was collected.

## 3.1. Study Locations

For this study, two countries were compared: Norway and Portugal. Even though a general assessment of the countries will be presented, the main focus will be on 5 locations, 2 in Norway and 3 others in Portugal. From Norway, the two selected sites were Oslo's EGE (Romerike Biogas Plant - RBA) and Grenland Vestfold (Greve) biogas plant, both located in the south. From Portugal, Valorsul and Tratolixo – located in the south - and Suldouro in the north were chosen. In the Figure 3-1 below, the pinpointed locations in its respective maps are presented.

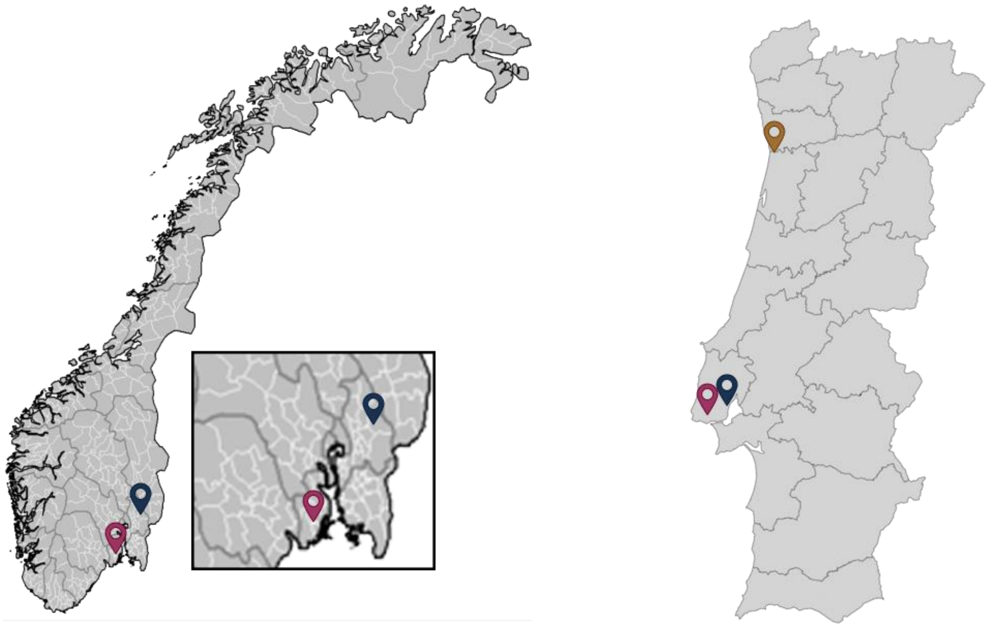

Figure 3-1 - At left, Norway's map (385 203 km$^2$) pinpointed with RBA (blue) and Greve's Biogas Plant (pink); At right Portugal's Map (92 212 km$^2$) pinpointed with Tratolixo (pink) Valorsul (blue) and Suldouro (orange)

## 3.1.1. Introduction to Norway's Locations

### 3.1.1.1. Oslo Municipal Energy Recovery Agency (EGE)

Oslo's EGE was chosen since it was a requirement from the WASTE2ROAD project. It covers an average of 670 000 habitants. It is mainly constituted by Haraldrud's waste-to-energy plant (incineration) and its optical waste sorting plant, by Klemetsrud's optical waste sorting plant and its incineration plant (owned 50% by Oslo city and 50% by Fortum, a Finnish company [55]), and by Romerike biogas plant (transforming organic waste into biomethane & biofertilizer). The pre-sorted municipal waste (and equivalent industrial waste) originated from the Oslo municipality is collected by the Oslo Municipal Waste Management Agency and through EGE's optical sorting centres (Haraldrud & Klemetsrud), it is further separated into three fractions: food waste, plastic and residual waste. The food waste fraction is sent to Romerike's biogas plant which is one of the main focus of this work.

As Romerike's biogas plant was built on an old landfill, the landfill gases are used as energy for the plant. In the end, the upgraded biomethane product is used in transportation (buses & heavy vehicles) and the biofertilizer is used for agricultural proposes, returning important substances to the earth such as nitrogen, carbon, phosphorus, and potassium.

### 3.1.1.2. Grenland Vestfold Biogas (Greve)

Greve's biogas production plant was chosen due to its proximity to Oslo's EGE and data availability. Grenland Vestfold Biogass AS's operations started in 2013, however in 2019 the company was reorganized and therefore split into two: a company for handling food waste and sludge and a biogas operations management company, being the latter Greve Biogas AS.

The municipal and industrial bio-waste it receives (from an average of 254 000 habitants) is organic waste & manure, from 12 owner municipalities (initially 17 municipalities in 2013), and 28 other municipalities, collected by Vesar and Renovasjon in Grenland (RIG), among other waste handling companies. Equivalent to Romerike biogas plant, Greve's biogas plant also transforms the bio-waste into biomethane and biofertilizer. The biofuel produced is used for transport in the majority of buses present in Vestfold, Grenland and Moss regions and in waste trucks in Vesar's area and RIG's area. However, unlike EGE, it also adds value to the $CO_2$ present in the biogas by pumping it to a greenhouse, as an experimental project, located in the facilities, that produces tomatoes. The added $CO_2$ increases the growth rate of the tomatoes.

## 3.1.2. Introduction to Portugal's Locations

Three plants from Portugal were chosen due to its similar values to the ones pre-evaluated from Norway, resulting in a good comparison measure.

### 3.1.2.1. Valorsul

Portugal's Valorsul was created in 1994 and is responsible for the treatment and recovery of municipal waste, in about 19 municipalities of Greater Lisbon and the West Region, covering an average of 1 590 000 habitants. This municipalities are present in the section B.2 in annex. Its intervention area is about 4% of Portugal – even though it is a small percentage, this corresponds to 1/5 of all municipal waste produced. Like most waste management systems in Portugal, this company is owned mainly by EGF[5]. Valorsul's system has 2 landfills, 1 Treatment and Organic Recovery plant, 1 Incineration plant, 1 facility for the Treatment and Valorisation of slag, 2 Sorting Plants, 2 Transfer Stations and 3 Ecocenters. For the selective collection of glass, paper & cardboard and plastic & metal, the covered population also has punctually the solution of a door-to-door collection. Regarding the organic selective collection, its services are mainly covering big producers (hotels, markets, canteens..), through the '+Valor' program, created in 2005. This program is only available for the following municipalities: Amadora, Lisboa, Loures and Odivelas. However, in the Portela urbanization (Loures) a pilot door-to-door collection of bio-waste in apartments occurs, offering specific containers for its disposal. Another pilot project, called “Restos de Comida não são lixo” takes place in the Lumiar and Santa Clara municipalities, where small brown containers were delivered to 7 thousand families with the final goal of expanding the collection throughout the city until 2023 [57].

This system plans to use the funding from POSEUR[6], among other objectives, in the improvement of the selective collection in the commercial and services sectors.

The biogas production takes place at the Organic Recovery Plant, where organic substances like green waste from garden cleaning, food from restaurants and markets (from the metropolitan area of Lisbon), among others, are received. Through anaerobic digestion, both biogas and compost (soil organic amendment) for agriculture are produced from source segregated biowaste. The biogas is used in the production of electric energy and the soil organic amendment is used for agriculture and gardening [59-63].

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[5] EGF is presently a private Portuguese company that deals with waste's treatment & valorisation with a high percentage in Portuguese waste management services, which had previously public capital as predominant [56]

[6] POSEUR is a programme created through the European Commission Implementing Decision from 16th December 2014, meant to operationalize the "Portugal 2020" strategy. Portugal received 25 billion euros until 2020 to contribute to its sustainable growth and to smooth its transition to a low carbon economy [58]

### 3.1.2.2. Suldouro

Suldouro's activity started in early 1999, and like the previously mentioned Valorsul, it is mainly owned by EGF[5]. It has 2 landfills, 1 Organic Recovery plant, 1 Energy Recovery Centre, 1 Sorting station and 5 Ecocenters. It only covers 2 municipalities (Vila Nova de Gaia e Santa Maria da Feira), in the Porto metropolitan area (covering an average of 439 000 habitants) and offers a door-to-door collection for local business (regarding packaging wastes) and started some initiatives for residences (excluding apartments) collecting paper & card, plastic & metal and glass, in determined areas. This pilot door-to-door collection project covers about 40 000 households.

At this waste management system, through a Mechanical Biological Treatment that includes the Organic Recovery Station, the biogas is produced by anaerobic digestion of the mechanically separated organic fraction (from the mixed fraction) and the processed matter (digestate) is sent to a composting process in order to get a soil organic amendment. The biogas is transformed into electricity for auto-consumption and inserted into the grid as well [63-66].

### 3.1.2.3. Tratolixo

Tratolixo started its activity in 1980, when 3 municipalities joined forces to treat the generated waste within their area. It belongs entirely to, presently, 4 municipalities (Cascais, Mafra, Oeiras and Sintra). As of 2019, it owns the following infrastructures: 1 landfill, 1 Treatment and Organic Recovery Station, 1 Mechanical Treatment Unit, 3 Ecocenters and 1 Sorting Station. It covers an average of 1 708 000 habitants.

Tratolixo also has a separate collection of bio-waste (organic & green waste), which was about 11% in 2019, a value that has been oscillating over the last years, however, in a general assessment, slowly increasing over the years. Much like Valorsul, Tratolixo has a selective collection of bio-waste towards businesses, collecting it from canteens, kitchens, gardens, and parks.. etc. However, in their Mechanical Biological Treatment, the system treats both municipal waste (<80mm, previously subjected to a mechanical treatment) and organic waste selective collected from businesses.

In 2019, Tratolixo applied for funding from POSEUR[6] which aims to adapt their Mechanical Treatment's automatic sorting to help their future project «*greenbags*» - an experimental collection of food waste in green bags. These bags will be placed by the population in the unsorted waste container to be collected. Afterwards, they will be separated in the system's infrastructure. With this, the system will also need and increment in their Biological Treatment's capacity – it is in their future plans to upgrade the current capacity (80 000 tonnes/year) to 120 000 tonnes/year. Additionally, along with other parties, Tratolixo submitted the "Move2LowC" project to Portugal 2020[7], whose goal is the development of biological-based jet fuels to be used 5-10% in planes and

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[7] A partnership agreement between Portugal and the European Commission which make use of 5 European Structural and investment funds, which are meant to promote the a smart, sustainable, and inclusive growth pursued by Europa 2020 Strategy. The programme POSEUR is part of this partnership [67].

biofuels for heavy vehicles, which use hydrogen fuel cells powered motors or methane combustion motors. Tratolixo will provide the biogas.

Mechanically separated from the unsorted waste, bio-waste is then treated by anaerobic digestion, transforming it into biogas and compost (after composting of the digestate). The biogas is used exclusively to produce electricity and subsequently injected it into the grid (having no auto consumption) and the compost is used as soil amendment, mostly in vineyards [63, 68, 69].

## 3.2. Data Collection

Two main data categories were collected: waste and biogas & compost production.

The development status of both countries regarding the collection of waste is very different. And so, in order to understand the general situation of both countries, an overall view is presented regarding the waste collection & sorting. Therefore, in the waste data section (4.1), municipal waste and household waste numbers are shown, along with waste handling information. In a more specific scope, since the purpose of the WASTE2ROAD project is to develop advanced biofuels (refer to section 2.1) information on collected bio-waste is also presented. As is was mentioned beforehand, bio-waste refers to biodegradable waste, like green waste and wet organic waste.

Regarding the system's themselves, information about the processes schemes and specific treated waste are assessed, as well as biogas & compost production, and biogas upgrading into biomethane (in Norwegian's locations) or its transformation into electricity (Portuguese's locations).

All the present data was obtained from statistical sources like EUROSTAT and more specific to each country such as APA and Pordata (for Portugal) and Statistics Norway (for Norway). For more specific data regarding the entities, financial reports organized by the companies themselves were analysed. Most of the obtained data was showcased directly or treated for a better comparison: organizing the information into *per capita* values, percentual values or relative values. Data on Hydrothermal Liquefaction was obtained directly from the literature.

# Chapter 4. Data & Interpretation

All the gathered information about the countries in general and regarding the 5 systems is presented in this chapter following the previous chapter guidelines. Waste and biogas & compost data are shown, followed by the respective interpretation of the shown tables and figures.

## 4.1. Waste Data

In the following tables, general information about the five locations is presented, mostly regarding waste production per capita and selective collection schemes. As mentioned in section 3.2, due to the differences of handling waste of both countries, different tables will be presented. The general overview including data for municipal waste collected in both countries is presented in section 4.1.1. Data on household waste, types of treatment for separately collected food and wet organic[8] waste in Norway, data on organic waste collected in Oslo Municipality and Telemark and Vestfold, and data on waste collection for the selected Portuguese locations are presented.

It is important to outline that there is a difference in data collection regarding municipal waste and household waste. According to the European Union Commission, municipal waste is described as "household waste and waste similar in nature and composition to household waste" [70]. Being part of the EU, Portugal follows this guideline and presents its statistical values in the light of municipal waste. On the other hand, Norway's statistics website (Statistics Norway) presents its waste data mostly regarding household waste. Norway's municipal waste was obtained accessing Eurostat.

### 4.1.1. Household & Municipal Waste

In the tables below, both municipal waste and household waste are presented. Portugal's official data only covers municipal waste (see definition above), whilst Norway's data addresses both municipal and household.

For Portugal, the latest official report (assembled by APA – Environmental Portuguese Agency) is from 2018. It presents an overall country status and, among other performance indicators, states the physical characteristics of the received waste. In that sense, it was possible to have a statistical idea of the bio-waste in terms of capitation (amount of waste produced per capita), in order to have an idea of what could be taken advantage of. In other words, it presents an idea of waste quantity that

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[8] Collected from households; Contain food as well as other wet material (e.g. with kitchen paper and white napkins)

could be potentially used for biofuel production or production of other higher value products. In the annex section, for the years 2016,2017 and 2018, the bio-waste percentage is presented in Table B-1.

Since it was not possible to find a characterization of Norway's Municipal Waste which would provide an estimate of bio-waste fraction, it was not possible to present a corresponding statistical value for the amount of bio-waste in Norway (Table 4-1). On Table 4-2, Norway's household waste collection through the years is presented – with the respective capitation – and in Table 4-3 the wet organic waste collection is presented.

A different behaviour is displayed by the two countries. While Portugal's municipal waste keeps increasing, Norway's municipal and household waste decreases. It is believed that Norway's positive outcome is due to the public campaign awareness (in fact, both EGE and Greve provide environmental education) and to the increasing of source segregated collection. Additionally, more waste is reused (in 2018, 2.6% of the household waste in Oslo was reused) therefore the production of new raw materials can be avoided. Food waste is used as a fuel and soil improver while plastic can be recycled in fleece products, for example. Residual waste produces heat and electricity through energy recovery processes, e.g. incineration [71]. While in 2016, 2017 and 2018 wet organic waste in Norway was increasing, in 2019 the same does not happen. In the first three mentioned years, the increase is due to a better sorting by the population. The data in 2019 may still be provisory.

TABLE 4-1 - ANNUAL MUNICIPAL WASTE IN THOUSAND TONNES, PER CAPITA IN KG/(HAB.YEAR) AND POSSIBLE BIO-WASTE POTENTIAL PER CAPITA FOR BOTH COUNTRIES, FOR 2016, 2017 AND 2018, TAKEN FROM EUROSTAT [72-74]

| | Portugal | | | Norway | |
|---|---|---|---|---|---|
| | Municipal Waste | Capitation | Possible Bio-waste Capitation[9] | Municipal Waste | Capitation |
| 2016 | 4 891 | 474 | 176 | 3 946 | 754 |
| 2017 | 5 006 | 486 | 178 | 3 949 | 748 |
| 2018 | 5 213 | 507 | 185 | 3 927 | 739 |

TABLE 4-2 – ANNUAL HOUSEHOLD WASTE IN THOUSAND TONNES, ANNUAL HOUSEHOLD PER CAPITA, IN KG/(HAB.YEAR) FOR 2016, 2017, 2018 AND 2019, TAKEN FROM STATISTICS NORWAY [75, 76]

| | Norway | |
|---|---|---|
| | Household Waste | Capitation |
| 2016 | 2 277 | 433 |
| 2017 | 2 256 | 426 |
| 2018 | 2 241 | 421 |
| 2019 | 1 980[10] | 372[10] |

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[9] This value is only statistical, meaning that it was multiplied with the recorded bio-waste percentage of the respective year. The percentages are present in Table , present in the annex section.

[10] Estimated value

TABLE 4-3 - ANNUAL WET ORGANIC WASTE SELECTIVELY COLLECTED IN TONNES AND ITS RESPECTIVE PER CAPITA IN KG/(HAB.YEAR) FOR NORWAY, FOR 2016, 2017, 2018 AND 2019, TAKEN FROM STATISTICS NORWAY [76]

| | Norway | |
|---|---|---|
| | Wet Organic Waste | Wet Organic Waste Capitation |
| 2016 | 189 313 | 36.3 |
| 2017 | 191 540 | 36.4 |
| 2018 | 200 562 | 37.9 |
| 2019 | 173 937 | 32.6 |

### 4.1.1.1. Waste Handling - Norway

In Figure 4-1, a general scheme of how the waste is handled, in EGE and Greve's covered area is presented. For household waste in Norway, in most of the country, there are four different specific fluxes: "wet organic waste" (collected in green bags), "plastic" (in blue bags), "paper & card", and "glass & metal". The colour code of the bins changes throughout Norway, but for Greve's covered are this are to be inserted in black bins, green bins, and black bins with orange lid for door-to-door collection, like it is exemplified in Figure 4-1 below. Organic and plastic waste is to be inserted in the same container along with unsorted/residual waste, in bags of different colours. Due to the distinguished colour nature of the bags (green & blue, shown in Figure 4-2) optical sorting is possible, having no need to open the bags.

Throughout Norway, the mentioned bags (for wet organic waste, plastic, and residual waste) can be collected in the same bin or not, depending on the collection method decided by the municipality. Some have the *Optibag System* where residual, plastic (in blue bags) and wet organic waste (in green bags) goes into the same bin, while others have a system where the bin has a split lid, and the food waste is disposed into one of the chambers (the garbage truck is also divided into two chambers, like it is presented in Figure 4-2) [77].

