Yann Studlé

Comparison of biogas production in France and Norway

A multi-layer Material Flow Analysis

Master's thesis in Miscellaneous Courses - Faculty of Engineering
Supervisor: Sigrun Jahren
Co-supervisor: Karl Klingsheim

June 2023

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Abstract

The objective of the Master's Thesis is to compare French and Norwegian biogas production system on several aspects. To do so, a Material Flow Analysis (MFA) study has been carried out, based on a similar system for both countries. In order to discuss about every aspect of interest when it comes to biogas, three different layers have been developed in the MFA study:

- A Mass Layer comparing the volume of materials in weight,
- An Energy Layer comparing the energy production and losses,
- A Nutrient Layer comparing the nutrient recovery,

First, a mathematical model has been built for each layer with associated calculations. Then, an uncertainty analysis has been held thanks to a Python program and a Monte-Carlo simulation, which allowed data reconciliation using the STAN software. Finally, sensitivity analysis has been led on key flows to understand better how the two biogas production systems were functioning. After this complete MFA study, I was able to have a clear overview of the similarities and differences in the strategies and policies of the two countries.

The results show that France develop much more the digestate aspect compared to Norway with a digestate production of 347 kg/capita in France against 175 kg/cap in Norway. In France, it was even the reason why biogas has emerged. Many farmers are using digestate as an organic fertilizer, reducing their dependence on foreign chemical fertilizer producers. In Norway, digestate use is very uncommon because of heavy safety regulations and administrative constraints.

Biowaste from households is also an important difference. While Norway is source sorting and treating separately biowaste, France is still sending it to incineration alongside residuals. As an example, Norway relies on biowaste for 24% of their intrant mix while for France, it is only 4% (in mass). For France, putting efforts on this sector will be mandatory for next year as the EU regulation will force States to propose a source sorting possibility for biowaste for every citizen, be it in important cities or in small villages. Especially as in France, biogas from biowaste could be an interesting source of energy as it could cover around 2% of the annual natural gas consumption.

Overall, energy production and quantity of nutrients back in soil from biogas production, even if efficiencies are interesting, are very low compared to fossil fuel use and chemical fertilizer volume.

Nowadays, annual electricity and biomethane production from biogas account for less than 1% of annual national electricity and natural gas consumption for both countries. For nutrients, be it nitrogen, phosphorus or potassium, the quantity back in soil from digestate covers less than 2% of the national soil requirements in both countries.

A lot of efforts still need to be done to reduce the carbon footprint of the energy sector and the dependence to fertilizer producers in both countries. However, we will see that biogas production is an efficient weapon to tackle the issue of waste management.

Sammendrag

Formålet med masteroppgaven er å sammenligne franske og norske produksjonssystemer for biogass på flere områder. For å gjøre dette er det gjennomført en materialstrømsanalyse (MFA) basert på et lignende system for begge land. For å kunne diskutere alle aspekter av interesse når det gjelder biogass, er det utviklet tre ulike lag i MFA-studien:

- Et masselag som sammenligner materialvolumet i vekt,
- Et energilag som sammenligner energiproduksjon og tap,
- Et næringslag som sammenligner næringsstoffgjenvinning,

Først er det utviklet en matematisk modell for hvert lag med tilhørende beregninger. Deretter er det gjennomført en usikkerhetsanalyse ved hjelp av et Python-program og en Monte-Carlo-simulering, som gjorde det mulig å avstemme data ved hjelp av STAN-programvaren. Til slutt ble det gjennomført en sensitivitetsanalyse av viktige strømmer for å få en bedre forståelse av hvordan de to biogassproduksjonssystemene fungerte. Etter denne komplette MFA-studien fikk jeg en klar oversikt over likhetene og forskjellene i de to landenes strategier og politikk.

Resultatene viser at Frankrike satser mye mer på råtnerest enn Norge, med en råtnerestproduksjon på 347 kg/innbygger i Frankrike mot 175 kg/innbygger i Norge. I Frankrike var det til og med grunnen til at biogass vokste frem. Mange bønder bruker råtnerest som organisk gjødsel, noe som reduserer avhengigheten av utenlandske kunstgjødselprodusenter. I Norge er bruk av råtnerest svært uvanlig på grunn av strenge sikkerhetsforskrifter og administrative begrensninger.

Bioavfall fra husholdninger er også en viktig forskjell. Mens Norge kildesorterer og behandler bioavfall separat, sender Frankrike det fortsatt til forbrenning sammen med restavfall. I Norge utgjør for eksempel bioavfall 24 % av avfallsmiksen, mens det i Frankrike bare utgjør 4 % (i masse). For Frankrike vil det bli obligatorisk å satse på denne sektoren fra neste år, ettersom EU-forordningen vil tvinge statene til å foreslå en kildesorteringsmulighet for bioavfall for alle innbyggere, både i store byer og i små landsbyer.

Totalt sett er energiproduksjonen og mengden næringsstoffer som tilbakeføres til jorda fra biogassproduksjon, selv om effektiviteten er interessant, svært lav sammenlignet med bruken av fossilt brensel og mengden kunstgjødsel.