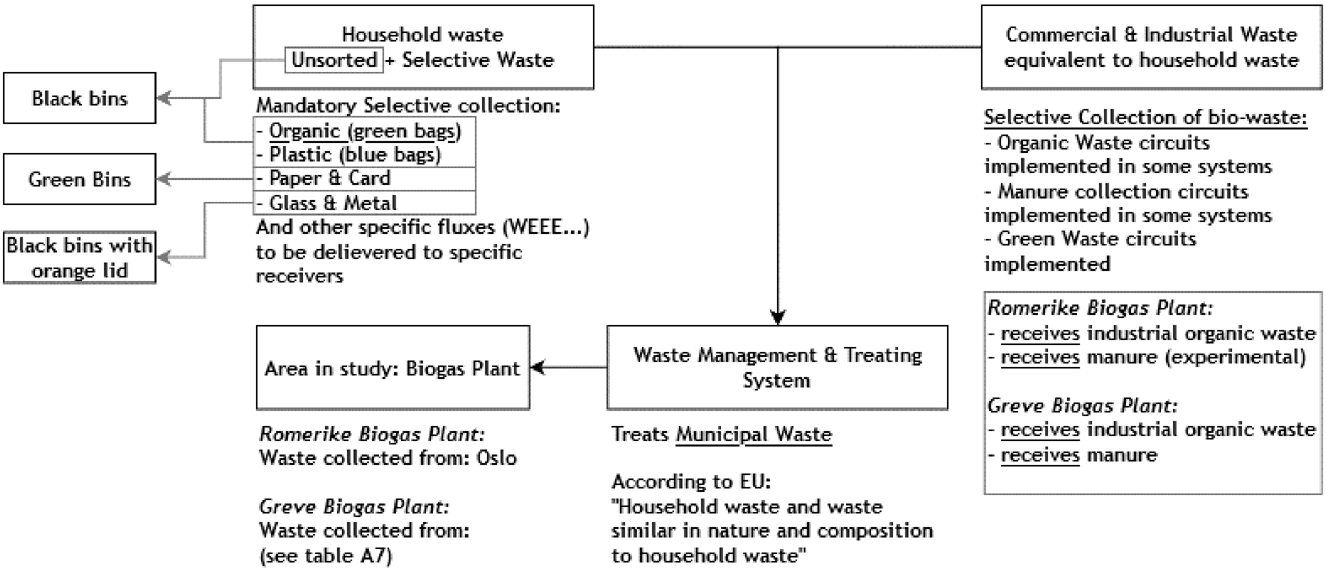

FIGURE 4-1 - SCHEMATIC FIGURE OF THE WASTE HANDLING IN NORWAY, EGE AND GREVE'S COVERED AREA (WITH GREVE'S EXAMPLE OF BINS)

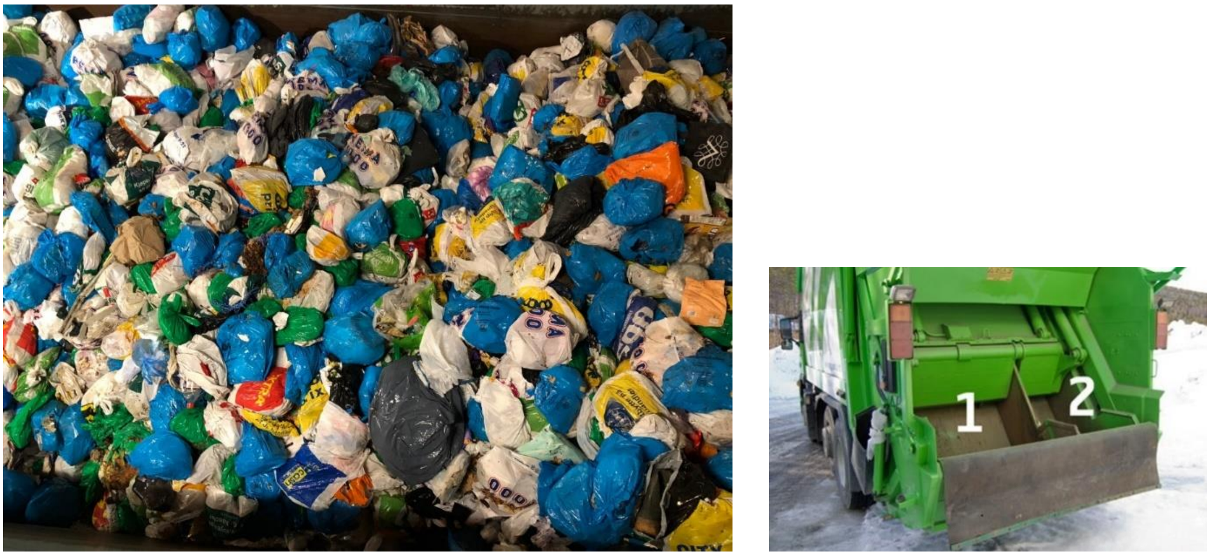

Figure 4-2 - Different coloured bags (Organic - Green; Plastic - Blue), took by SINTEF (left) and a garbage truck divided into two chambers, wet organic waste goes into chamber 2 and other waste in 1, taken from [78]

As a direct destiny, almost all urban biodegradable waste (collected from the households) ends up in biogases and composting plants, while a fewer percentage is sent to other destinies (this information in presented in Table 4-4).

Table 4-4 - Main destinies of the food and wet organic waste in tonnes, in Norway and its respective percentage for the years 2016, 2017, 2018 and 2019 [76]

| | Norway | | | | | |
|---|---|---|---|---|---|---|
| | Sent to Biogas production | | Sent to Composting | | Other direct destinies[11] | |
| 2016 | 104 580 | 55.2% | 76 583 | 40.5% | 8 150 | 4.3% |
| 2017 | 108 028 | 56.4% | 79 231 | 41.4% | 4 282 | 2.2% |
| 2018 | 116 263 | 58.0% | 75 249 | 37.5% | 9 049 | 4.5% |
| 2019 | 141 003 | 81.0% | 31 943 | 18.4% | 990 | 0.6% |

Above, it is possible to observe that the waste sent to biogas production is increasing throughout the years (in 2019, 81.1% of the food waste selective collected was sent to biogas production plants whereas in 2016 the value it was sent only 55.2%), naturally decreasing in the other destinies. This is a very pleasant outcome since more biogas can be produced - and consequently compost. The forwarding to other direct destinies is not very significant, meaning that almost all food waste is being recycled. These other destinies do not include landfill because it is forbidden to send biodegradable waste (except for waste where TOC is below 10%) since 2009, with the landfill ban (section 9.4(a) of the Waste Regulations) [79].

While the prioritized destination is the biogas plants, due to different circumstances (the biogas plant cannot accept more food waste, for example), collected wet organic waste may end up in other

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[11] Other direct destinies include Recycling, Incineration, and others

destinies outside of biogas production or composting. Currently, 10 biogas plants in Norway receive household wet organic waste (for a more detailed look check Table B-5). It should be noted that separated food waste collection is done in most of the municipalities. These municipalities account for 73% of Norway's area in 2019. In other words, in 73% of Norway's area wet organic waste is being put in different bags. [76, 80]. In the areas in which there is no selective collection or if the sorting of wet organic waste is poor, organic waste ends up going within residual waste – that normally is sent to incineration plants to be recovered as heat.

### 4.1.1.2. Waste Handling - Portugal

Contrary to Norway, in Portugal presently there is no mandatory selective collection towards the organic fraction, for household waste. Some big management sites like Lipor collect it from door-to-door circuits (however still with a small expression) and big producers while others, like Valorsul (one of the studied locations), only receives selective organic fraction from big producers like restaurants and canteens [81-83].

The common selective collection is regarding plastic & metal (yellow bin), paper & card (blue bin), and glass (green bin) packages. In this usual system, the organic fraction is collected in the same bag as part of the unsorted waste. Below, in Figure 4-3, a general schematic figure is presented to make the comprehension easier.

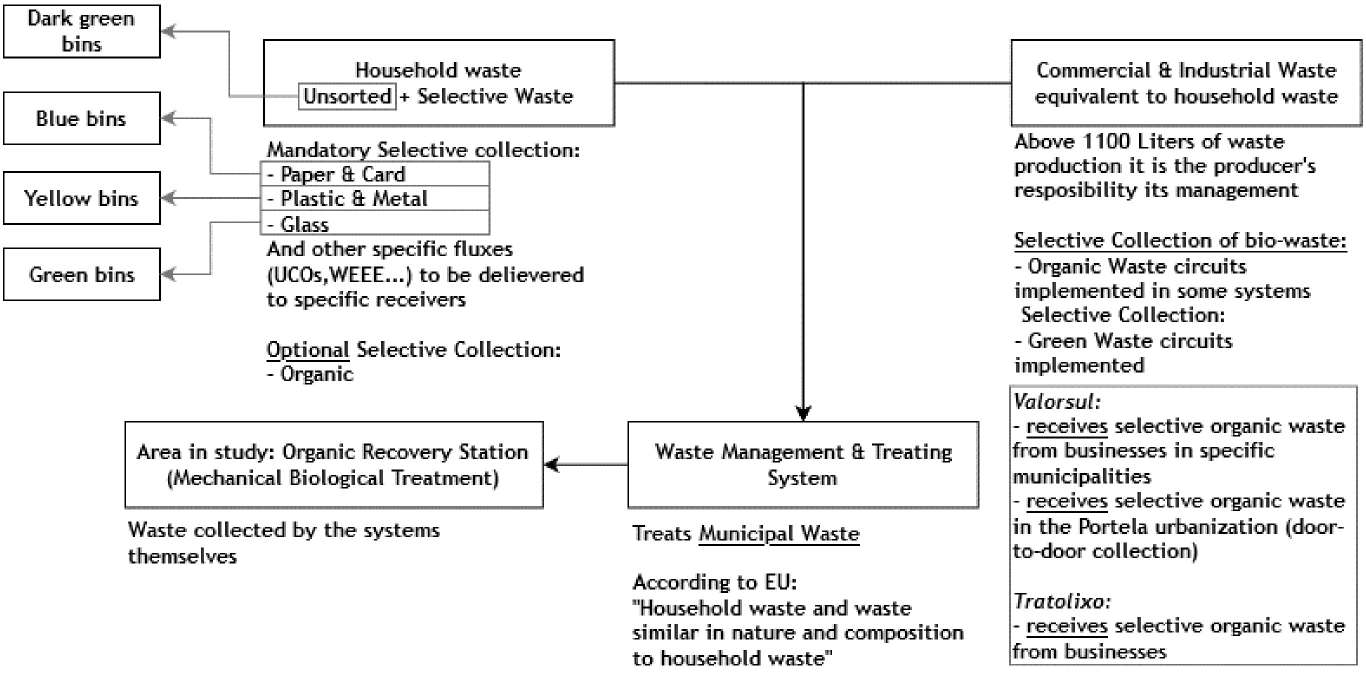

FIGURE 4-3 – SCHEMATIC FIGURE OF THE WASTE HANDLING IN PORTUGAL, ADAPTED FROM APA

#### 4.1.1.3. Overall look of the selected locations

The two Portuguese locations Suldouro & Tratolixo collect generic household waste (consequently sorting it and sending it to the appropriate treatment) whilst the two Norwegian biogas sites (Romerike and Greve) and Valorsul's Organic Recovery Station (ORS) are dedicated to organic waste, receiving only this fraction. Therefore, the data available differs a bit: for Norway, it is possible to present the real capitation regarding food waste.

To obtain Norway's food waste capitation numbers, the values were calculated based on the received food waste reported by the systems, and therefore divided by the number of habitants in the municipalities that both EGE and Greve cover. The annual values recorded by EGE also take into account some non-household waste that has been additionally collected, such as kindergartens and schools. This information in present in Table 4-5.

The wet organic waste capitation is overall increasing over the years in the systems (with the exception of 2018 in EGE), even though in Norway as a whole (Table 4-3), in 2019, the value decreases. This is a positive outcome, meaning the inhabitants are more interested in separating food waste. However, as it can be observed, there is a notorious gap between EGE and Greve's capitation numbers, which reflects the differences in sorting in these different zones. A possible answer would be the differences in socio-economic levels, a high diversity in cultural backgrounds, and in age groups. In Oslo most inhabitants are young (20-35 years old, [84]) and live alone, possibly distancing themselves from such environmental practices, while in Greve's covered area inhabitants belong in a more older age group, more family-oriented.

Table 4-5 – Organic waste received, from households, in tonnes and Annual per capita, kg/(hab.year), for Norway's Location, for 2017, 2018 and 2019

| | EGE | | Greve | |
|---|---|---|---|---|
| Norway's Locations | Wet Organic Waste | Capitation | Organic Waste | Capitation |
| 2016 | 16 635 | 25.3 | - | - |
| 2017 | 17 578 | 26.4 | 33 719 | 88.2 |
| 2018 | 16 853 | 25.0 | 42 523 | 103.5 |
| 2019 | 18 936 | 27.8 | 47 344 | 114.18 |

For Portugal, the annual capitation was calculated through the annual municipal waste report, where the number of habitants and waste received by urban waste management systems is recorded by the National Authority APA.

As mentioned, Portugal does not have mandatory organic selective collection for households, being recently slowly starting pilot projects due to the European requirement for the end of 2023 (Directive 2018/851 [9]). The values presented in the Table 4-6 below are regarding the total system's collection, therefore most of the collection is unsorted municipal waste. However, using the percentage of bio-waste in Table B-1, it was possible to calculate a statistical value for the bio-waste capitation.

Since the official Portuguese data from APA, regarding the system's annual performance (presenting an overall country evaluation) for 2019 is still not available – as discussed above – the possible bio-waste for Tratolixo was estimated with the percentual value of bio-waste from 2018 (36.40%). Another consideration taken into account was regarding capitation: seeing that Tratolixo's 2019 financial report is already available, however Portuguese official population's statistics for the same year is not, this system's capitation was calculated using 2018's population (858 700 habitants in the municipalities it covers, see section B.2 in annex).

In all three systems, the total collected waste is increasing - which matches Table 4-1. Even though the total waste values are significatively different in the systems, the capitation values are similar. This means that the waste production does not vary within these geographical areas. A clearly high biowaste potential might be observed.

Table 4-6 – Total waste in tonnes, Annual per capita, kg/(hab.year) regarding municipal waste and possible Bio-waste for Portugal's locations, for 2017 and 2018

| | Valorsul | | | Suldouro | | | Tratolixo | | |
|---|---|---|---|---|---|---|---|---|---|
| Portugal's Locations | Total Waste | Cap[12] | Possible Bio-waste[13] | Total Waste | Cap[12] | Possible Bio-waste[13] | Total Waste | Cap[12] | Possible Bio-waste[13] |
| 2016 | 765 064 | 482 | 284 604 | 187 640 | 427 | 69 802 | 411 697 | 484 | 153 151 |
| 2017 | 795 453 | 500 | 290 818 | 190 443 | 434 | 69 626 | 422 206 | 494 | 154 359 |
| 2018 | 832 350 | 521 | 302 975 | 197 999 | 452 | 72 072 | 444 972 | 518 | 161 970 |
| 2019 | - | | | - | | | 446 174 | 520 | 162 407 |

## 4.1.2. Waste sent to the AD

### 4.1.2.1. Norway

In Norway, both RBA (EGE's biogas plant) and Greve accept industrial wet organic waste. Both of this companies accept animal manure, however, unlike RBA, Greve accepts animal manure on a regular basis – being the only biogas plant that does it, as it can be seen in Table B-5 (in the annex section) - which will provide organic matter and water to forthcoming processes. These values are presented in Table 4-7 below. The numbers inside the brackets represent the total share in percentage.

For RBA, the substrate column refers to food waste that is originally from other waste management entities. Even though this management site accepted manure in the past years, it was only experimental. As it is clear, the use of industrial wet organic waste is decreasing throughout the

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[12] "Cap" refers to capitation, meaning waste per capita

[13] This value is only statistical, meaning that it was multiplied with the recorded bio-waste percentage of the respective year. The percentages are present in Table B-1, present in the annex section.

years as RBA has a maximum capacity of 30 000 tonnes and the wet organic waste from households is increasing (see Table 4-5).

TABLE 4-7 –MAIN FEEDSTOCK RECEIVED IN RBA, IN TONNES AND RESPECTIVE PERCENTAGE

| | RBA | | | |
|---|---|---|---|---|
| | Manure | Industrial Wet Organic | Substrate | Household |
| 2016 | | 11 505 (38.1) | 2 055 (6.8) | 16 635 (55.1) |
| 2017 | 43 (0.1) | 10 041 (35.2) | 885 (3.1) | 17 578 (61.6) |
| 2018 | 54 (0.2) | 8 612 (31.9) | 1 490 (5.5) | 16 853 (62.4) |
| 2019 | 123 (0.4) | 7 725 (25.5) | 3 488 (11.5) | 18 936 (62.6) |

TABLE 4-8 - MAIN FEEDSTOCKS RECEIVED BY GREVE, IN TONNES

| | Greve | | | | |
|---|---|---|---|---|---|
| | Manure | Industrial Wet Organic | Liquid Industrial Waste | Substate from Lindum | Household |
| 2017 | 63 172 (57.2) | 9 509 (8.6) | 3 831 (3.5) | 172 (0.2) | 33 719 (30.5) |
| 2018 | 64 110 (52.4) | 9 678 (7.9) | 6 034 (4.9) | 128 (0.1) | 42 523 (34.7) |
| 2019 | 70 363 (51.8) | 12 709 (9.4) | 3 886 (2.9) | 1 531 (1.1) | 47 344 (34.9) |

Regarding Greve's data, both manure & industrial wet organic are increasing over the years which is a favourable outcome, since it means that a higher biogas volume will be produced (see Table 4-12). The difference between 'Industrial Wet Organic' and 'Liquid Industrial Waste' is the state in which the matter is. In another words, 'Liquid Industrial Waste' is stored in a tank and can be pumped and 'Industrial Wet Organic' is handled as a solid feedstock. This system also received a small amount of waste from Lindum, another waste handling company.

In Table 4-9, the values presented concern the waste that enters the treatment, that is, the added value of household waste and industrial waste (Table 4-5 & Table 4-7). While in Greve the total waste entering the biogas plant is clearly rising every year, in RBA the values oscillate a bit, keeping consistency – since the maximum capacity is set at 30 000 tonnes of waste per year.

TABLE 4-9 - TOTAL FEEDSTOCK ENTERING THE TREATMENT PHASE FOR THE 2 ENTITIES STUDIED IN NORWAY, IN TONNES FOR THE YEARS 2016, 2017, 2018 AND 2019

| | Norway | |
|---|---|---|
| | RBA | Greve |
| 2016 | 30 196 | |
| 2017 | 28 546 | 110 403 |
| 2018 | 27 008 | 122 473 |
| 2019 | 30 272 | 135 833 |

#### 4.1.2.2. Portugal

At Portugal, Valorsul receives selective green waste and, through the '+Valor' program, collects organic matter from restaurants, canteens, markets, and hotels, admitting about 31 646 tonnes of organic waste in 2018. According to APA, this represents around 24% of its selective collection [62, 63]. Suldouro, however, does not receive food waste from selective collection, only green waste. Even though Tratolixo treats mixed waste, in terms of selective collection, the system accepts both green and organic waste from bigger producers.

The following table (Table 4-10) presents and overall look of the feedstock that was received by these systems, with the intention of being transformed into biogas and compost. Therefore, the values are regarding the tonnes of waste that entered the treatment for anaerobic digestion. In this sense, for Valorsul this is regarding its selective waste collected (Organic & Green), for Suldouro the unsorted waste (UW) that was sent to the Organic Recovery Station (ORS) and for Tratolixo the urban biodegradable waste selectively collected and unsorted waste (UW) that entered this organization's ORS. For Tratolixo the 2017 data was not obtainable.

For Valorsul and Tratolixo the treated waste is comparable since Valorsul has selective collection and Tratolixo receives unsorted waste already mechanical treated (< 80mm) gathering it with biodegradable waste. Regarding Suldouro, since the waste received in the unit is mixed, it was assumed that the entering waste on the digestor would be the bio-waste percentage reported by APA in each year (Table B-1). This corresponds to the “Estimated Organic fraction” in the table below.

Even though Tratolixo collects selective green waste, in this treatment it is not considered as a feedstock since it is mostly used as a structuring element in the composting process. More information about the selective organic collection done by Tratolixo (the received bio-waste reported by the facility) can be found in B.2 section in the annex.

In Valorsul the bio-waste is decreasing with each year; however, that was due to the scheduled maintenances. In 2017, one digestor needed to be stopped and cleaned in order to improve its efficiency – which lasted 3 to 4 months - and in 2018 another digestor had the same treatment. This meant that the collected waste had to be sent to another facilities [60, 61]. Regarding Suldouro, some issues arose as well: in the second semester of 2018 their ORS was stopped due to planned interventions that meant to elevate the biogas production efficiency [66].

TABLE 4-10 - MAIN FEEDSTOCK RECEIVED THAT ENTERED THE TREATMENT PHASE, BY THE PORTUGUESE LOCATIONS, IN TONNES, ADAPTED FROM [59-61, 64-66, 85]

| | Portugal | | | |
|---|---|---|---|---|
| | Valorsul | Suldouro | | Tratolixo |
| | Bio-waste | UW[14] | Estimated Organic fraction | UW[14] + Organic |
| 2016 | 40 600 | 88 372 | 32 874 | 77 722 |
| 2017 | 36 469 | 61 644 | 22 537 | |
| 2018 | 35 053 | 33 270 | 12 110 | 77 242 |

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[14] Unsorted Waste

## 4.1.3. Waste Treatment

As mentioned beforehand (in section 3.1.1), the food waste selectively collected in Norway is used to produce both biomethane and organic compost, the latter applied afterwards in the agricultural sector. In Portugal, even though domestic food waste is generally not collected selectively (only in small scale projects, specific to each management system), it will be sent together with the unsorted waste to treatment plants, originating biogas and compost [60, 86-88].
In the table below, the main parameters for the anaerobic digestion plants analysed at both countries are presented. In almost all the locations, the treatment happens in a mesophilic range (about 20 to 45°C) and only in Valorsul takes place in a thermophilic range (>45°C). Regarding HRT, 4 locations have similar values, whilst Tratolixo has an unusual higher value (Table 4-11). In all the locations, the treatment happens in a semi-continuous process. It should be highlighted that the presented capacity is indeed the total capacity of the reactors.

TABLE 4-11 - ANAEROBIC DIGESTION'S PARAMETERS FOR NORWAY AND PORTUGAL, ADAPTED FROM [85, 87, 89-92]

| | Norway | | Portugal | | |
|---|---|---|---|---|---|
| Parameters | RBA | Greve | Valorsul | Suldouro | Tratolixo |
| Main Feedstock | Selective Organic | Selective Organic | Selective Organic | UW[14] + Selective Green Waste | UW[14] + Selective Organic |
| Total Reactors | 3 | 2+1 secondary | 2 | 2 | 3 |
| Total Capacity [$m^3$] | 9600 | 15 000 | 7600 | 4000 | 9300 |
| TS [%] | 13-15 | 13-15 | 3-5 | 10 | 37 |
| Temperature [°C] | 38 | 37 | 50-52 | 36-38 | 40-41 |
| HRT [days] | 24 | 30 | 22 | 25-30 | 40-42 |
| Biogas Use | Bus & Heavy Vehicles | Bus & Waste Trucks | Electricity & Heat | Electricity & Heat | Electricity & Heat |

### 4.1.3.1. Processes Schemes

All five locations' process schemes are presented in this section. In Portugal, since some of the studied locations (Suldouro and Tratolixo) treat unsorted waste, a more intense pre-treatment is needed. The overall difference is the biogas upgrading of Norway's locations, and how the compost is handled: in Portugal, through a press and thickening processes, the solid phase is segregated from the liquid phase; the solid fraction is after sent to the composting plant, fulfilling the water requirements. In Norway's locations, this segregation does not take place. Therefore, both Romerike's plant and Greve sell liquid biofertilizer, while Portugal sells off a solid amendment for agricultural purposes. This difference in handling the compost is expected to be due to both economic and safety issues: transporting a liquid fertilizer is more expensive than transporting a compost with a higher dry matter content. On the other hand, the anaerobic digestion processes in the studied Portuguese locations do not ensure a proper hygienization of the product – which is accomplished at the composting plant.

Below, in Figure 4-4, the overall process scheme of the Romerike Biogas plant is presented. Initially, the solid wet organic waste is lifted by a crane towards the pre-treatment step - while the liquid phase in sent directly to the buffer tank. The bags are opened, and their waste particle size is reduced through a shredder. Then, the metals are sorted out by a magnetic separator and afterwards forwarded to recycling. In the specific designed bio separators, with the addition of water, plastic, packages, and other larger unwanted waste is separated and a liquid bio substrate with reduced particle size is formed. After being reduced to 10mm particle size in the sieve after the screw press, the substrate is stored in three buffer tanks.

The next step is the thermal hydrolysis, which is composed by several pressure tanks. In the preheating tank, the substrate is heated between 80-100ºC and then sent to a reactor tank where pathogens and other noxious bacteria/fungi are eliminated. The flash tank is used to damage the cell walls, due to rapid change of pressures, so that in the biogas reactor there is an elevated contact area. In the three bioreactors, the decomposition of the substrate takes place in mesophilic temperature and anaerobic conditions (see section 2.3.1 for a more detailed view on anaerobic decomposition). The digestate is stored and the biogas is sent to be upgraded.

The created biogas is approximately 60% methane and 40% carbon dioxide, having also hydrogen sulphide in small quantities. The removal of $CO_2$ takes place in water scrubbers – process in which this compound is absorbed in water (saturated) with the help of plastic granules present in the water. The gaseous phase is now 97% methane. To achieve the 99%, the gas is compressed in very high pressures (about 30 bar) so that the $CO_2$ can be adsorbed in molecular filters. After, the gas is cooled down to -166ºC and the heat exchange takes place. Then, the pressure drops to 2 bar and the now liquid product is stored in very low temperatures (about -159ºC). By upgrading it into LBG, the logistics of its transport and the associated costs are reduced. This biomethane is sold to the company Linde, which handles the distribution. Additionally, if problems arise (the upgrading unit is not working properly, for example), the raw biogas can be flared.

The stored substrate meant to be turned into compost passes a 2 mm sieve and is then pumped into a storage tank. Three types of biofertilizer can be produced: a liquid biofertilizer (meant for organic and conventional agriculture, being its production share about 77%), a solid digestate (suitable for soil production, around 13% of the compost produced annually) and a bio concentrate (for conventional agriculture, with 10% share of production). The liquid fertilized after the sieve has a TS content of about 4.5%, and in terms of chemical compounds – nitrogen, phosphorous and potassium – can be compared to chemical fertilizers. As an alternative production, RBA also dewaters it (by the addition of a polymer and centrifuged) turning into a more solid substrate rich in phosphorous, having a TS content of 30-40%. The bio-water originated in the centrifuge process can be acidified, evaporated, and accumulated creating a bio-concentrate rich in potassium and nitrogen. This bioconcentrate with a TS content of 15-25% can be used in conventional agriculture, horticulture, gardens and for landscape construction [89, 93, 94].

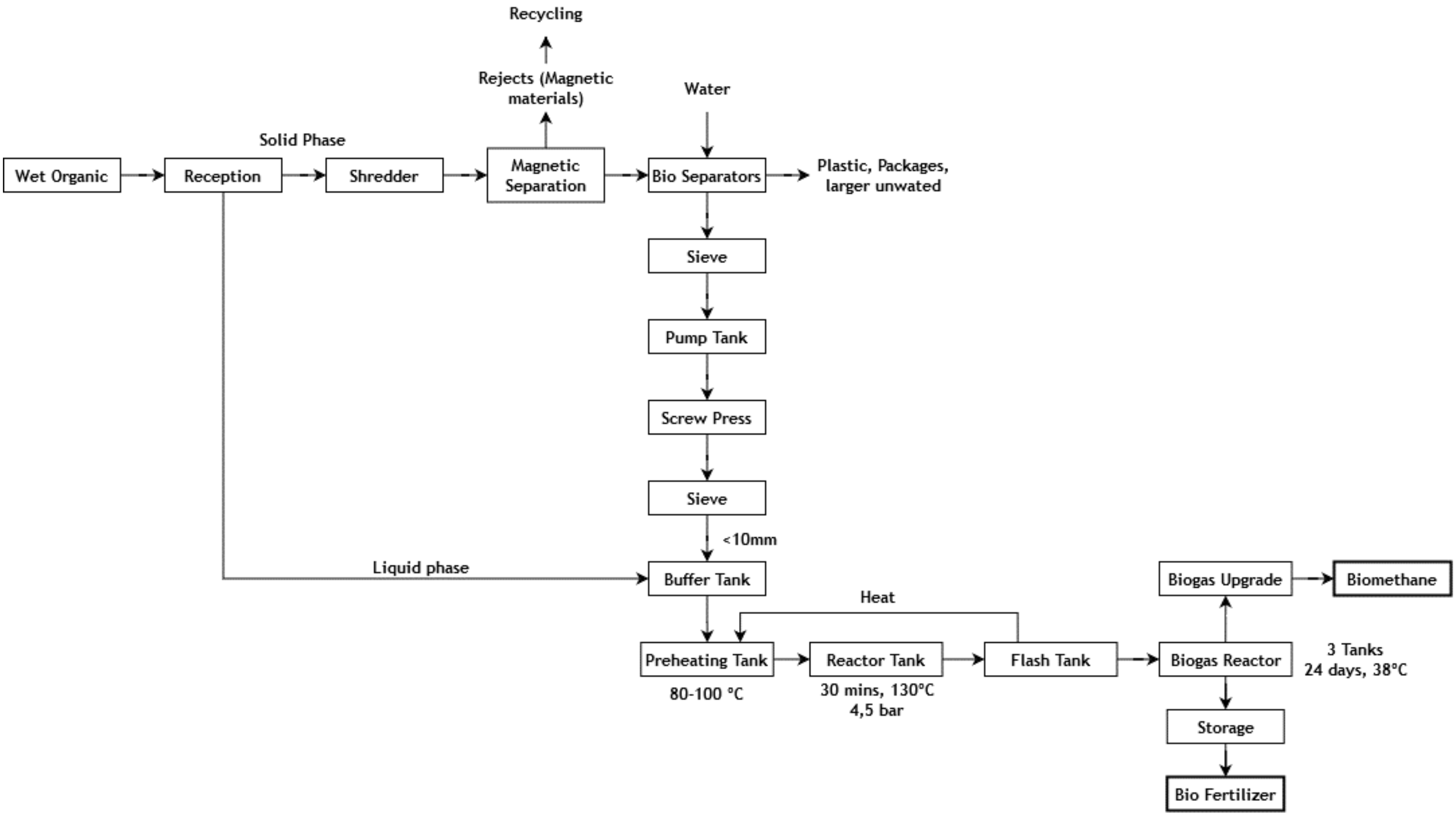

FIGURE 4-4 - PROCESS SCHEME OF THE ROMERIKE BIOGAS PLANT, EGE, ADAPTED FROM [89]

In Figure 4-5 below, Greve's biogas plant scheme is displayed. This plant has two different types of feedstock: it accepts manure from cattle and pig and wet organic waste from households.

The manure that is stored goes to a mixing tank – to make the matter more homogenous – and then is sent to a hydro cyclone which removes sand and other heavier particles. These heavier particles go to the reception stage of the wet organic feedstock. The liquid manure passes through a press that extracts the present water to a water tank. The solids go to a buffer tank.

The wet municipal organic waste is received (along with some industrial waste) and goes to a shredder which opens the bags and reduces the waste particle size. From here, the waste is forwarded to a pulper that with the addition of water slurries the substrate. The substrate then passes through a 6 mm sieve – removing unwanted materials that are later incinerated. The now inferior to 6 mm waste is stored and later sent to a hydro cyclone that sorts out materials like sand and eggshells, among others, that are forwarded to a landfill. Finally, it passes a press – in which the water is stored in the water tank – and joins the manure in the buffer tank.

After the buffer tank, the substrate is sanitized in three hygienization tanks that operate in a semi continuous state and sent to the three biogas reactors where anaerobic degradation takes place in a completely mixed tank. The reactors are designed to receive a feed of 13-15% of TS content. The heat from the hygienization process (70ºC) is recovered in heat exchangers meant to heat the feed entering the hygienization

From the top of the reactors, raw biogas is collected and sent to be upgraded. Its passes a water scrub, where the $CO_2$ is removed through air after its absorption in the water. Due to different circumstances the raw biogas can be flared if needed (if process problems arise, such as pump malfunctioning, problems in the upgrading unit…). The biomethane is sold to the company Air liquid Skagerak AS.

The digestate from the biogas reactor is collected and, after a sieve to improve the product's quality, it is stored in a cold environment. The released heat is recovered. The biofertilizer is used for only agriculture and is supplied to farmers in the area around. The biofertilizer must fulfil legal regulations, being the main issue the presence of metals. To ensure the quality of the product, analyses are carried out at regular intervals (usually monthly) by an accredited laboratory and the farmers receive the certificate's copy. All the air is released into the atmosphere after its passage through a biofilter, with bark from trees as its substrate [87].

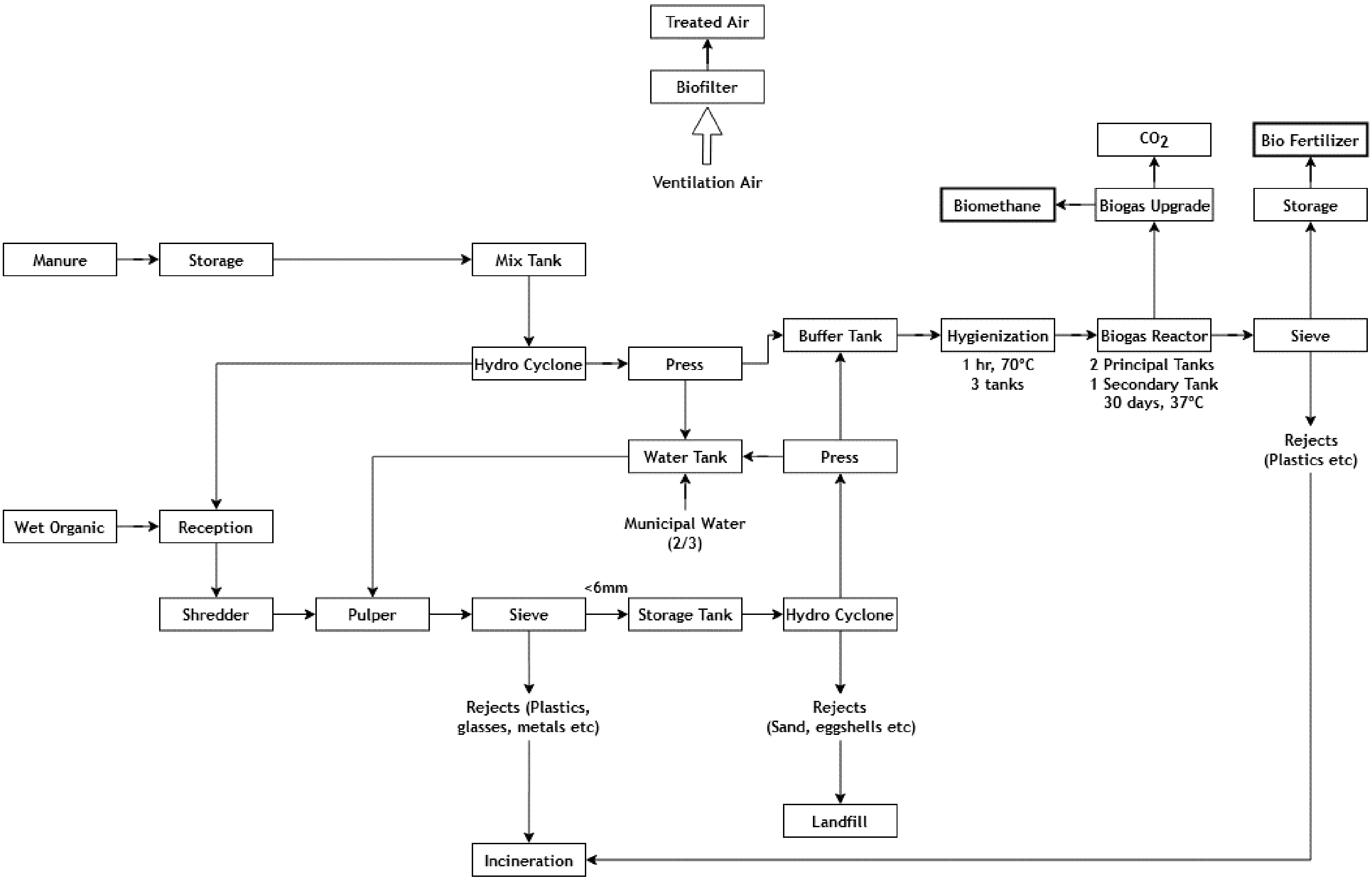

FIGURE 4-5 - PROCESS SCHEME OF THE GREVE BIOGAS PLANT, ADAPTED FROM [87]

In Figure 4-6, below, a scheme about Suldouro's Organic Recovery Station is presented. The unsorted waste arrives at the plant in a storage zone designed to be able to hold waste for three days. The waste passes a shredder that opens the bags and is then sent to a trommel screen (a rotating sieve) with a grid's diameter of 80 mm. Since this small fraction may have metals it passes a magnetic separator to remove the ferrous materials. The removed metals are sent to preparation for recycling. After that, the organic matter is sorted in a dynamic disc screen with a particle size of 40 mm and temporarily stored in a bunker.