I dag utgjør den årlige produksjonen av elektrisitet og biometan fra biogass mindre enn 1 % av det årlige nasjonale forbruket av elektrisitet og naturgass i begge land. Når det gjelder næringsstoffer, enten det er nitrogen, fosfor eller kalium, dekker mengden som tilbakeføres til jorden fra biorest mindre enn 2 % av det nasjonale jordbehovet i begge land.

Det gjenstår fortsatt mye arbeid for å redusere karbonavtrykket fra energisektoren og avhengigheten av gjødselprodusenter i begge land. Vi kommer imidlertid til å se at biogassproduksjon er et effektivt middel for å løse problemet med avfallshåndtering.

Nomenclature

MFA: Material Flow Analysis

CO_2: Carbon dioxide

CH_4: Methane

H_2O: Water

H_2S: Hydrogen sulfide

O_2: Oxygen

WWTP: Waste Water Treatment Plant

CHP: Combined Heat and Power

BioLNG: Bio Liquified Natural Gas

kWh: kilo Watt hour

TWh: Tera Watt hour

pH: potential Hydrogen

kg: kilogram

ktons: kilotons

m^3: cubic meter

ABP: Animal By-Products

CCS: Carbon Capture and Storage

N: Nitrogen

P: Phosphorus

K: Potassium

PM: Particulate Matter

STAN: subSTance flow ANalysis

Cap: capita

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I. Introduction

I.1. Background

Global warming and climate change are part of the more critical issues humanity will have to face in the 21st century. It is now well known that human activities are responsible for greenhouse gas emissions at standards never seen before.

The energy sector is by far the sector emitting the largest amount of greenhouse gas emissions.

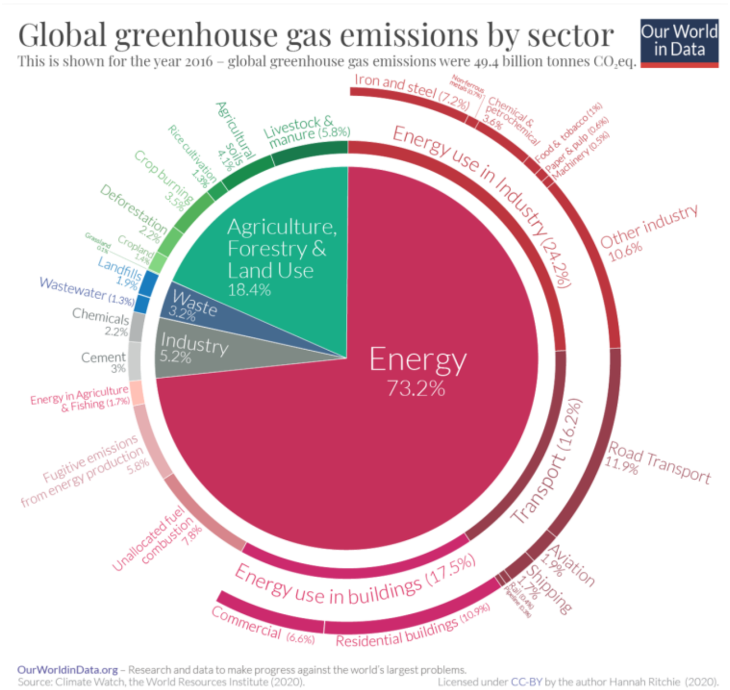

Figure 1: Repartition of global greenhouse gas emissions by sector

Fossil fuel extraction and massive use account for around three-quarters of global greenhouse gas emissions. To limit global warming to 1.5°C compared to the preindustrial period, which is the objective sets by the Paris Agreements ratified by 194 countries, the energy sector must be transformed. The major objective is to substitute fossil fuel with renewable energies.

Among other renewable energies, biogas appears as a relevant option to tackle the issue of decarbonated energy production, especially as biogas also deals with the issue of waste management.

Biogas production required organic materials that will be degraded into a mixture of several gases, mainly methane (CH_4) and carbon dioxide (CO_2), in the absence of oxygen. To produce biogas, several types of waste are used as intrants, such as agricultural waste, municipal waste, industrial waste but also sewage sludge.

The production of biogas occurs in a digestor, an oxygen-free environment, and takes around 20 to 30 days. Inside the digestor, organic waste is degrading under actions of bacteria in a process called anaerobic digestion.

After a sufficient retention time, two by-products are going out of the digestor, biogas itself and digestate.

Biogas consists of a complex mixture of several gases, but it mainly contains CH_4, the energy-rich portion, and CO_2. Biogas can be used in a Combined Heat and Power (CHP) engine to produce heat and electricity or undergoing additional treatments to be transformed into biomethane, a substitute to natural gas, or into bio Liquified Natural Gas (bioLNG) a substitute to fossil oils for the transportation sector.

Biogas production offers several benefits. First, it is a renewable source of energy that could replace fossil fuel in various applications, helping to reduce carbon footprint of the energy sector. It also tackles the issue of waste management, as it helps to manage and dispose of organic waste while recovering energy, presenting an alternative to incineration or landfilling.

The digestate is a nutrient-rich material, mainly nitrogen, phosphorus, and potassium, that can be used as a fertilizer or soil amendment. Digestate can be used in different forms, it can be spread directly after anaerobic digestion or separated into solid and liquid phases, presenting distinct characteristics.

The use of digestate presents advantages. It provides a circular approach to nutrient management by recycling nutrients from organic waste back into the soil, reducing the dependency on chemical fertilizers. It also enhances soil health and sustainability by increasing organic matter content.

Biogas production is rising since 2010 but its development has been uneven across world. This is due to the feedstock availability but also to policies that support or not biogas production and digestate use.

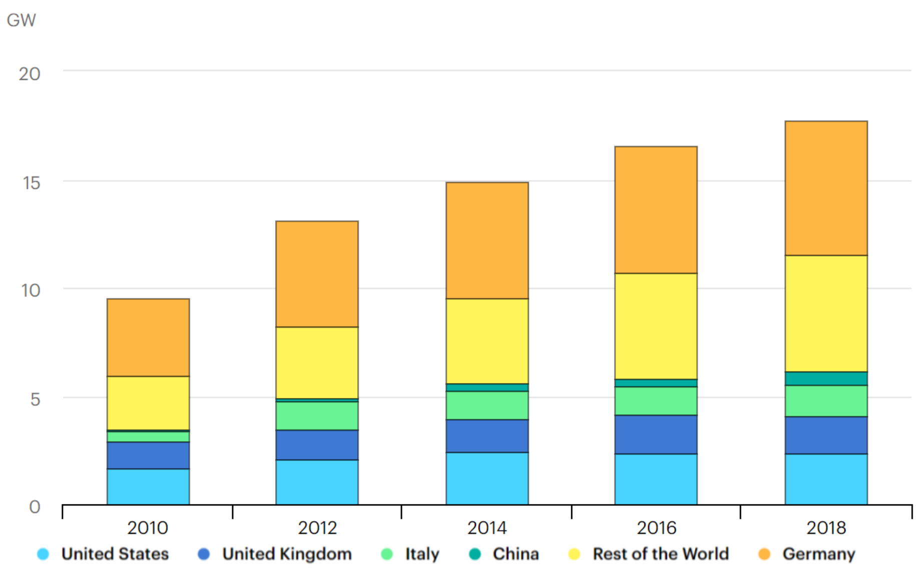

Figure 2: Biogas installed power capacity from 2010 to 2018 (Source: IEA)

Europe is the largest producer of biogas with Germany, which is, by far, the largest market. Europe, China, and the United States account for 90% of global production.

I.2. Objectives and general questions

The objective of this thesis is to understand France and Norway strategies and policies regarding biogas production and to compare the two countries.

- France, because it is the country I come from, and I wanted to know more about its biogas development strategy and policy. If it is well-known that France already produce a decarbonated energy with nuclear, no one really speaks about biogas production.
- Norway, because it is where I make my exchange and because it is often one of the countries taken as example when it comes to biogas production. In addition, during the first semester, I followed the course "Solid Waste Technology and Resource Recovery" and during the course, we visited a biogas plant, Ecopro in Verdal. It was a very interesting visit helping me to understand the stakes of biogas production associated with waste management.

General questions that will be answered in the thesis for the two countries are:

- What are the types of waste used as intrants in the biogas production system?
- How are the waste sorted and treated before undergoing anaerobic digestion?
- What is the composition of biogas and how is it used?
- How could digestate present an opportunity for agriculture to become more independent and sustainable?
- What are global and specific efficiencies of biogas production?
- How can biogas energy content be valorized?
- Why is biogas production more interesting regarding nutrient recycling compared to other waste management systems?
- Why is digestate one of key drivers for biogas production?

To compare both countries, other questions would be answered:

- In what extent are French and Norwegian strategies different regarding biogas production and valorization?
- What are the similarities between both countries?
- How can the two countries learn from each other to reduce their fossil fuel dependency?

I.3. Presentation of the Thesis

To compare France and Norway regarding biogas production, MFA study has been carried out for the two distinct biogas production system.

The MFA study aims to compare the various inputs, losses, outputs, energy efficiencies and nutrient valorizations between France and Norway.

To do so, there will be three distinct MFA layers for the two countries:

- A mass Layer comparing the volume of materials in weight,
- An energy Layer comparing the energy production and losses,
- A nutrient Layer comparing the nutrient recovery,

In total, there will be 6 MFA systems to build and analyze to provide a complete overview of biogas strategies in the two countries.

II. MFA study

In this part, the MFA study will be presented and explained. After a summary of MFA basics, I will present in detail what the MFA systems consist of.

II.1. Definition of MFA

As Brunner and Rechberger defined it in their book *Practical Handbook of Material Flow Analysis (MFA)*, 2004, MFA is a “systematic assessment of the flows and stocks of materials within a system defined in space and time.”

MFA is based on the law of conservation of matter. To control the results of a MFA system, a simple material balance comparing inputs, outputs, and stocks of a process must be held.

It is a tool for identifying the sources, quantities, and destinations of materials, as well as the potential environmental impacts associated with their use and disposal. As it is relatively simple, MFA is a worldwide tool used to take decisions on various fields like waste management for instance.