The bigger fraction (>80mm) passes a ballistic separator which sorts out the waste in three fluxes: sieved fraction (underscreen fine fraction), flat and light fraction, and heavy and rolling fraction. The fine fraction passes a 60 mm sieve by gravity's action and joins the fraction that passed the trommel screen (< 80mm) through a conveyor belt. The flat and light fraction is sorted by the friction of the moving plates and sent to a sorting cabin, where manual sorting takes place. Finally, at the same time, the heavy and rolling fraction is not that much affected by friction and is collected in the inferior part of the separator. Then, it goes to an optical separator, that identifies plastics such as PET, PEAD, Tetra Pak, among others – to be recovered. The rejects from the ballistic separator pass through a magnetic separator to recover the ferromagnetic metallic fraction.

The residues stored in the bunker, after the dynamic disc screen, are forwarded to two pulpers with a lag of 40 minutes between them. Water from the water tank (residual and process water) is added and an aqueous substrate with smaller particle size, 10 mm, is formed with a TS content about 5%. The heavy fraction (like rocks, glass, bigger bones, metallic objects, among others) is collected at the end of the tank by the centrifuge force's action. The light fraction is then removed when the equipment cleaning takes place. The aqueous organic fraction passes a hydro cyclone (grit removal system), where heavier fraction, like sand, is removed and goes to a thickener, achieving a TS content of around 10%. The next step is a buffer tank, which homogenizes the substrate by the insertion of compressed air and where the bacterial hydrolyses starts in aerobic conditions. After this, the suspension is pumped to the reactor tanks in an automatic semi-continuous state, being the discharge done during workweek.

In the digestors, anaerobic digestion (in a mesophilic range) takes place in a completely mixed reactor, so that: the maximum degradation can be achieved, the temperature and chemical proprieties can be the most homogenous possible, avoiding biomass sedimentation. This mixture is done by compressed biogas and the heat is recovered. About 50-55% of the organic matter is converted in biogas in 25-30 days. In order to avoid problems with $H_2S$, a diluted a $FeOH_2$ solution with atmospheric $O_2$ is injected.

The formed digestate passes a press that increases the solid content of the substrate and the released water goes to the water tank. With a continuous sludge circulation, the filtration is easier. The hygienization of the digestate happens in a thermophilic range (55-80°C) in 7-14 days. This pre-composting happens in a 14 day period and no additional energy is needed since the composting process is exothermic. Straw is used and the air is passed though forced aeration to control the oxygen present. Then, in the post composting stage (in an covered open area) the pre-composted material is stacked in a ventilated environment to ensure maturation for 12 weeks.

The produced biogas goes to a condensation collector filled with gravel, that also retains solid compounds (like foam) and the water contained in the biogas is removed. Then, the biogas is stored in a double-membrane gasometer with a ventilation system and a storage capacity of 4000 m$^3$. In case something happens, there is a flare to burn, for instances, the biogas excess. There are two biofilters in the system: a bigger one that treats the air from the ORS and another one to treat the air from pre-composting, that was already chemical treated (using acid scrubbing) before passing the biofilter. The biofilter bed composition was not available [92].

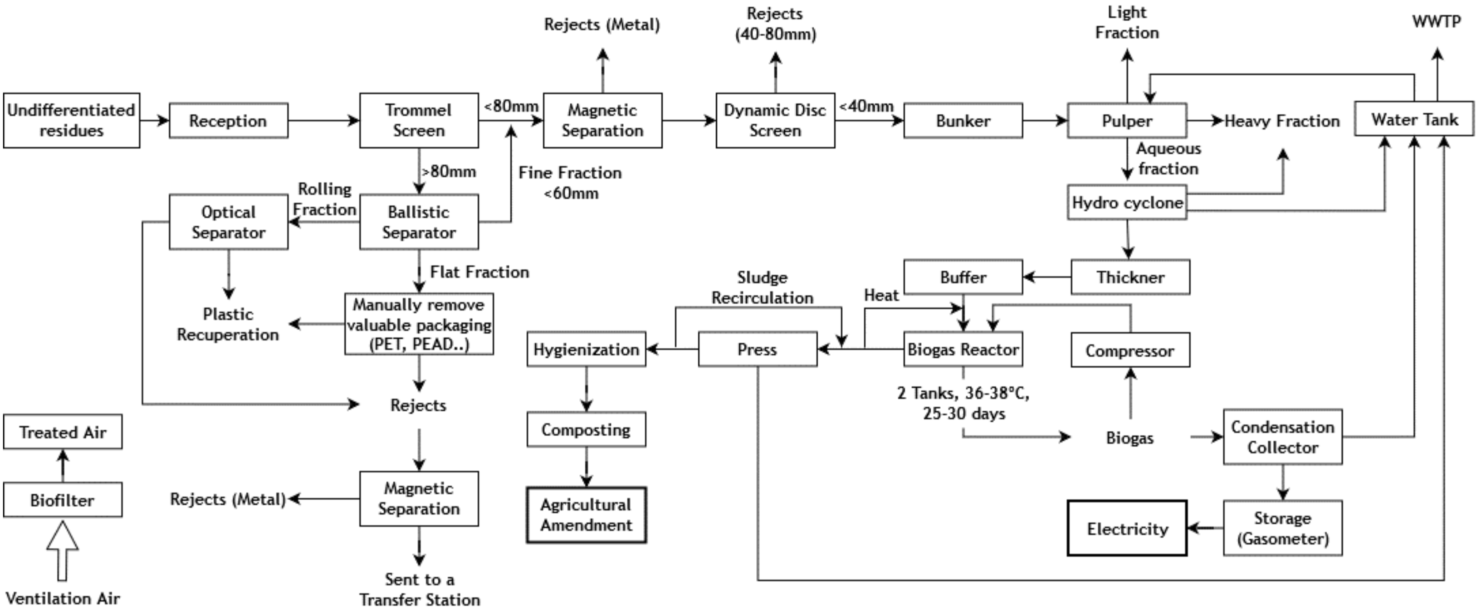

FIGURE 4-6 - PROCESS SCHEME OF THE SULDOURO'S ORS, ADAPTED FROM [24, 92]

The scheme presented in Figure 4-7 corresponds to Valorsul's plant. As stated, this system receives organic waste from big producers: restaurants, canteens, hotels, markets, among other businesses. After receiving the waste, in a closed discharge area with air treatment, this is sent to the pre-treatment step. Two main inputs are received: wet and dry waste. The wet waste (mostly from markets) is sorted out from the dry waste and they follow different paths. This system also can includes possible addition liquid waste (like cooking oils) that are sent directly to the anaerobic reactors.

The wet waste's particle size is reduced by hammer mills to a size about 15 mm. Then, this waste is stored in an equalizer tank and pumped to the hydrolysis tank. From the dry waste (restaurants, canteens, hotels), unwanted materials like glass, rocks, plastics are removed, through manual sorting and using a magnetic separator (the rejected materials are sent to incineration). Then, the waste is shredded and mixed with recirculated water in a pulper, which sorts out contaminants, reduces the particle size and provides final total solid content (around 3-5%). These contaminants are mostly heavy inert materials like glass, rocks, and metals. The substrate that exits the pulper passes a trommel screen that sorts out residual bigger materials (plastic, wood, paper) and fine, heavy, and inert ones (like sand). After this, the substrate passes a sand classifier (where sand sediments and plastics float) and goes to the hydrolysis tank, where it joins the wet fraction obtained after passing the hammer mills. In this stage, the easily biodegradable fraction of digestate is decomposed, through a pre acidification process, for about 2 days. Then, it is pumped to the two biogas reactors, operated in parallel and controlled in an independent way, where anaerobic digestion takes place – during about 21-22 days, with a temperature of 50 ºC. The $H_2S$ formation is controlled with gas mixed with very small air quantities, which is meant to suppress it.

The produced biogas is collected and treated by cooling and then compressing, being afterwards stored is a gasometer. Concentrations of methane, carbon dioxide, hydrogen sulphide and oxygen in the biogas are monitored. If needed, there is a flare to burn the biogas. Then, it is sent to the motor generators (with nominal power of 836 kW each) to produce electricity. The heat needed for the system's processes is obtained by the cooling of the motor. The generated electricity is enough to supply it to the infrastructures and commercialize.

The digestate is collected under the reactors and is dewatered by two parallel centrifuges – whose water is used in the process (and the excess sent to the WWTP). Then, the dewatered product goes to the composting process, which has a 15% w/w of structing material (woodchips). First, there is a pre composting in a ventilated – using the exhaustion air collected in the infrastructures - tunnel composting. After that, the post composting process matures the digestate in an open area, yet covered to avoid rain infiltration, for about 12 weeks (2 weeks in tunnel composting and 10 in post composting). In the end, the compost passes a sieve and a densimetric separation table and its ready to be stored and sold. All the air in the installation is collected and used as process air in the composting phase and treated afterwards in two biofilters (a closed one and an open one). The biofilters substrate’s specifications were not available. Before entering the open biofilter, the air passes through an acid scrubbing, to ensure the ammoniac removal. [90, 91, 95].

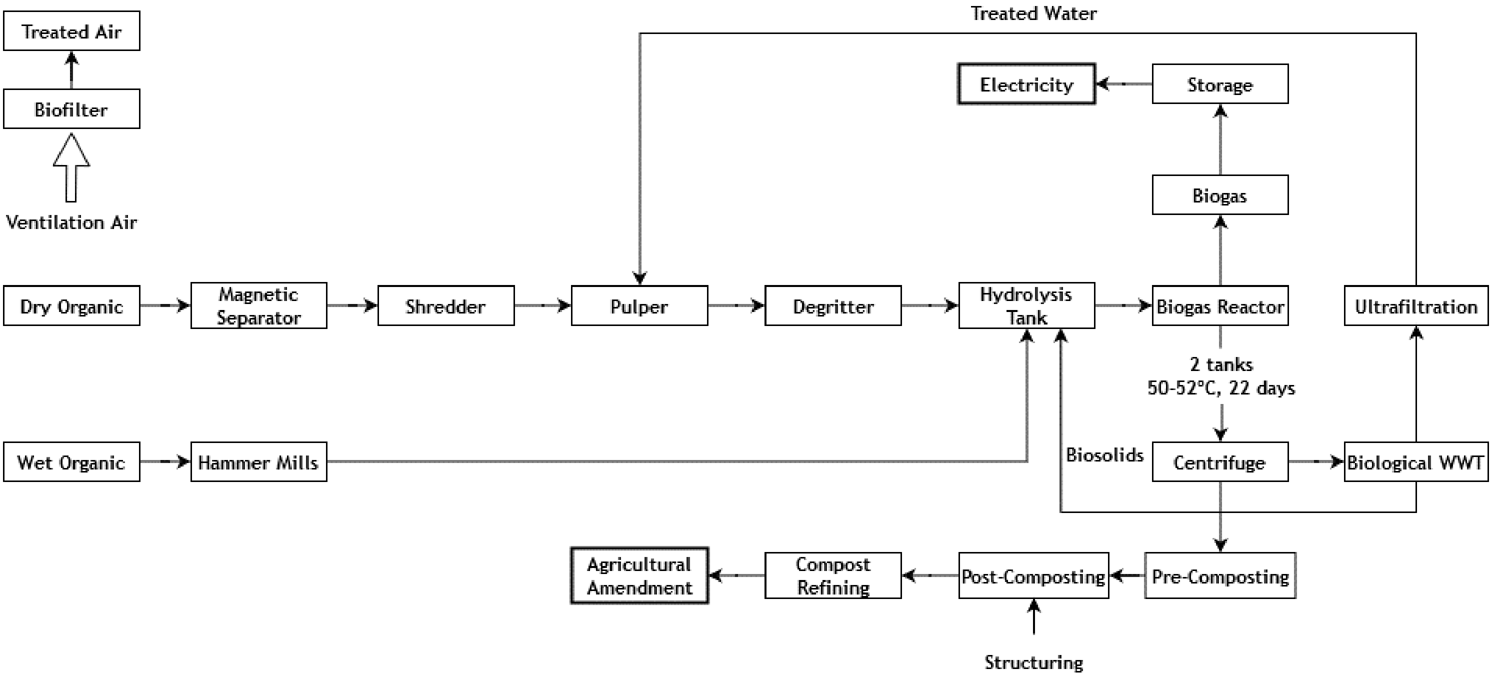

FIGURE 4-7 - PROCESS SCHEME OF THE VALORSUL'S ORS, ADAPTED FROM [90, 95]

Finally, the last process scheme – corresponding to Tratolixo's – is presented in Figure 4-8. The process scheme was provided by the system itself. It receives two different feedstocks: UW and wet organic waste from selective collection. They are discharged in two different reception pits. The pre-treatment starts with manual sorting, meant to remove large contaminants such as materials with high volume (e.g. bulky waste - furniture and mattresses) and other identifiable ones intended for recycling, like plastic and cardboard. Then, the waste flow passes through three trommel screens that not only reduce the particle size, but also open the bags with incorporated knifes. The waste fraction below 60 mm passes a magnetic separation process (overbands) and then by another sieve (flip flow), intended to reduce the inert content. The fraction below 15 mm (usually about 30%) can bypass further sorting. On the other hand, the fraction between 15 mm and 60 mm passes a shredder (that reduces the particle size to about 20 mm) and it is sent to a ballistic separator – sorting out heavy materials, like rocks and glass, fine materials and flat materials. The pre-treatment rejects are subjected to a magnetic separation (ferrous metals) and a Foucault current separator (non-ferrous metals). From this, the materials that can be recycled are sent to recycling and the rejects to landfill or to Valorsul's incineration plant.

The next stage is the anaerobic digestion. The sorted waste is mixed with recirculated digestate and with liquid effluent from the dewatering step ahead. This mixing step is performed in order to boost the process with the recirculation of bacteria and to regulate the TS content. The flow enters three biogas reactors and stays there for about 38 days in a mesophilic temperature (40°C). The homogenization is achieved without any mechanical equipment – the injection of compressed recycled biogas in the bottom not only promotes mixing, but also avoids the inert settling at the bottom. In the top of the reactor the biogas is collected, and if needed it can be burned. It passes a cleaning first filter, a second filter and desulfurization. The clean biogas is then directed to motor generators for energy production. Electricity is injected into the grid and the produced heat passes a heat exchanger (producing water vapour) meant to be used in the anaerobic digestion process.

Regarding the digestate, it is sent to the dewatering stage. It passes by three screw presses, 2 parallel sieves and 3 parallel centrifuges. The liquid effluent is treated in the WWTP at the site and being further recycled in the processes. The digestate is mixed with structuring material (a mixing of the rejected material in the refining step ahead (<12mm) and woodchips) so that there's an easier penetration/circulation of the air in the solid matter. After about 14 days in 10 ventilated tunnels, the it is sent to the maturation step (performed in mechanically stirred stacks), that takes about 4 weeks for bio-waste and 1 week for MSW. There are biofilters meant to treat the enclosed air. Next, the matured matter passes a sieve that reduces the particle size to maximum 12 mm and through a densimetric separation table. The rejects are sent to landfill. The compost is now ready to be stored and sold [96].

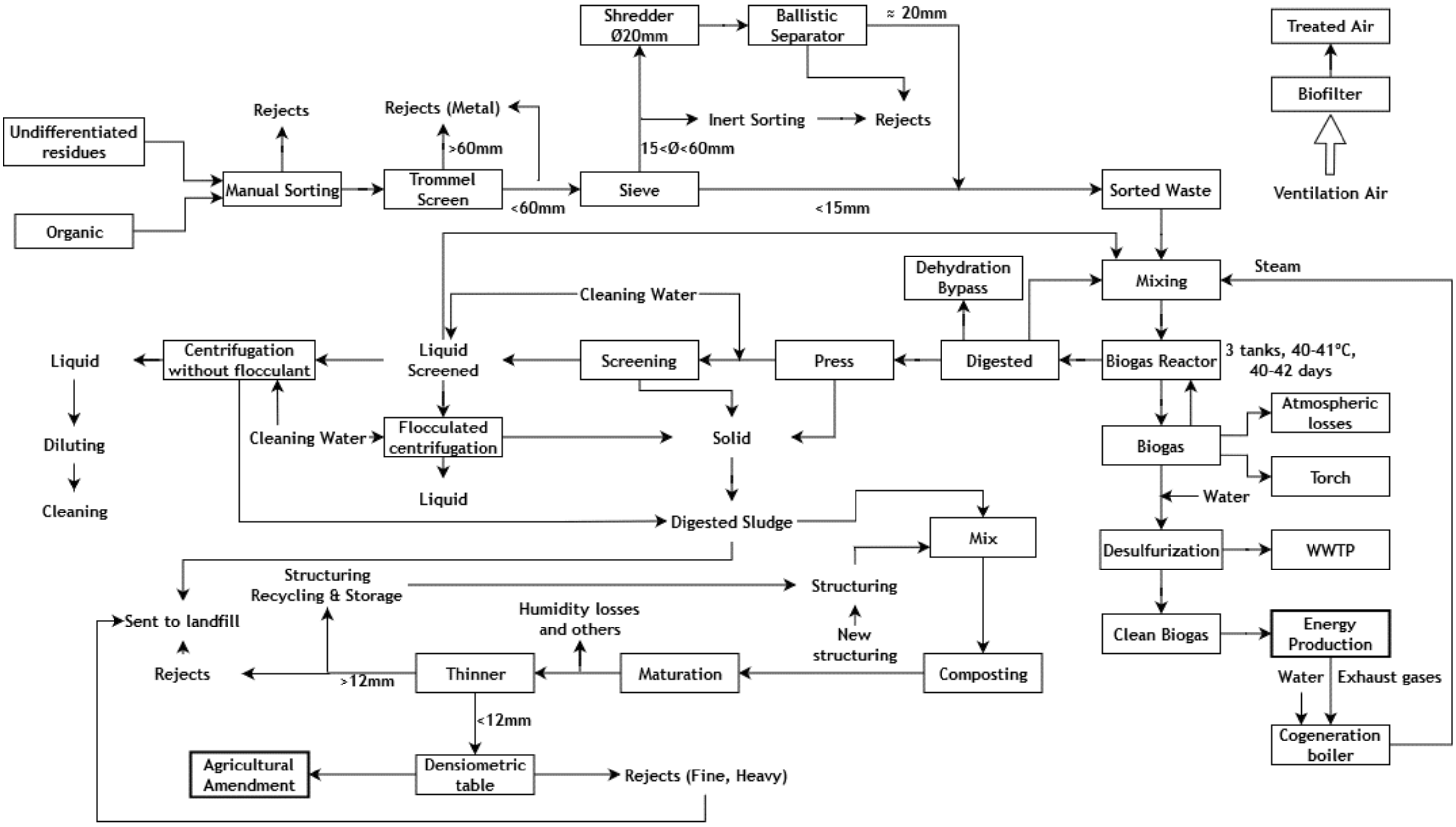

FIGURE 4-8 - PROCESS SCHEME OF THE TRATOLIXO'S ORS

#### 4.1.3.2. Concrete Study Case - EGE

In this document, a more detailed analysis will happen over EGE's food waste collection, as a criterion for being part of the WASTE2ROAD EU project. The data regarding the food waste collection in each week of each year (2016, 2017, 2018 and 2019) provided by the system, was reorganized into graphs for a better understanding. Below, in Figure 4-9, four graphs for each year are presented, regarding the collection of food waste from households.

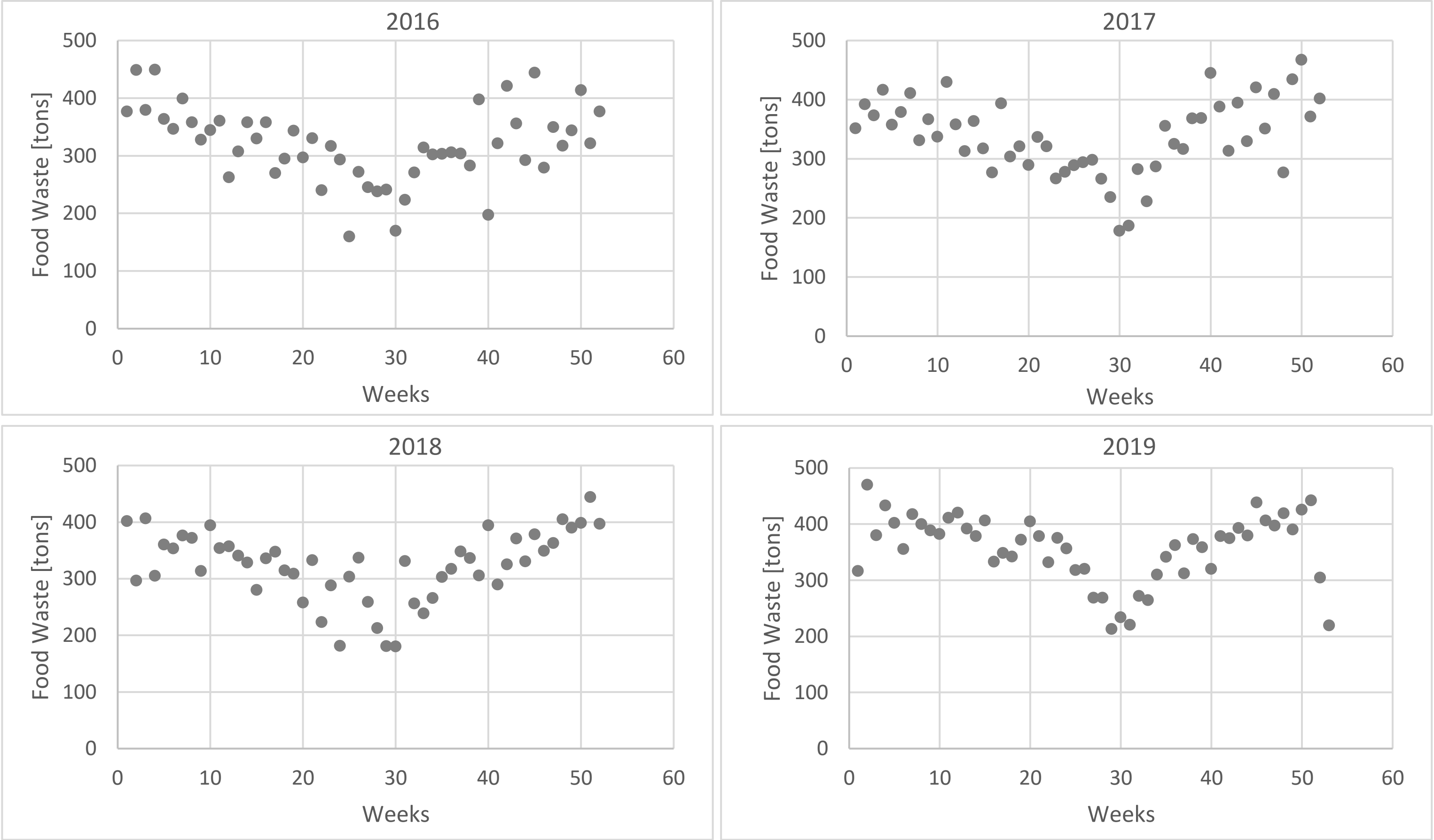

FIGURE 4-9 - RECEIVED FOOD WASTE, FROM HOUSEHOLDS, IN TONNES, BY THE EGE ROMERIKE BIOGAS PLANTS. FROM TOP LEFT: 2016, 2017, 2018 AND 2019

This figure shows that the received waste is consistent, having a break around the summer, in week 30 – which corresponds to mid-July, where vacations take place. As most Norwegian habitants enjoy their vacations in cabins (where the selective wet organic waste collection is hard), or abroad, the sorting of food waste is weaker. The most accentuated break happened in 2016 (with 160,02 tonnes in week 25 – 2 times inferior to the average - and 170,12 in week 30 – with a variation of 88%), even though not very extreme while comparing it to the other years. The higher values take place in the end and in the beginning of the year, being coincident with festivities such as Christmas and New Year, where the disposal of food waste is bigger.

In the years 2017 and 2019 (up and bottom right), there is a higher consistency of collection between weeks, since the dots are closer, when compared to the other years, in which a bigger dispersion takes place. This can be translated into a better recording of the waste data or a more efficient handling of the waste, avoiding fluctuations.

As it can be observed in Table 4-5, even though the waste collection rounds the similar values, in the years 2017 and 2019 the values were higher, where 2019 has the highest collection, about 19 thousand tonnes. It should be noted that an increasing value does not directly translates to a higher waste production. Norway's production of waste is indeed decreasing, as it can be observed in Table 4-1 and Table 4-2. Therefore, an increment in food waste collection seems to better interpreted as a better and efficient way of waste collection , which then reduces greenhouse gas emissions by producing biomethane, a gas that replaces fossil fuels in buses and heavy vehicles, and by enhancing circular economy, for the reasons previously stated. The production of the biofertilizer also contributes to this positive effect by replacing artificial fertilizers and returning the nutrients (carbon, nitrogen, phosphorus, and potassium) to the soil.

As stated before in 4.1.2 section, Oslo's EGE also receives industrial waste. Analogously, below it is possible to find the trends in the studied years concerning this industrial waste.

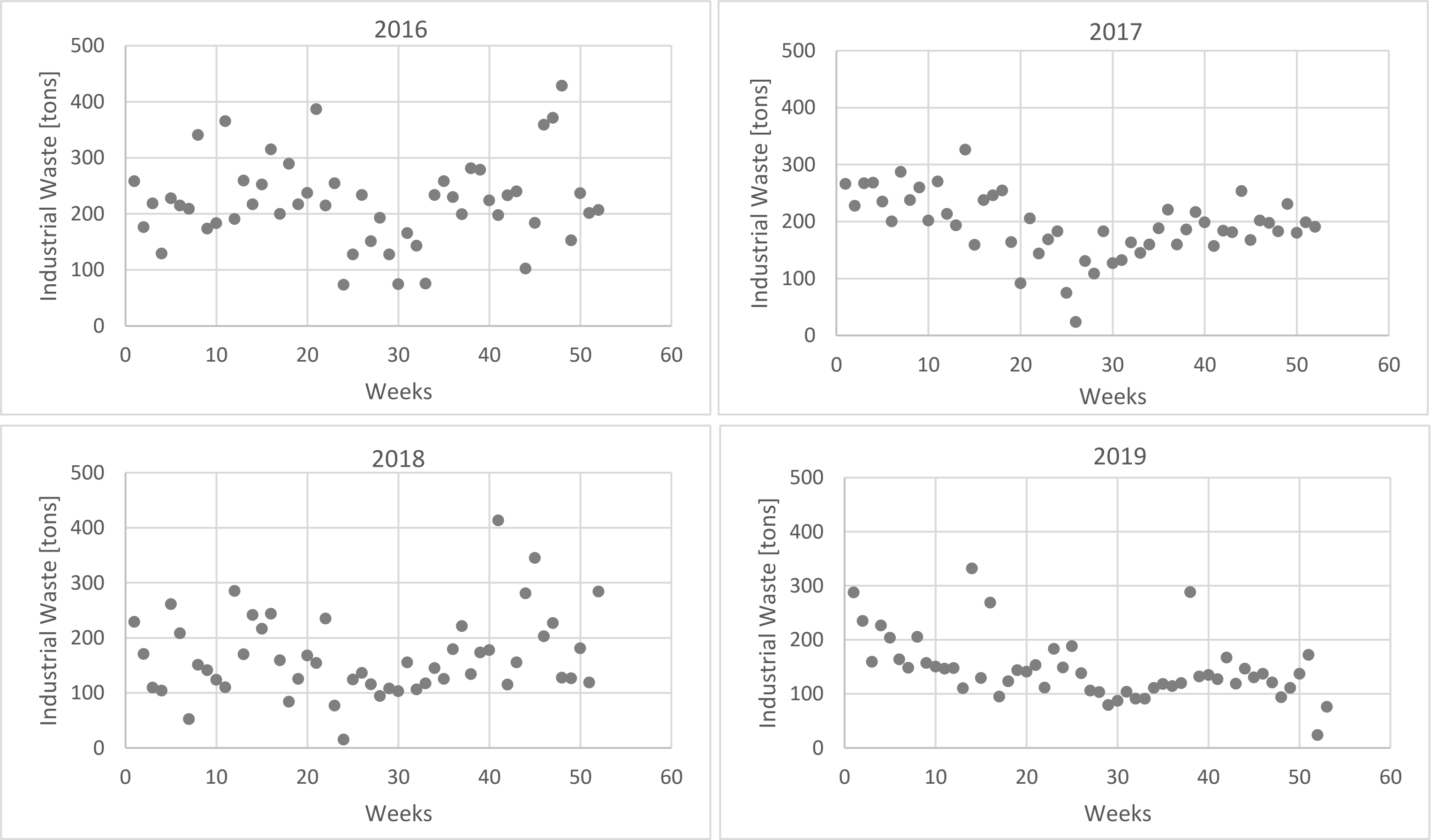

FIGURE 4-10 - RECEIVED INDUSTRIAL WASTE, IN TONNES, BY THE EGE ROMERIKE BIOGAS PLANT. FROM TOP LEFT: 2016, 2017, 2018 AND 2019

As it was obvious in Table 4-7, the collection of industrial waste by EGE has been falling over the years, since food waste collection is increasing – due to the installed capacity of the plant - 30 000 tonnes. In a similar way to the collection of food waste from households, in the year 2019 it was also verified a more consistent collection of industrial waste, and a less constant trend in the year of 2018. This can both mean a better and more efficient collection or a better recording of the data.

After an overall look, this type of waste does not seem to present a consistent collection pattern, antagonistically to what was observed for the food waste handling. However there seems to be a somewhat similar behaviour in the years 2016 and 2017, where there is a light break in mid-July as well. Other than that, this collection appears to be fairly constant.

As for the receival of manure, since the values are so low (Figure 2-1), there was no need to organize the data into graphs. Unlike the biogas plant in Greve, the Romerike biogas plant does not process manure on a regular basis. This type of feedstock is not for the time being EGE's focus. Any manure received in the last 3-4 years in the Romerike biogas plant was included in processing only for testing in order to develop the process for manure processing in the future.

## 4.2. Anaerobic Digestion – Biogas & Compost

### 4.2.1. Biogas

Although the process schemes differ from location to location, all of them rely on anaerobic digestion, where organic matter is biologically degraded without oxygen. In this section, data on biogas and compost production will be presented and compared for the selected locations in Norway and Portugal. Some of the presented values were provided directly by the waste management sites.

In the table below (Table 4-12), the produced biogas values are shown, corresponding to the raw biogas that comes out of the reactors, not upgraded. Therefore, it was possible to include a Portugal location, Tratolixo, since it is comparable. The waste management company only provided data for the years 2016 and 2018. Either way, the system reports that the data does not differ much in these years, and so these balances are representative. The other two Portuguese locations (Valorsul & Suldouro) are not shown in this table because the recorded biogas values were only translated in energy terms (Table 4-16).

As it was expected, in absolute terms, Greve produces annually a lot more biogas than RBA, since the overall waste collected is significatively higher (about 4 times more) – collecting also from more municipalities and a lot of manure from the farms. It is also observed that Tratolixo's biogas production appears to be equivalent to Greve's, being the only direct comparable year 2018 – in which Tratolixo's biogas production was only 3.4% superior to Greve's.

In Table 4-13, the specific value of biogas produced/entering waste is shown. Tratolixo's ratio of the produced biogas was 64% higher in 2018 when compared to Greve and 66% superior than RBA in 2016 – which may have to do with how the waste is handled and treated, and even due to differences in processes. When comparing the mean values, Tratolixo was 13.7% superior to RBA's production and 60.7% superior to Greve's. The most significative difference is in the temperature, HRT of the process and Total Solid Contents. While RBA and Greve operate in 38ºC and 37ºC respectively, Tratolixo operates in 40-41ºC. On the other hand, RBA and Greve have an HRT of 24 and 30 days respectively, and Tratolixo has a much higher value of 40-42 days. Regarding TS% content, RBA and Greve with 13-15% and Tratolixo with 37%, which may have an impact on such results. According to Guendouz et al [97] in high solid anaerobic digestion it is expected a higher biogas production efficiency.

TABLE 4-12 - BIOGAS PRODUCED FOR THE AVAILABLE LOCATIONS, IN NM3/YEAR [98]

| | | Norway | | Portugal |
|---|---|---|---|---|
| | | RBA | Greve | Tratolixo |
| Biogas Produced | 2016 | 2 907 955 | | 10 012 016 |
| | 2017 | 2 641 548 | 8 690 439 | |
| | 2018 | 3 031 923 | 10 059 791 | 10 404 433 |
| | 2019 | 4 912 822 | 11 568 127 | |

TABLE 4-13 - BIOGAS PRODUCED, IN NM$^3$, PER TONNE OF ENTERING WASTE

| | | Norway | | Portugal |
|---|---|---|---|---|
| | | RBA | Greve | Tratolixo |
| Biogas Produced per tonne of Entering Waste | 2016 | 96.3 | | 128.8 |
| | 2017 | 92.5 | 78.7 | |
| | 2018 | 112.3 | 82.1 | 134.7 |
| | 2019 | 162.3 | 85.2 | |

After the biogas is produced, some of it is flared (since it cannot be release into the atmosphere, due to its high methane content). This happens due to various reasons, such as the infrastructures not being able to treat all biogas, among others. RBA's flared biogas is oscillating a little bit, increasing a lot in 2019, due to the fact that the liquefaction system was not working. On the other hand, regarding Greve, even though the year 2018 was an abnormal year (with many nonconformities), in the next year the flared biogas decreased a lot, even when compared to 2017.This translates in a higher biomethane production and use, as it can be seen in Table 4-15. Tratolixo's flared biogas has also been decreasing.

The biogas that is not sent to the torch or to auto consumption is either sent to upgrading into biomethane (in Norway) - in order to be a fuel that can replace fossil fuels – or to the motor generators to transform it into electricity (Portugal), and take advantage of the heat. Thus, the sold product is different from raw biogas. These values are presented in Table 4-15 and Table 4-16. Once again, Greve's biogas plant achieved higher biomethane results per year, in absolute terms. The ratio of biomethane/biogas could be calculated since the upgrade that takes place in this system's infrastructure purifies biogas into 99% biomethane. It is interesting to note that the percentage of biomethane in raw biogas in Greve is also higher, which could be due to the original feedstock received (Greve also receives manure), since the process parameters (Table 4-11) are similar.

Table 4-14 - Volume of flared biogas in Nm$^3$

| | | RBA | Greve | Tratolixo |
|---|---|---|---|---|
| Flared Biogas | 2016 | 1 166 270 | | 658 436 |
| | 2017 | 793 728 | 153 154 | |
| | 2018 | 994 694 | 284 316 | 458 885 |
| | 2019 | 1 418 992 | 62 566 | |

Table 4-15 - Biomethane Production for Norway, in Nm3/year

| | | RBA | | Greve | |
|---|---|---|---|---|---|
| | | Biomethane | % in Biogas | Biomethane | % in Biogas |
| Sold Biomethane | 2016 | 1 121 951 | 64.42 | | |
| | 2017 | 1 185 950 | 64.18 | 5 446 397 | 62.45 |
| | 2018 | 1 362 954 | 66.90 | 5 832 592 | 57.98 |
| | 2019 | 1 471 166 | 52.76 | 7 076 616 | 61.17 |

As it was mentioned several times before, Portugal's organizations do not upgrade the biogas into biomethane, instead, they transform it into electric power through motor-generators, also taking advantage from the heat. In Table 4-16, the electricity produced is presented. The higher production comes from Tratolixo, which was expected, since it receives more waste (2 times more than Valorsul and 27% superior to Suldouro). Although, in the year 2016, both Suldouro and Tratolixo registered an equivalent waste entering the anaerobic digestion (with Suldouro being 12% superior, Table 4-10), however there is a huge difference in electricity produced. However, when compared the produced electricity per treated waste, Valorsul and Tratolixo's values don't differ that much: Valorsul's average production is only 4% higher than Tratolixo's. Suldouro has the lowest production per treated waste. Those differences might relate with processes specifications, such as HRT and temperature, and mostly total solids contents: Suldouro operates 10% of dry waste and Tratolixo has a TS% of 37% while Valorsul operates between 3-5%. It should be mentioned that in Tratolixo, in 2019 there was a breakdown in the motor generators in the 1st trimester.