II.2. MFA Vocabulary

As MFA is a widely spread technic, it is necessary to use a common language to be understandable all around the world. The entire scientific community recognizes the following terms:

- *Material* stands for both goods and substances,
    - A *substance* is defined as any chemical element or compound composed of uniform units. If the units are atoms, substance is an element like oxygen or carbon. All substances are characterized by a unique and identical constitution and are thus homogenous.
    - A *good* is defined as economic entities of matter, independent of whether the economic value is positive (car, fuel), negative (municipal solid waste, sewage sludge) or not measured at all. Goods are made up of one or several substances.
- A *Process* is defined as a balanced volume, in which different things can happen such as chemical or physical transformation, transport, or storage of materials. Processes are generally connected with the rest of the world through inputs and outputs of goods. Example: human body, manufacturing plant, etc…
- *Flow* is defined as an amount of a good or substance per time. For example, the total amount of phosphorus in the Norwegian aquaculture system. *Flows* across systems boundaries are called imports, when they enter the system, or exports, when they leave

the system. Inputs are flows entering a process while outputs are flows exiting a process. *Flows* are the links between processes inside a system.

- A *stock* is defined as the material reservoir of a system. It is part of a process comprising the mass that is stored within the process.
- A *System* is defined as a group of processes and flows of goods that connect these individual processes. For example, a factory with processes as com' and marketing and interactions between these processes.

II.3. MFA steps

MFA typically involves four steps:

1. Definition of the system boundaries: This involves defining the geographic and temporal boundaries of the system being analyzed, as well as the materials and substances of interest.

2. Data collection: This involves gathering data on the quantities and characteristics of the materials and substances flowing through the system, as well as their sources and destinations.

3. Analysis: This involves using mathematical models to analyze the data and identify patterns and trends in the material flows. This can include calculating input-output balances, and assessing the environmental impacts associated with the material flows.

4. Interpretation and communication: This involves interpreting the results of the analysis and communicating them to stakeholders in a clear and understandable way, to inform decision-making and promote sustainable resource use and management.

II.4. MFA study on French and Norwegian biogas production systems

The main advantage of MFA is that it considers every flow entering or leaving a process, making flows of waste and environmental burdens visible and their sources identifiable. In addition, as the stock of a process is considered, the depletion or accumulation of it can be identified. It can be an incentive to countermeasures or to promote future utilization. Finally, as the time scale of a MFA study can be quite long, it is possible to identify minor changes that have few impacts in short time, but which can slowly become a long-term burden.

For these reasons, I decided to lead MFA study on both French and Norwegian biogas production systems. I chose to develop a stationary model, as I only consider one time period, an entire year, in which stocks and stock changes are not considered.

The aim of the MFA study is to compare the two systems, to find their more significant differences but also their similarities, in order to identify what can be improved whether in France or in Norway.

The base of the MFA system is quite similar for both countries with only few changes.

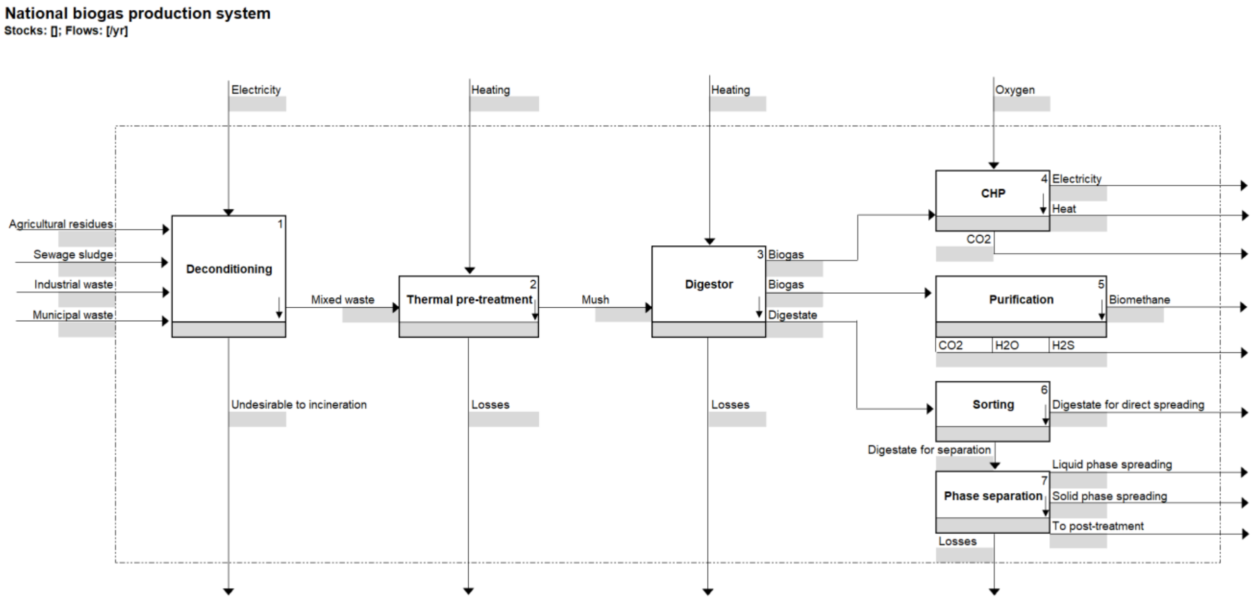

Figure 3: Base of the MFA system for the two countries

II.4.1. Process

There are seven processes:

- **Deconditioning**: as the sorted waste used to produce biogas can be packed in plastic bags or in over materials, this process is mandatory to have higher ratio into the digestor.
- **Thermal pre-treatment**: as the unpacked sorted waste needs to be treated at high temperature to remove every bacterium and virus. It is mandatory to respect the EU sanitary regulations regarding the waste entering the digestor.
- **Digestor**: it is the process where biogas is produced from various intrants. The quantity and the quality of the biogas depends on numerous parameters such as temperature, retention time or pH.
- **CHP**: one possible utilization for the biogas produced. Thanks to its energy content, biogas can be used to produce electricity and/or heat, directly by the producer or sold to customers.
- **Purification**: another option for the biogas is to undergo a purification step to get transformed into biomethane, then used in natural gas grids or to produce biofuel. Biogas contained a lot of methane but also impurities that must be eliminated during this step.
- **Sorting**: The digestate coming out of the digestor needs to be sorted to separate the digestate that will be directly spread and the digestate that will undergo further treatment
- **Phase separation**: a possible further treatment is phase separation. For the digestate that has not been spread directly, liquid, and solid phases will be separated. The two phases have different characteristics and can be used for different purposes. The rest of the digestate can be sent to another post-treatment like composting for example.

II.4.2. Flows

The model consists of 29 flows. It begins with the intrants I listed before going into the deconditioning process. To work, the process requires electricity. After deconditioning, there are the mixed waste going into the thermal treatment process and the undesirable waste going into incineration.

I chose to only consider electricity as energy input as most of the deconditioning processes only require electricity. A few are using a gas engine, but it is marginal.

For the outflows, I could have separated the undesirable materials such as plastics, woods, heavy metals residuals, etc… But as there are outflows leaving the system, it is not interesting to focus on what types of materials are going out. This is why I chose to gather them into one flow *Undesirable to incineration*.

Back to the mixed waste, it is going into the thermal pre-treatment process, which requires heating. The thermal pre-treatment process is mandatory to sanitize the waste. It can be done before anaerobic digestion or after it. I chose to put it before anaerobic digestion to make easier the understanding of the system. There is no change if this process is put after.

The thermal pre-treatment sanitizes the mixed waste and transform it into what I call the *mush*. As the efficiency of the process is not 100%, there are some losses, mainly some materials that stays at the bottom of the tank and that cannot be transferred into the digestor.

The mush is then transferred to the digestor to undergo anaerobic digestion. If this process is oxygen free, heating is required to ensure the chemical transformation of the mush. There are losses for the same reason as in the thermal pre-treatment process, some materials stay at the bottom of the tank and cannot be transformed into neither biogas nor digestate. Indeed, as the tank is never really emptied, there are some residues that stay in the tank for long time. Into the digestor, the mush is transformed into biogas and digestate.

I chose to separate the biogas into two flows. The first one is going into CHP and the second one is going into purification step to produce biogas.

In most of the biogas plants, there is only one process treating biogas, CHP or biomethane production. As I wanted to be as complete as possible, I chose to represent both treatment process together. Indeed, I am not representing a single biogas plant but rather a the national biogas production process.

In my system, the digestate is not used directly after anaerobic digestion. Before, it goes into the sorting process to separate the digestate that will be spread and the digestate that will be treated further.

The transformation taking place in the CHP process is combustion. Alongside biogas, oxygen needs to be imported to achieve combustion. The products of this combustion, the outputs, are electricity, heat, and carbon dioxide. These are the products of a complete combustion. In fact, complete combustion does not exist and there are a lot of other by-products. In this study, we are not focusing on combustion that is why I only consider carbon dioxide as by-product.

However, I consider incomplete combustion in the mathematical study as I took the actual combustion efficiency.

The purpose of the purification process is to eliminate all undesirable in the biogas composition to recover only biomethane. Indeed, biogas is mainly made of biomethane, 60%, but also of other gaseous particles. The other major component is carbon dioxide, 39%. There are also traces of water and hydrogen sulfide among many others.

I chose to only represent four components as outputs of the purification process. Of course, biomethane as it is the component I am interested in, carbon dioxide because it is the other major component, water, and hydrogen sulfide as they are causing trouble because of their corrosion potentials. Other components must be withdrawn but do not present interest in the study.

The digestate produced in the digestor is going into the sorting process. This process will separate the digestate that will be directly spread and the digestate that will undergo phase separation. The digestate going for spreading is considered as an outflow leaving the system. The rest is going to the last process of the system, the phase separation process.

In the phase separation process, the digestate is going to be separated into liquid and solid phases. As it will be explained later, the two phases have different impacts on soils. That is why it is interesting to have two distinct phases, making possible separate spreading.