Table 4-16 - Electricity Production for plants analysed in Portugal, in kWh/year [59-61, 64-66, 99, 100]

| | | Valorsul | Suldouro | Tratolixo |
|---|---|---|---|---|
| Electricity Production | 2016 | 10 899 000 | 4 618 000 | 20 033 000 |
| | 2017 | 9 915 000 | 4 234 000 | 21 105 500 |
| | 2018 | 9 200 000 | 1 553 000 | 21 225 800 |
| | 2019 | - | - | 21 190 420 |

Table 4-17 – Electricity Production for plants analysed in Portugal, in kWh/(tonnes.year)

| | | Valorsul | Suldouro | Tratolixo |
|---|---|---|---|---|
| Electricity Production per treated waste | 2016 | 268.5 | 140.5 | 257.8 |
| | 2017 | 271.9 | 187.9 | - |
| | 2018 | 262.5 | 128.2 | 274.3 |
| | 2019 | - | - | - |

### 4.2.2. Compost/Agriculture Amendment

The amount of fertilizer produced is presented in the table below (Table 4-18). It should be noted that Norway's fertilizer is liquid, there is no phase separation as it can be seen in section 4.1.3.1, in the processes schemes (only in RBA for specific biofertilizer type). Once again, Greve's fertilizer achieves higher values when compared to RBA due to larger amounts of waste treated (Greve treats an average of 4 times more), and possible higher quality (manure).

Since Tratolixo provided the process' mass balance, it was possible to point the most comparable value with Norway, the value which approximately corresponds to the digestate before it enters the press. Considering the typology of the waste received in the unit, it can be assumed that it is comparable – since the unsorted waste received already went through a mechanical treatment in other unit (<80mm). In 2018, this value was 81 159 tonnes, slightly inferior to that obtained at the Greve plant yet a similar value.

In Norway, the fertilizer production has been increasing overall, which contrasts with the two Portuguese locations: Valorsul and Tratolixo. According to their annual reports, for Valorsul, in 2018, the amount of fertilizer produced was very low because the infrastructures stopped almost a year for maintenance. For Tratolixo, in 2017, even though the number was lower (an almost 30% reduction) when compared to the previous year, it was reported that its quality increased. This happened due to the sieves' particle size reduction, avoiding some plastics, for example. The next year the value increased significantly due to improvements which reduced the rejects. Regarding Suldouro, the value is increasing throughout the years, producing the least quantity in 2016 (52% less than 2017 and 86% less than 2018).

Table 4-18 - Fertilizer produced in both countries in tonne/year

| | | Norway | | Portugal | | | |
|---|---|---|---|---|---|---|---|
| | | RBA | Greve | Valorsul | Suldouro | Tratolixo Final Fertilizer | Tratolixo before press |
| Fertilizer | 2016 | 44 849 | | 1 107 | 1 310 | 12 307 | 78 758 |
| | 2017 | 45 118 | 112 415 | 825 | 2 010 | 8 671 | |
| | 2018 | 33 775 | 103 566 | 669 | 2 440 | 11 334 | 81 752 |
| | 2019 | 47 778 | 124 679 | | | 9 870 | |

When organizing the data of produced fertilizer per treated waste (present in Table 4-19), it's possible to point out that the best performance belongs to RBA, with an obtained value superior to 1.2 in the four studied years. Nevertheless, Greve's performance has production of tonnes of fertilizer per tonnes of treated waste per year around 0.9. Such high values were expected due to the fertilizer being in a liquid form. Within the Norwegian's locations and between Valorsul and Suldouro, the values are in the within the same order of magnitude, with the exception of the year 2018 for Suldouro – which displays an unusual high value when comparing to the other years. The year 2016 was the year in which this entity produced less tonnes of fertilizer per treated waste (as it did when analysing absolute values). Tratolixo is the Portuguese system with the best performance, having an average production of 0.16 tonnes of agricultural amendment per tonnes of treated waste, per year – even though that Suldouro achieved the highest absolute value in 2018. It is interesting to note that the value corresponding to Tratolixo before the press and other thickening processes seems equivalent to Greve's, being only 15% higher.

TABLE 4-19 - TONNES OF FERTILIZER PRODUCED PER TONNE OF TREATED WASTE IN BOTH COUNTRIES PER YEAR

| | | Norway | | Portugal | | | |
|---|---|---|---|---|---|---|---|
| | | RBA | Greve | Valorsul | Suldouro | Tratolixo Final Fertilizer | Tratolixo before press |
| Fertilizer | 2016 | 1.5 | | 0.03 | 0.04 | 0.16 | 1.0 |
| | 2017 | 1.6 | 1.0 | 0.02 | 0.09 | | |
| | 2018 | 1.3 | 0.8 | 0.02 | 0.20 | 0.15 | 1.1 |
| | 2019 | 1.6 | 0.9 | | | | |

# Chapter 5. Discussion

Regarding anaerobic digestion, an energy balance for Valorsul and Greve's Biogas plant was performed. These were the selected systems due to data availability. Since both receive selective organic waste as its feedstock it was assumed that the systems were comparable. For the HTL technology, since the hydrothermal liquefaction processes are still being developed in a lab scale, it was compared to the AD technology with literature values. Additionally, an alternative scenario that combines both processes will be explored to take advantage from the biogas plant and the HTL technology, available on section 5.5.1.

## 5.1. Overall Waste and Biogas & Compost Assessment

The most obvious difference between the systems handling & collection is how the waste is collected (Figure 4-1 and Figure 4-3). Norway has a collection system that values source separation, with wet organic waste having its own green coloured collection bag. This type of collection facilitates optical sorting for valuable materials and avoids the need for pre-treatments of contaminant sorting and/or removal, when treating waste meant to be turned into biogas.

Regarding trends, overall municipal waste seems to be increasing in Portugal while in Norway is decreasing (Table 4-1). This may have to do with the different environmental education in both countries, or even with the economic instability of Portugal. Throughout the last four years, food waste in Norway has increased overall (Table 4-3), which is a positive outcome: a better sorting is taking place and consequently more food waste is being recovered. Additionally, over the years, more wet organic waste has been sent to biogas production – the value increased from 55.2% in 2016 to 81.0% in 2019.

The Norwegian selected locations (RBA and Greve Biogas Plant) both receive wet organic waste (Greve receives also manure) feedstock while the Portuguese locations differ. In their ORS, Valorsul receives selective collected organic waste from business (e.g. hotels, canteens, markets), Suldouro receives unsorted waste and Tratolixo received both unsorted waste (yet already went through a mechanical treatment - < 80 mm) and selective collected organic waste from businesses.

Throughout the years, RBA's entering waste has been slightly constant (with some oscillations) while Greve's has increased, as it can be seen in Table 4-9. RBA's lowest waste receiving happens in mid-July (Figure 4-9). RBA's main feedstock is household waste (between 55% and 63% through the years) followed by industrial wet organic waste (between 25%-39% through the years). In Greve, its main feedstock is manure (between 50%-57% through the years) followed by household waste (between 30%-35% through the years).

In the years 2017 and 2018, at Valorsul and Suldouro malfunctions or needed upgrades/cleaning in the Portuguese locations occurred at the ORS, affecting the interpretation of the collected data. Therefore, in these two systems the received waste is decreasing, which may not reflect the produced waste that could be handled. In the years with data availability for Tratolixo, 2016 and 2018, the received waste for the Anaerobic Digestion was constant, between 77 and 78 thousand tonnes.

Regarding the Anaerobic Digestion itself, the two Norwegian locations present similar parameters (Table 4-11) for total solid contents, temperature and hydraulic retention time. On the other hand, in the Portuguese entities, Valorsul stands out in the operating temperature (belonging to the thermophilic range, 50-52ºC) while in hydraulic residence time, Tratolixo operates at higher timeline, between 40-42 days, due to it's high solid content (37%). While both RBA and Greve upgrade the biogas into biomethane, meant to be used as a fuel for buses and heavy vehicles, the Portuguese locations transform it into electricity and heat.

When the biogas produced is compared by entering waste (Table 4-13), between RBA, Greve and Tratolixo, the highest value was recorded by RBA in 2019 (162.3 Nm$^3$/tonnes) followed by Tratolixo's values in 2016 and 2018 (in 2017 there was no data available), 128.8 Nm$^3$/tonnes and 134.7 Nm$^3$/tonnes respectively. Even though RBA produced more biogas per treated waste, it was also the system that burnt more biogas, being the highest value 1 418 992 Nm$^3$ in 2019 (Table 4-14). Regarding absolute values, Greve sold more biomethane than RBA, achieving in 2019 its highest value of 7 076 616 Nm$^3$ (Table 4-15). Electricity wise, Valorsul registered the highest values, even though Tratolixo reached the highest value in 2018 with 274.3 kWh/tonnes. Valorsul's average was only 4% higher than Tratolixo's average and 76% superior to Suldouro's average production.

Both RBA and Greve sell liquid fertilizer, therefore its high values when comparing the fertilizer produced per treated waste (Table 4-19) were expected, being RBA's average fertilizer production of 1.5 tonnes per tonnes of treated waste and Greve's being 0.9. Between the Portuguese locations the highest values correspond to Tratolixo (with the highest value being 0.16 in 2016). Valorsul and Suldouro's values were in the same magnitude order. When studying the Tratolixo's value of compost before the thickening processes, the reported values were comparable to the Norwegian's locations, with an average of 1.1.

## 5.2. Energy Balance

A simplified energy balance will be performed in order to compare the systems' energy efficiency to those reported on literature review for HTL. One location from Norway and another for Portugal were used. These two were chosen due to data availability. The obtained results were only used to have a simple idea of the system's performance, since many simplifications took place. In the Figure 5-1 below, a simplified scheme is shown.

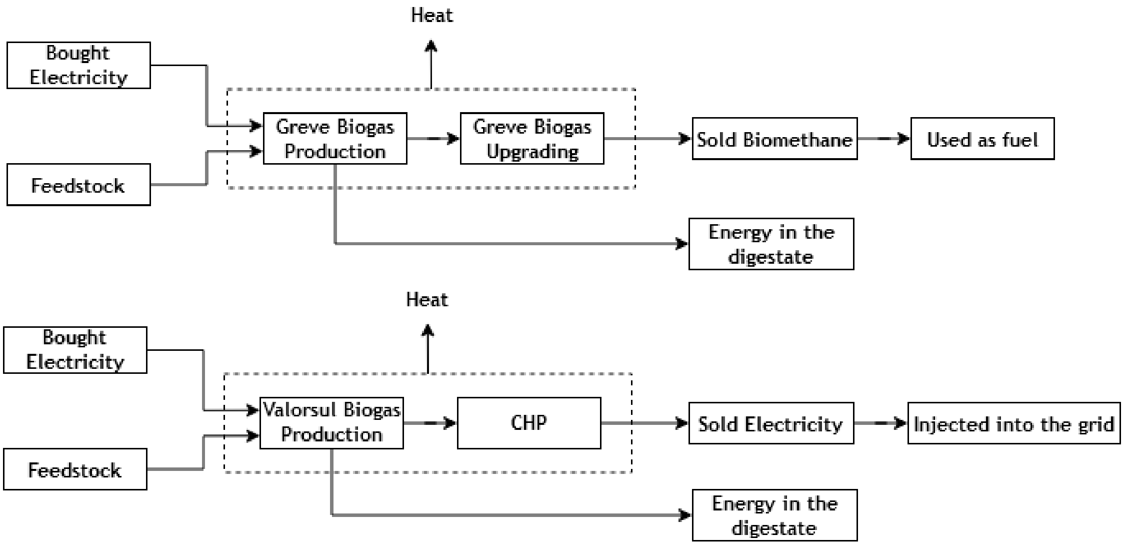

FIGURE 5-1 - SIMPLIFIED SCHEME OF THE ENERGY BALANCE IN BOTH SYSTEMS: GREVE (UP) AND VALORSUL (DOWN)

### 5.2.1. Energy Efficiency

A yield calculation regarding the electricity inputs and outputs was performed. The energy efficiency was calculated by the general equation: the energy input is divided by the energy output and multiplied by 100.

In both systems, the electricity used is bought (even though Valorsul transforms the produced biogas into electricity, in this unit, everything is injected into the grid and consequently exported). In Table 5-1, the electricity consumptions reported by the two locations are displayed. At first glance, it Greve's injected energy is higher than Valorsul's, but when the data is organized in supplied kWh/tonnes of wet treated waste, Valorsul's value is a bit, yet not significatively, higher. These

TABLE 5-1 - ELECTRICITY CONSUMPTION, IN KWH [61]

| | | Greve | Valorsul |
|---|---|---|---|
| Electricity Input | 2016 | | 3 898 000 |
| | 2017 | 5 939 485 | 3 713 000 |
| | 2018 | 6 589 647 | 3 594 000 |
| | 2019 | 7 236 095 | |

TABLE 5-2 - EXTERNAL ENERGY NEEDED IN KWH PER TONNES OF WET WASTE

| | Valorsul | Greve |
|---|---|---|
| 2016 | 96 | |
| 2017 | 102 | 54 |
| 2018 | 103 | 54 |
| 2019 | | 53 |

values are presented in Table 5-2. It can be concluded that processes needs are slightly similar energy wise, and even though Greve plant needs extra energy to upgrade the biogas to biomethane, the external energy input is still lower. This can be due to a better efficiency in handling and treatment (since the feedstocks from both locations are similar, apart from manure) since the pre-treatment step in both systems are comparable (see Figure 4-5 and Figure 4-7).

The input factor in the energy balance is the external electricity used (Table 5-1) and the energy content (EC) present in the food waste, as it can be seen in Figure C-1. According to [101], who evaluated the calorific power on different food waste groups (fruits, vegetables, meats, etc.) the common food waste has an average energy density of 14.31 MJ/kg, which corresponds to 3.975 kWh/kg, approximately. On the other hand, according to the *Phyllis 2* platform, swine manure High Heating Value (HHV) is about 16.93 MJ/Kg and cow manure is about 16.16 MJ/kg (for the total solids content assumed), which gives an average of 16.56 MJ/Kg (4.6 kWh/kg).

The first step to obtain the EC of the food waste is to calculate the quantity of dry feedstock. For Valorsul, the TS% content was admitted to be 26.5%, an average from the 'received dry feedstock' (29%) and the 'received wet feedstock' (24%), obtained from [91]. For Greve, it was admitted a TS% content of 27% for the food waste, 7% for the manure and 12% for the substrate received from Lindum. This information was organized in the two tables below.

TABLE 5-3 - WET FEEDSTOCK RECEIVED BY VALORSUL AND GREVE, IN TONNES [59-61]

| | Wet feedstock | | | |
|---|---|---|---|---|
| | Valorsul | Greve | | |
| | Biowaste | Manure | Food Waste | Lindum |
| 2016 | 40 600 | | | |
| 2017 | 36 469 | 63 171 | 47 060 | 172 |
| 2018 | 35 053 | 64 440 | 57 905 | 128 |
| 2019 | | 70 363 | 63 939 | 1531 |

TABLE 5-4 - DRY FEEDSTOCK RECEIVED BY VALORSUL AND GREVE, IN TONNES

| | Dry feedstock | | | |
|---|---|---|---|---|
| | Valorsul | Greve | | |
| | Biowaste TS% 26.5 | Manure TS% 7 | Food waste TS% 27 | Lindum TS% 12 |
| 2016 | 10 759 | | | |
| 2017 | 9 664 | 4 422 | 12 706 | 21 |
| 2018 | 9 289 | 4 511 | 15 634 | 15 |
| 2019 | | 4 925 | 17 264 | 184 |

In Table 5-5, the simplified food waste energy content is presented, by multiplying the energy content described above in kWh/kg with the dry feedstock (Table 5-4). Therefore, the total energy input is the sum of the EC present in the entering dry waste and the added electricity. The total input is present in Table 5-6.

TABLE 5-5 - ENERGY CONTENT OF THE RECEIVED FEEDSTOCK BY VALORSUL AND GREVE, IN KWH

| | Energy Content | |
|---|---|---|
| | Valorsul | Greve |
| | Biowaste | Food waste and Manure |
| 2016 | 42 767 025 | |
| 2017 | 38 415 533 | 70 930 144 |
| 2018 | 36 923 954 | 82 956 848 |
| 2019 | | 92 010 027 |

TABLE 5-6 – TOTAL ENERGY INPUT BY VALORSUL AND GREVE, IN KWH

| | Total Input | |
|---|---|---|
| | Valorsul | Greve |
| 2016 | 46 665 025 | |
| 2017 | 42 128 533 | 76 869 629 |
| 2018 | 40 517 954 | 89 546 495 |
| 2019 | | 99 246 122 |

Regarding the energy output, it was done differently for the two locations since the final product is different (Valorsul exports electricity while Greve upgrades the biogas into biomethane). According to Valorsul, the motor generator's efficiency is 30%, therefore the produced biogas will be the produced electricity divided by 0.3. On the other hand, Greve purifies biogas to 97% methane, and since 1 $Nm^3$ of pure methane corresponds to 10 kWh, thus the value was obtained multiplying the biomethane in $Nm^3$ by 9,7.