There is also a part of the separate digestate that will go to post-treatment. Usually, it is the solid phase that goes to composting to mature and acquire some additional values. There are some losses in this process since phase separation is not hundred percent efficient.

II.4.3. Layers

To have an overview of French and Norwegian strategies regarding biogas production, I chose to develop three layers:

- The mass layer.
- The energy layer.
- The nutrient layer.

II.4.3.1. Mass Layer

For the mass layer, the aim is to compare the volume of materials used in the biogas production process. With both absolute and relative comparisons, taking population into account, this layer will underline the strategies of the two countries regarding intrants, digestate production and losses.

Regarding intrants, the study on masses would show on what kind of material France and Norway rely on to produce biogas. There are multiple sources available to produce biogas.

I decided to focus on five distinct sources:

- Agricultural residues
- Sewage sludge
- Industrial waste
- Municipal waste
- Aquaculture waste, specific to the Norway production system

With these 5 categories, almost all intrants are considered. The mass layer will help to understand on what types of waste the biogas production relies on and so what political strategies have been implemented in the two countries.

The mass layer will also show how many digestate is produced and how it is used. Regarding the system, there are more than one possibility for the digestate, being used for direct spreading just after leaving the digestor, undergoing phase separation to only spread liquid or solid phase or even going to post-treatment to undergo further treatments.

Thanks to this mass study, we will be able to determine which solutions are used and which are not if some are used together and if some are more profitable than others.

Finally, the mass layer will show where the losses are concentrated and where they can be eliminated to improve the efficiency of the system and so the biogas production.

II.4.3.2. Energy Layer

The main objective of the energy layer is to determine the energy production of the two systems. This is the driving layer as the objective of producing biogas is to recover the energy from it.

There are three outflows where energy production can be determined, the electricity production, the heat production and the biomethane production.

Thanks to absolute and relative calculations, it will be possible to compare the energy recovery from biogas production in the two countries. We will see if one country is more efficient than another or if they are quite similar.

The energy layer also makes possible to determine efficiencies. It will be interesting to determine the efficiency of the entire production system as well as the efficiency of the digestor, CHP and purification step. The energy losses will also be underlined.

This layer will help us understand where the strengths and weaknesses of each system are and how it can be improved to maximize the energy recovery, the main driver to reduce our fossil fuel dependency.

II.4.3.3. *Nutrient Layer*

The other major driver in biogas production is the digestate. It represents a source of nutrients available to tackle the issue of soil amendments in agriculture. The needs of the soil to make a plant grown is today mainly fulfilled with mineral and chemical fertilizers. These are leading biodiversity depletion as long as climate change because of their production processes. For these reasons, I wanted to lead a study on the nutrient contents of the digestate, to see if they can counterbalance the domination of chemical fertilizers.

I focus on the three main nutrients used in agriculture: Nitrogen, Phosphorus and Potassium.

For these nutrients, I determine their concentration on every flow, starting from the nutrient content in intrants to the nutrient content in digestate.

Thanks to these calculations, I determined the annual production of Nitrogen, Phosphorus and Potassium from biogas production in France and in Norway, making possible the comparison to the chemical fertilizer use.

III. Mathematical model resolution

The aim of this part is to present the mathematical model developed in the MFA study for every layer of each country.

III.1. Mass Layer

To present the mathematical model of the mass layer, French and Norwegian MFA systems will be separated.

III.1.1 French system

We start by listing the processes.

PROCESS N°	PROCESS NAME
1	Deconditioning
2	Thermal pre-treatment
3	Digestor
4	CHP
5	Purification
6	Sorting
7	Phase separation

Table 1: List of processes of the French Mass Layer

Then, we list all variables and unknowns.

VARIABLE N°	VARIABLE NAME	GOOD FLOW NAME	FROM	TO
1	$A_{0\text{-}11}$	Agricultural residues	0	1
2	$A_{0\text{-}12}$	Sewage sludge	0	1
3	$A_{0\text{-}13}$	Industrial waste	0	1
4	$A_{0\text{-}14}$	Municipal waste	0	1
5	$A_{1\text{-}0}$	Undesirable to incineration	1	0
6	$A_{1\text{-}2}$	Mixed waste	1	2
7	$A_{2\text{-}0}$	Losses	2	0
8	$A_{2\text{-}3}$	Mush	2	3
9	$A_{3\text{-}4}$	Biogas	3	4
10	$A_{3\text{-}5}$	Biogas	3	5
11	$A_{3\text{-}6}$	Digestate	3	6
12	$A_{3\text{-}0}$	Losses	3	0
13	$A_{0\text{-}4}$	Oxygen	0	4
14	$A_{4\text{-}01}$	Water	4	0
15	$A_{4\text{-}02}$	CO2	4	0
16	$A_{5\text{-}01}$	Biomethane	5	0

17	$A_{5\text{-}02}$	CO_2	5	0
18	$A_{5\text{-}03}$	H_2O	5	0
19	$A_{5\text{-}04}$	H_2S	5	0
20	$A_{6\text{-}0}$	Digestate for direct spreading	6	0
21	$A_{6\text{-}7}$	Digestate for separation	6	7
22	$A_{7\text{-}01}$	Liquid phase spreading	7	0
23	$A_{7\text{-}02}$	Solid phase spreading	7	0
24	$A_{7\text{-}03}$	To post-treatment	7	0
25	$A_{7\text{-}04}$	Losses	7	0

Table 2: List of variables and unknows of the French Mass Layer

We have 25 variables, so we need 25 equations. First, we define mass balance equation of every process. As a reminder, stocks and stock changes are not considered in the study.

PROCESS	MASS BALANCE EQUATIONS
1 - DECONDITIONING	$0 = A_{0-11} + A_{0-12} + A_{0-13} + A_{0-14} - A_{1-0} - A_{1-2}$
2 – THERMAL PRE-TREATMENT	$0 = A_{1-2} - A_{2-0} - A_{2-3}$
3 - DIGESTOR	$0 = A_{2-3} - A_{3-4} - A_{3-5} - A_{3-6} - A_{3-0}$
4 - CHP	$0 = A_{3-4} + A_{0-4} - A_{4-01} - A_{4-02}$
5 - PURIFICATION	$0 = A_{3-5} - A_{5-01} - A_{5-02} - A_{5-03} - A_{5-04}$
6 - SORTING	$0 = A_{3-6} - A_{6-0} - A_{6-7}$
7 – PHASE SEPARATION	$0 = A_{6-7} - A_{7-01} - A_{7-02} - A_{7-03} - A_{7-04}$

Table 3: Mass balance equations of the French Mass Layer

We now have 7 equations; we need 18 more to resolve the system. To do so, we consider model approach equations.

EQ N°	EQUATION LABEL	EQUATION
8	Amount of agricultural residues available for biogas production	$A_{0-11} = AR$
9	Amount of sewage sludge available for biogas production	$A_{0-12} = SS$
10	Amount of industrial waste available for biogas production	$A_{0-13} = IW$
11	Amount of municipal waste available for biogas production	$A_{0-14} = MW$
12	Deconditioning rate	$A_{1-0} = k_{1-0} * (A_{0-11} + A_{0-12} + A_{0-13} + A_{0-14})$
13	Losses during thermal pre-treatment	$A_{2-0} = k_{2-0} * A_{1-2}$
14	Mass of biogas going to CHP from energy layer	$*A_{3-4} = \frac{DB}{PCS} * B_{3-4}$
15	Mass of biogas going to Purification from energy layer	$*A_{3-5} = \frac{DB}{PCS} * B_{3-5}$
16	Share of mush becoming waste	$A_{3-6} = PM * A_{2-3}$

17	Stoichiometric equation for oxygen	$A_{0-4} = k_{3-41} * A_{3-4}$
18	Stoichiometric equation for water	$A_{4-01} = k_{3-43} * A_{3-4}$
19	Amount of carbon dioxide removed	$A_{5-02} = \frac{COC * DCO}{DB} * A_{3-5}$
20	Amount of water removed	$A_{5-03} = \frac{HOC * DHO}{DB} * A_{3-5}$
21	Amount of hydrogen sulfide removed	$A_{5-04} = HSC * EHSC * A_{3-5}$
22	Share of digestate for direct spreading	$A_{6-0} = PDS * A_{3-6}$
23	Share of liquid phase after phase separation	$A_{7-01} = PLP * A_{6-7}$
24	Share of solid phase after phase separation	$A_{7-02} = PSP * A_{6-7}$
25	Share of solid phase sent to post treatment after phase separation	$A_{7-03} = PPT * A_{6-7}$

*Variables B_{3-4} and B_{3-5} are from the energy layer detailed later.

Table 4: Model approach equations of the French Mass Layer

Here is the parameter table:

PARAMETERS	LABELS	VALUE
AR	Agricultural residues	14 000 ktons
SS	Sewage-sludge	6 010 ktons
IW	Industrial waste	9 000 ktons
MW	Municipal waste	1 270 ktons
$\mathbf{k_{1-0}}$	Deconditioning rate	5%
$\mathbf{k_{2-0}}$	Losses during thermal pre-treatment	5%
DB	Density of biogas	1.15 kg/m^3
PCS	PCS of biogas	7 kWh/m^3
PM	Share of mush becoming digestate	85%
$\mathbf{k_{3-41}}$	Mass of oxygen per mass of biogas	1.19 kg_{O2}/kg_{biogas}
$\mathbf{k_{3-43}}$	Mass of water per mass of biogas	0.56 kg_{H2O}/kg_{biogas}
COC	CO2 content in biogas (volume)	0.26 m^3_{CO2}/ m^3_{biogas}
DCO	Density of CO2	1.87 kg/m^3
HOC	H2O content in biogas (volume)	0.06 m^3_{H2O}/ m^3_{biogas}
DHO	Density of H2O (gas)	0.59 kg/m^3
FHSC	H2S content in biogas	0.005 m^3_{H2S}/ m^3_{biogas}
EHSC	Efficiency of H2S cleaning	95%
PDS	Share of digestate for direct spreading	55%
PLP	Share of liquid phase after phase separation	18%
PSP	Share of solid phase after phase separation	7%
PPT	Share sent to post treatment after phase separation	76%

Table 5: Parameters of the French Mass Layer

The sources for all figures are available in Appendix 1.