TABLE 5-7 - BIOGAS ENERGY CONTENT IN KWH PRODUCED BY VALORSUL

| | Valorsul | |
|---|---|---|
| | Electricity Produced [kWh] | Biogas Produced [kWh] |
| 2016 | 10 899 000 | 36 330 000 |
| 2017 | 9 915 000 | 33 050 000 |
| 2018 | 9 200 000 | 30 666 667 |
| 2019 | | |

TABLE 5-8 - BIOMETHANE ENERGY CONTENT IN KWH PRODUCED BY GREVE

| | Greve | |
|---|---|---|
| | Biomethane [$Nm^3$] | Biomethane [kWh] |
| 2016 | | |
| 2017 | 5 446 397 | 52 830 051 |
| 2018 | 5 832 592 | 56 576 142 |
| 2019 | 7 076 616 | 68 643 175 |

This way, the energy efficiency can be calculated. The values are present in the table below.

TABLE 5-9 - ENERGY EFFICIENCY OF THE TWO LOCATIONS: VALORSUL AND GREVE

| | Valorsul | Greve |
|---|---|---|
| 2016 | 78% | |
| 2017 | 78% | 69% |
| 2018 | 76% | 63% |
| 2019 | | 69% |

Looking at the numbers, since many assumptions and simplifications took place, it is plausible to conclude that both systems have a comparable performance. It should be noted that Greve's energy input also considers the upgrading unit; therefore, the overall efficiency is a little lower when compared to Valorsul's.

In Table 5-10, the energy produced per dry waste is presented. While the values are similar, Greve's are a little lower, an expected development due to the used feedstocks. Valorsul only uses bio-waste as its feedstock and instead, Greve used both manure (from cattle and from pigs) and food waste. Generally speaking, food waste and equivalent waste produce more volume of biogas than manure, since the latter already went through some digestion stages in the organism (see Figure C-1 in the annex section). Therefore, the use of both feedstocks ends up decreasing a bit the overall yield. However, the principal objective for the usage of manure is its ability to provide water later used in the process.

TABLE 5-10 - ENERGY PRODUCED IN KWH PER DRY WASTE IN KGS

| | Valorsul | Greve |
|---|---|---|
| 2016 | 3,377 | |
| 2017 | 3,420 | 3,08 |
| 2018 | 3,301 | 2,81 |
| 2019 | | 3,07 |

Assuming that the lost heat is 5%, it is possible to calculate the energy content present in the digestate (see Equation 1 in page VI). The obtained values are presented in the table below (Table 5-11).

TABLE 5-11 - ENERGY CONTENT OF THE PRODUCED DIGESTATE, IN KWH

| | Valorsul | Greve |
|---|---|---|
| 2016 | 8 001 774 | |
| 2017 | 6 972 106 | 20 196 096 |
| 2018 | 7 825 390 | 28 493 028 |
| 2019 | | 25 640 640 |

### 5.2.2. Use (Fuel & Electricity)

In both uses, by having waste as a feedstock, methane emissions of its deposition are avoided. By transforming the biogas in electricity through motor generators, there is a substantial loss of energy content in terms of heat (in the case of Valorsul, 70%), within the CHP unit. However, on the other hand, after upgrading the biomethane (meant to be used as a fuel), in the car combustion there is also energy loss as heat. This heat is not recovered – contrary to the heat released when the transformation into electricity takes place (be it for heating process water – like Valorsul does – or for *district heating*. Therefore, even if there is no heat loss within the system's boundary (in the upgrading) it will take place further in the chain.

According to [26], the typical efficiency of the using biogas derived fuel, energy wise, is located between 70% and 85%, taking into account factors such as «losses during biomass transport and storage», «efficiency of the digestion rate and methane losses», «energy needed for upgrading and energy requirements for biogas transportation». Additionally, using the biomethane as a substitute for fuel can reduce GHG in at least 60% when compared to gasoline (see Figure C-2 on the annex section) – being this one of the big advantages of using biomethane. This can be done either for light vehicles (a gasoline car can be converted in an NGV powered car by adding a second fuel supply system and storage cylinders for methane[15]) or heavy ones.

Statistically speaking, municipal waste from 250 persons during a year can power a distance of 60 000km [26], assuming that an average person in Portugal spends about 9 000 km per year [102], and a Norwegian 12 390km [103], it was possible to estimate how many people could drive per year fuelled only by biomethane (BM) (in a scenario where Portugal upgrades biogas). It was used the average habitants from the years 2016, 2017 and 2018 for Portugal plus 2019 for Norway. Due to the high population covered, the highest value is from Valorsul. Knowing that the use of pure biomethane as a fuel emits 5 g $CO_2$eq/km and that Petrol emits 164 g $CO_2$eq/km [104] (around 33 times more) it was possible to estimate the quantity of emissions that could been saved (Figure C-3). This data is presented is the table below (Table 5-12).

TABLE 5-12 - ESTIMATIVE OF THE QUANTITY OF PEOPLE THAT CAN DRIVE SOLELY ON BIOMETHANE FOR EACH SYSTEM AND RESPECTIVE EMISSIONS IN TONNES OF $CO_2$EQ/KM

| | Norway | | Portugal | | |
|---|---|---|---|---|---|
| | EGE | Greve | Valorsul | Suldouro | Tratolixo |
| Habitants [average] | 669 922 | 338 530 | 1 591 946 | 438 953 | 854 196 |
| Distance with BM [km] | 160 781 340 | 81 247 200 | 382 066 960 | 105 348 640 | 205 007 120 |
| Person/year | 12 977 | 6 557 | 42 452 | 11 705 | 22 779 |

| | | | | | |
|---|---|---|---|---|---|
| Emissions Petrol | 26 368 | 13 324 | 62 658 | 17 277 | 33 621 |
| Emissions Pure BM | 804 | 406 | 1 910 | 527 | 1 025 |

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[15] According to [26], this option costs about 2 000 EUR, being the most expensive parcel the cylinders

Looking in an electricity point of view, Norway is a country whose electricity is based already in renewable sources. Its RES-E value in 2018 was 107% (with 97% of its electricity originated from hydropower), meaning that renewable energy status was already achieved. However, in Portugal, the RES-E in 2018 was 52%. Therefore, it is understandable each countries priority: Norway has no need to transform biogas into electricity, while Portugal has. Additionally, national politics that favour the upgrading of biogas to biomethane must be enforced, since it can be a costly measure without any help/incentive. From Figure C-4 in the annex section, it was possible to estimate how much the upgrading would cost for Tratolixo, since it is the only Portuguese location with biogas production values available. Having an average production of 1 165 Nm$^3$/h (having an average of 10 208 225 Nm$^3$/year), the treatment with the cheapest option (water scrubber from Greenlane) can have a cost between 0.1 and 0.15 \$/m$^3$ of $CH_4$. In a year, this would translate into an additional cost of 1 020 822\$ to 1 531 233; assuming 1\$ as equivalent to 0.89€ (average value from 2019 [105]) it would equal to 908 532€ to 1 362 797€ per year.

Another challenge is of its use as biofuel for individual transport is the need for filling stations. This is the major step that needs to be taken if this is the objective. The transportation of biomethane could be done either by trucks (in high-pressure, liquified), or, if close, through the public gas grid (or a local gas pipeline), in a compressed gaseous state. The most economic option would be the transportation by the gas grid [26]. For this one, the associated costs are regarding the grid injection and the transport itself. However, not every country has a solid NGV infrastructure, which may incur additional costs. In Norway, the biomethane is being used on heavy vehicles (buses and collection trucks) since one big advantage of this biofuel is its high density: it can withstand longer distances with the same fuel storage category. And, regarding heavy vehicles, not many renewable energy sources are available. Its filling is done in the respecting bus garage.

## 5.3. Nutrients Cycle – AD VS HTL

In a biogas plant, the digestate matter can be turned into a biofertilizer (liquid phase). In this sense, important nutrients such as Nitrogen, Phosphorus and Potassium are returned to the soil in the form of a biofertilizer, closing the cycle – no external feedstocks are added, promoting a circular economy. It provides both to the soil and to the plants relevant macro and micronutrients that in industrial scale agriculture would have to be obtained from synthetic origins. When compared to manure used as fertilizer, digestates have a higher ammonium content and overall nitrogen ratios, with lower carbon content and organic matter. Additionally, the carbon cycle is also closed, due to the fact that the stored carbon within the lifecycle of the waste product is returned to the soil, once again, avoiding external input.

As for the HTL technology, the phase rich in nutrients and organic compounds is the aqueous phase (being able to accumulate almost 80% of nutrients and some organics [106]). As mentioned in

2.4.2.2, in HTL not only lipids are converted in a fuel like product, but also proteins and carbohydrates. Therefore, the large part of valuable nutrients such as nitrogen and phosphorus are present in the aqueous product, where the bio-oil is present, not returning them to the soil. Instead, these nutrients will be present in the form of future emissions when the fuel combustion takes place. However, in order to recover or recycle these nutrients, some authors suggest the fermentation or anaerobic digestion of the aqueous phase or a two-step sequential hydrothermal liquefaction – improving the overall quality of the bio-oil and the production of product of high contents of phosphate, organic nitrogen and polysaccharides. This recovery of nutrients has been used for microalgae cultivation [107].

## 5.4. Anaerobic Digestions VS HTL

Regarding the energy balance, since it is still a developing technology, not many studies that consider the external electricity needed are available. Most of them only consider the product conversion energy, in terms of heating values. According to [108], the overall energy efficiency for HTL for woody biomass is about 52%, taking into account the energy in biomass, natural gas and required electricity. The obtained product was estimated to have a minimum fuel selling price of 4.44$/GGE[16] (the average price around the world for gasoline is 3.60$/gallon[17] [109]). Comparing with the obtained values in Table 5-9 (an average of 77% for Valorsul and 67% for Greve), if fully developed, this technology may achieve competitive values towards AD. Using HTL on food waste, the expected HHV is about 30-35 MJ/kg [51, 52, 54] while using AD the expected value of the biogas is between 20-23 MJ/kg [110, 111]. If upgraded to biomethane, the HHV is at least 37 MJ/kg [112]. Comparing these values, as fuels, the biofuel resulting from HTL is comparable with biomethane.

What makes the HTL a promising technology when compared to AD is its ability to withstand wet feedstock, without having the need to dry it – since the feedstock with be diluted in a solvent (being water the most common). Even regarding the pre-treatment step regarding particle size, it does not need to be so intensive as in the AD process. All these points can translate into an economic gain, however, a more intensive economic analysis must take place – since in the HTL technology high pressures a moderate temperatures must be achieved.

Through the HTL technology, a bio-oil (hereafter upgraded to biofuel) is produced. Its main challenges also include the same pointed out in the biogas upgrading, like the need for filling stations. However, for individual vehicles, there is no need to convert to a NGV car, since the upgraded bio-oil from HTL is considered to be a drop-in biofuel (refer to 2.1), contrary to what happens to biomethane as fuel. Additionally, the biomass conversion is more efficient than when using AD producing biogas.

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[16] Equivalent to 3.95€/GGE, with the average exchange in 2019

[17] Equivalent to 3.20€/gallon, with the average exchange in 2019

When used as a fuel, both fuels generally reduce GHG emissions. According to literature, the NOx (dissociation of N through combustion) emissions in the HTL processed fuel are dependent in the engine itself and its operation conditions, even though many studies assume that a high content in N feedstock will generate more $NO_x$ emissions. For sulphur emissions, the general conclusions are that the S present in the biofuel will always produce harmful emissions. While most of its stated emissions are lower than when diesel is used as fuel, in certain feedstocks (e.g. certain algae species) while emissions such as PM, HC and CO are lower, in some cases $NO_x$ emissions for the same species are either superior or inferior – showing data uncertainty. Nevertheless, studies regarding HTL biofuel's emission are still in early development, with many theoretical hypotheses – and studies that consider the engine's conditions are lacking. Additionally, most of the studies are regarding microalgae feedstock. Regarding biomethane as a fuel, studies about its emissions are more available. A reduction of about 18-21 $MtCO_{2eq}$ can be achieved using food waste as feedstock. When compared to other options such as natural gas or fuel cell electric vehicles, biomethane has lower GHG in its life cycle. The harmful $NO_x$ emissions from heavy vehicles can be reduced, for example. Another advantage is the noise reduction, very noticeable in urban traffic.

## 5.5. Scenario: Combination of a Biogas Plant and HTL Process

A scenario where a biogas plant is combined with the HTL process is presented here as to highlight the best of both processes.

### 5.5.1. Performing HTL on the digestate

In a study performed by Hoffman et al [39], a simulation in the *Aspen Plus* software was assessed, to evaluate the it's sustainability. Mainly manure was used as a feedstock. Its main conclusions were that 1000 kg/h of manure could originate 30-38 kg/h of fuel and 38-61 kg/h of biogas. In other words, at least 30% of fuel and 38% of biogas could be obtained by combining these two processes.

A simplified overview of the process is on **Error! Reference source not found.**. As it can be see, the HTL plant would receive the digestate and would convert it into biocrude, among other by-products (see Figure 2-4 and the text above): a solid fraction, a liquid/aqueous phase and a gas phase. After the separation of the biocrude, the other secondary products (mainly waste water) would be sent to be transformed into a soil amendment. This way, important nutrients would be returned to the soil. The biocrude would go to the upgrading unit (being the subject of deoxygenation and other important chemical reactions) and finally transformed into biofuel. The biogas product from the biogas plant would be used to form hydrogen (after passing through a membrane separator), later used in the upgrading unit and/or to generate heat and electricity for auto consumption.

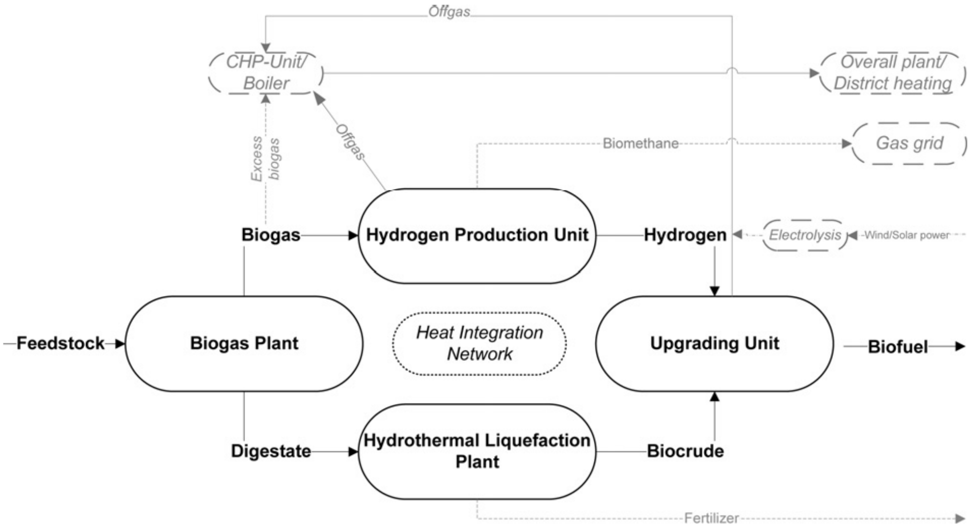

FIGURE 5-2 - SCHEMATIC VIEW OF THE EVALUATED PROCESS, ADAPTED FROM [39]

Therefore, there are 4 important stages taking place:

- Anaerobic Digestion: where the manure gets degraded by organisms, forming biogas and digestate (see section 2.3.1 in page 25)
- Hydrogen Production: where the biogas would originate hydrogen with the addition on water[18], with a conversion of methane of 75%
- Hydrothermal Liquefaction (see section 2.4.2.2 in page 32)
- Upgrading the biocrude (see section 2.4 in page 28)

Looking at the locations in study, the only one that could take advantage of this would be Greve, since it is the only one with enough manure supply. However, it is expected that it has a positive outcome and can be explored for other scenarios, using other types of feedstock such as wet organic waste and perhaps unsorted waste as well.

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[18] $CH_4 + H_2O \rightarrow 3H_2 + CO$
$CO + H_2O \rightarrow CO_2 + H_2$

# Chapter 6. Conclusions

In the present work, 2 Norwegian waste treatment locations and 3 Portuguese locations were compared, regarding its waste collection & handling, treatment and products obtained, along with the comparison of two technologies: Anaerobic Digestion and Hydrothermal Liquefaction. The study allows for a better understanding of the different methods of waste handling at the two countries.

The performance of the Anaerobic Digestion is conditioned since the beginning: both RBA and Greve Norwegian plants collect wet organic waste sorted at the source (door-to-door collection) while the organic waste selective collection in the Portuguese entities takes place mostly for business, for Valorsul and for Tratolixo (Suldouro does not perform selective collection on this waste flow). Greve was the only studied system which used manure as substrate. Regarding the treatment of waste, Suldouro plant has the most intense mechanical pre-treatment since it receives only unsorted waste, although at Tratolixo plant mechanical treatment occurs previously.

Between RBA, Greve and Tratolixo the highest absolute production of biogas per tonnes of treated waste was verified for the RBA plant in 2019, with 162.3 Nm$^3$/tonnes, even thought it was the system that burnt more biogas, 1 418 992 Nm$^3$ in 2019. When comparing the mean production, Tratolixo had a result around 14% higher to RBA's production and around 61% higher than that of Greve's plant. Regarding electricity, produced in Portugal, Valorsul registered the highest values, even though Tratolixo reached the highest value in 2018 with 274.3 kWh/tonnes. Valorsul's mean values were only 4% higher than that of Tratolixo's and 76% higher than Suldouro's mean production. RBA and Greve plants produce liquid fertilizer, with a production of 1.5 tonnes per tonnes of treated waste for RBA and Greve's being 0,9. Within the Portuguese locations, the highest value related to the production of the solid amendment corresponded to Tratolixo (with 0,16 in 2016). However, as it was expected, when the used value was corresponding to the compost before thickening processes, the value increased to the same order of magnitude as the Norwegian locations, achieving an average of 1.1 (Tratolixo values).

When comparing the energy efficiency between Valorsul and Greve plants, due to the simplifications that took place, it was admitted that the obtained performances were comparable – Valorsul with an average value of 77% and Greve with 67%.

Even though transforming biogas into electricity releases heat (Valorsul has a 30% efficiency) and upgrading it into biomethane in the facilities does not, the heat loss will take place in the car combusting system, latter in the chain. Between these two products, biomethane seems favourable due to its reduction of GHG, by substituting other fuels. However, its usage into light vehicles is not so easy, and the car needs to be converted into an NGV powered car. On the other hand, this upgrading can be expensive. If Tratolixo intended to upgrade the biogas produced into biomethane, it might translate into an additional cost of 1 020 822$ to 1 531 233$ (908 532€ to 1 362 797€) per year. Another challenge is the need for filling stations if it is meant for individual transport.

Since the Hydrothermal Liquefaction technology is still being developed, not so many conclusions can be drawn. Overall energy efficiencies for HTL (about 52% for woody biomass) are still lower than those obtained for Valorsul and Greve, and the reported Higher Heating Values on food waste are about 30-35 MJ/kg for HTL, 20-23MJ/kg for biogas and 37 MJ/kg for biomethane. However, the HTL technology can withstand wet feedstock and thus avoid the need to dry it, translating into an economic gain. Additionally, the particle size on HTL does not need to be as controlled as on AD. A good advantage of HTL is that the final upgraded product is a ‘drop-in’ biofuel, which contrasts with biomethane. Therefore, there is no need to convert the gasoline or diesel cars into NGV powered cars. Regarding emissions, both technologies are reported to reduce GHG emissions, even though more studies about HTL’s product need to be made.

## 6.1. Limitations & Future Perspetives

The biggest limitations on this work were the lack of data on HTL technology (since it is still under development) and regarding the data presented by the 5 studied systems: some data was missing and due to different raw material composition it’s comparison was difficult.

In this sense, a study considering practical results should be performed on HTL, using samples of each waste treatment plant, in order to allow for a more direct comparison – namely to perform energy and mass balances. Additionally, to achieve homogeneity in data, certain parameters such as the composition and quantity of waste that entered the treatment, energy consumptions and biogas production should be known through tests or directly obtained from the entities selected for comparison.

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# Annex Section

## A. Renewable Energy: National Targets

TABLE A-1 - NATIONAL OVERALL TARGETS, TAKEN FROM [8]

| Country | Target for share of energy from renewable sources in gross final consumption of energy, 2020 [%] | Country | Target for share of energy from renewable sources in gross final consumption of energy, 2020 [%] |
|---|---|---|---|
| Belgium | 13 | Luxembourg | 11 |
| Bulgaria | 16 | Hungary | 13 |
| Czech Republic | 13 | Malta | 10 |
| Denmark | 30 | Netherlands | 14 |
| Germany | 18 | Austria | 34 |
| Estonia | 25 | Poland | 15 |
| Ireland | 16 | Portugal | 31 |
| Greece | 18 | Romania | 24 |
| Spain | 20 | Slovenia | 25 |
| France | 23 | Slovak Republic | 14 |
| Croatia | 20 | Finland | 38 |
| Italy | 17 | Sweden | 49 |
| Cyprus | 13 | United Kingdom | 15 |
| Latvia | 40 | | |
| Lithuania | 23 | | |

# B. Municipalities, Habitants and Waste

## B.1. Portugal's Bio-waste rate in municipal waste

TABLE B-1 – URBAN BIO-WASTE, IN PERCENTAGE, COLLECTED IN PORTUGAL IN 2016, 2017 AND 2018 , TAKEN FROM APA

| Year | 2016 | 2017 | 2018 |
|---|---|---|---|
| Bio-waste % | 37,2 | 36,56 | 36,40 |

## B.2. Portugal's Valorsul, Suldouro and Tratolixo Plants

TABLE B-2 – MUNICIPALITIES COVERED BY VALORSUL AND RESPECTIVE HABITANTS AND RECEIVED WASTE IN TONNES, ADAPTED FROM

| Municipalities | Alcobaça | Alenquer | Amadora | Arruda dos Vinhos | Azambuja |
|---|---|---|---|---|---|
| | Bombarral | Cadaval | Caldas da Rainha | Lisboa | Loures |
| | Lourinhã | Nazaré | Óbidos | Odivelas | Penicha |
| | Rio Maior | Sobral de Monte Agraço | Torres Vedras | Vila Franca de Xira | - |

| Year | 2016 | 2017 | 2018 |
|---|---|---|---|
| Habitants | 1 586 020 | 1 591 763 | 1 598 054 |
| Received Waste | 765 064 | 795 453 | 832 350 |
| Received Bio-waste | 40 600 | 36 469 | 35 053 |

TABLE B-3 -MUNICIPALITIES COVERED BY SULDOURO AND RESPECTIVE HABITANTS AND RECEIVED WASTE IN TONNES, ADAPTED FROM

| Municipalities | Santa Maria da Feira | Vila Nova de Gaia |
|---|---|---|

| Year | 2016 | 2017 | 2018 |
|---|---|---|---|
| Habitants | 439 759 | 438 651 | 438 448 |
| Received Waste | 169 415 | 193 336 | 201 227 |
| Waste in ORS | 88 372 | 61 644 | 33 270 |

TABLE B-4 - MUNICIPALITIES COVERED BY TRATOLIXO AND RESPECTIVE HABITANTS AND RECEIVED WASTE IN TONNES, ADAPTED FROM

| Municipalities | Cascais | Mafra | Oeiras | Sintra |
|---|---|---|---|---|

| Year | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Habitants | 849 924 | 853 965 | 858 700 | 858 700[19] |
| Received Waste (Municipalities) | 411 697 | 422 206 | 444 972 | 446 174 |
| Received Waste (Private) | 4 218 | 7 880 | 10 556 | 9 029 |
| Received Bio-waste | 47 425 | 49 710 | 57 703 | 51 467 |

## B.3. Norway's Biogas Plants

TABLE B-5 - NORWAY'S' BIOGAS PLANTS WITH ITS RESPECTIVE FEEDSTOCK, OUTPUT AND USE, ADAPTED FROM [113]

| Plant | Location | Feedstock | | | | Biogas [GWh] | Use |
|---|---|---|---|---|---|---|---|
| | | Sewage Sludge | Manure | Food Waste | Industrial Waste | | |
| Ecopro | Verdal | x | | x | | 30 | CBG |
| Biokraft | Skogn | | | | x | 250 (design) | LBG |
| Mjøsanlegget | Lillehammer | | | x | | 27 | CBG |
| IVAR sentralrenseanlegg Nord | Jæren | x | | | | 30 | Inserts to the grid |
| IVAR biogassanlegg Grødaland | Hå | x | | x | x | 70 | Inserts to the grid |
| HRA Hadeland og Ringerike Avfallsselskap | Jevnaker | | | x | | 22 | CBG |
| Romerike biogassanlegg | Vormsund | | | x | x | 28 | LBG (CBG Backup) |
| VEAS | Slemmestad | x | | | | 69 | Installing LBG now |
| Lindum | Drammen | x | | x | x | 23 | CBG |
| Greve Den magiske fabrikken | Tønsberg | | x | x | x | 65 | CBG |
| FREVAR | Fredrikstad | x | | x | x | 29 | CBG |
| Borregaard | Sarpsborg | | | | x (wastewater) | 56 | Internal use for drying |
| Norske skog Saugbrugs | Halden | | | | x (wastewater) | 27 | CBG |
| Other small plants | - | | | | | 124 | - |

## B.4. Norway's EGE and Greve Plants

TABLE B-6 - MUNICIPALITIES COVERED BY EGE AND RESPECTIVE HABITANTS AND RECEIVED WASTE IN TONNES, ADAPTED FROM

| | |
|---|---|
| Municipalities | Oslo |

| Year | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|
| Habitants | 658 390 | 666 759 | 673 469 | 681 071 |

---

[19] Since there are not official data from 2019, the population number from 2018 was used as an approximation value

| | | | | |
|---|---|---|---|---|
| Received Waste | 16 635,33 | 17 577,93 | 16 853,37 | 18 936,22 |

TABLE B-7 - MUNICIPALITIES COVERED BY GREVE AND RESPECTIVE HABITANTS AND RECEIVED WASTE IN TONNES, ADAPTED FROM

| | Habitants | | |
|---|---|---|---|
| Municipalities | 2017 | 2018 | 2019 |
| Asker | 60781 | 60926 | 61523 |
| Askim | 15720 | 15810 | 15865 |
| Aurskog-Høland | 16162 | 16390 | 16500 |
| Bamble | 14138 | 14183 | 14089 |
| Drammen | 68363 | 68713 | 68933 |
| Eidsberg | 11406 | 11414 | 11424 |
| Enebakk | 10927 | 10945 | 11026 |
| Færder | - | 26734 | 26700 |
| Florø | 11999 | 11988 | 11852 |
| Gjerdrum | 6546 | 6704 | 6823 |
| Halden | 30790 | 31037 | 31177 |
| Hobøl | 5557 | 5621 | 5642 |
| Holmestrand | 27202 | 27317 | 27334 |
| Horten | 27202 | 27317 | 27334 |
| Hurum | 9462 | 9450 | 9521 |
| Kongsberg | 27216 | 27410 | 27481 |
| Kragerø | 10586 | 10506 | 10406 |
| Larvik | 44922 | 45360 | 45976 |
| Lier | 25740 | 25980 | 26373 |
| Lillestrøm (2020-) | - | - | - |
| Lørenskog | 37406 | 38670 | 40106 |
| Marker | 3597 | 3567 | 3592 |
| Modum | 13786 | 13880 | 13980 |
| Nedre Eiker | 24718 | 24917 | 24963 |
| Nittedal | 23213 | 23545 | 24089 |
| Odda | 7025 | 6835 | 6745 |
| Øvre Eiker | 18562 | 18926 | 19117 |
| Porsgrunn | 36198 | 36091 | 36224 |
| Rælingen | 17730 | 17874 | 18161 |
| Re | 9486 | 9621 | 9730 |

| | | | |
|---|---|---|---|
| Røyken | 21931 | 22452 | 22635 |
| Sande | 9496 | 9726 | 9904 |
| Sandefjord | 44922 | 45360 | 45976 |
| Siljan | 2357 | 2351 | 2329 |
| Skien | 54316 | 54510 | 54645 |
| Skiptvet | 3783 | 3831 | 3797 |
| Spydeberg | 5765 | 5853 | 6042 |
| Tinn | 5894 | 5856 | 5780 |
| Tønsberg | 44922 | 45360 | 45976 |
| Trøgstad | 5367 | 5337 | 5347 |

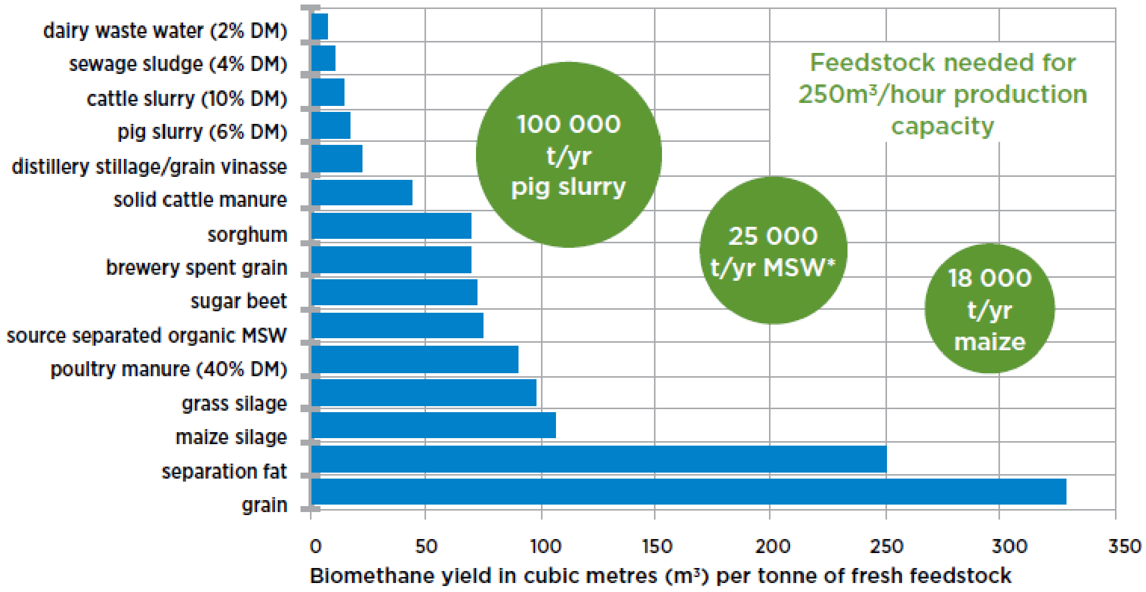
| | | | |
|---|---|---|---|
| Total Habitants per year | 335 685 | 338 445 | 341 460 |
| Received Waste per year | 33 718,9 | 42 522,6 | 47 344,3 |

# C. Energy Balance

$$Energy\ content\ in = Energy\ content\ out$$

$$Electricity\ in + Feedstock\ EC = Output^{*} + Digestate\ EC + Heat\ EC \tag*{[1]}$$

*Output means either the EC in the biomethane or electricity produced.



DM = dry matter MSW = municipal solid waste t/yr = tonnes per year

FIGURE C-1 – BIOMETHANE YIELD OF DIFFERENT FEEDSTOCKS, TAKEN FROM [26]

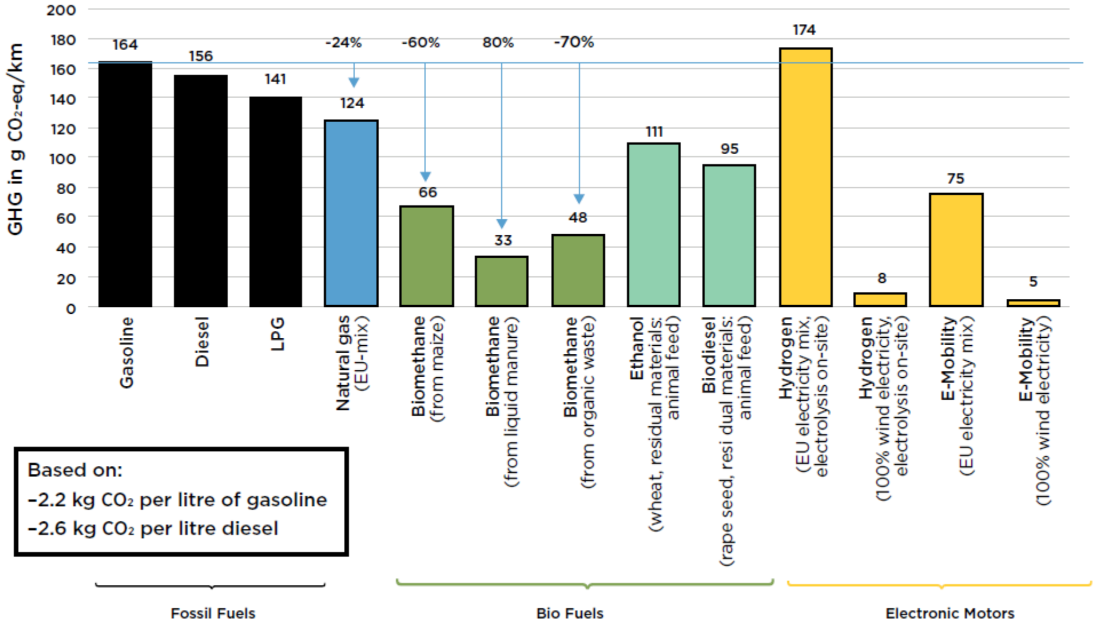


FIGURE C-2 - COMPARATIVE GHG EMISSIONS FROM PASSENGER CARS RUNNING ON DIFFERENT FUELS, TAKEN FROM [26]

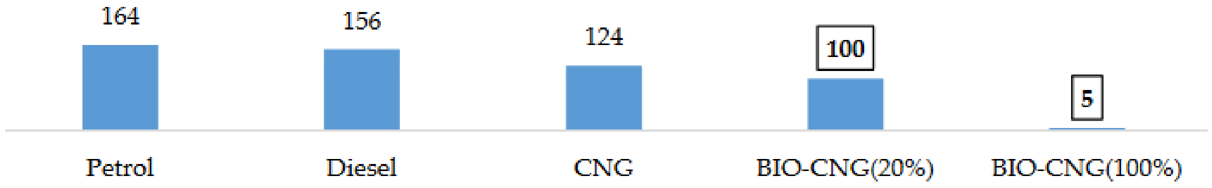


Figure C-3 – Petrol, Diesel, Compressed Natural Gas (CNG), CNG composed of 20% biomethane (BIO-CNG (20%)) and Pure Biomethane GHG emissions in $gCO_2eq/km$, taken from [104]

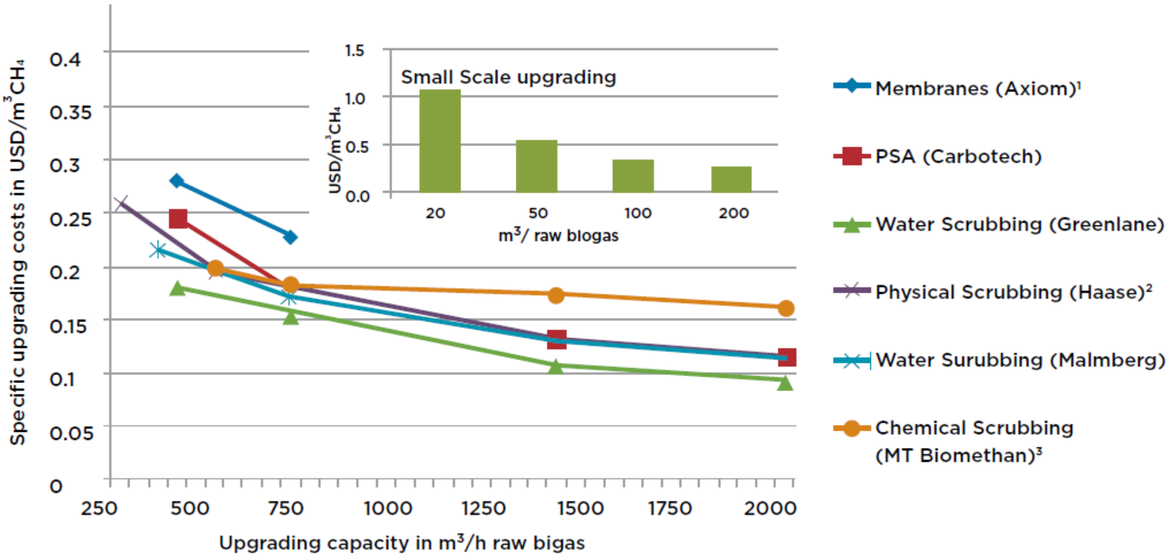


Figure C-4 - Specific costs for biogas upgrading, taken from [26]