Thanks to these 25 equations and the parameters, I was able to determine every value of my system.

Here are the results for the mass layer in the French biogas production system:

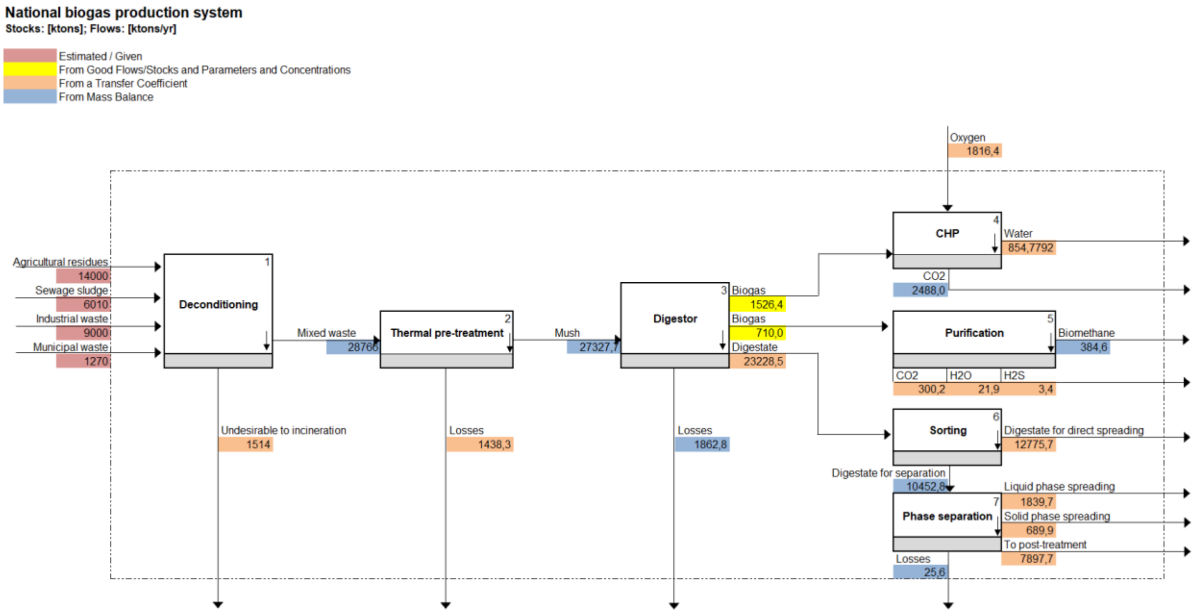

Figure 4: Mass Layer of the French biogas production MFA system

III.1.2. Norwegian system

We start by listing the processes.

PROCESS N°	PROCESS NAME
1	Deconditioning
2	Thermal pre-treatment
3	Digestor
4	CHP
5	Purification
6	Sorting
7	Phase separation

Table 6: List of process of Norwegian Mass Layer

Then, we list all variables and unknowns.

VARIABLE N°	VARIABLE NAME	GOOD FLOW NAME	FROM	TO
1	A_{0-11}	Agricultural residues	0	1
2	A_{0-12}	Sewage sludge	0	1
3	A_{0-13}	Industrial waste	0	1
4	A_{0-14}	Municipal waste	0	1
5	A_{0-15}	Aquaculture waste	1	
6	A_{1-0}	Undesirable to incineration	1	0
7	A_{1-2}	Mixed waste	1	2
8	A_{2-0}	Losses	2	0
9	A_{2-3}	Mush	2	3
10	A_{3-4}	Biogas	3	4
11	A_{3-5}	Biogas	3	5
12	A_{3-6}	Digestate	3	6
13	A_{3-0}	Losses	3	0
14	A_{0-4}	Oxygen	0	4
15	A_{4-01}	Water	4	0
16	A_{4-02}	CO2	4	0
17	A_{5-01}	Biomethane	5	0
18	A_{5-02}	CO2	5	0
19	A_{5-03}	H2O	5	0
20	A_{5-04}	H2S	5	0
21	A_{6-0}	Digestate for direct spreading	6	0
22	A_{6-7}	Digestate for separation	6	7
23	A_{7-01}	Liquid phase spreading	7	0
24	A_{7-02}	To post-treatment	7	0
25	A_{7-03}	Losses	7	0

Table 7: List of variables and unknowns of the Norwegian Mass Layer

The difference compared to France is the adding of *aquaculture waste* as intrants, intrant specific to Norway as the aquaculture production is one of the drivers of the economy, and the removal of *Solid phase spreading*, as it is forbidden by the law. The solid phase must go to composting to be used as soil amendment.

We have 25 variables, so we need 25 equations. First, we define mass balance equation of every process. As a reminder, stocks and stock changes are not considered in the study.

PROCESS	MASS BALANCE EQUATIONS
1 - DECONDITIONING	$0 = A_{0-11} + A_{0-12} + A_{0-13} + A_{0-14} + A_{0-15} - A_{1-0} - A_{1-2}$
2 – THERMAL PRE-TREATMENT	$0 = A_{1-2} - A_{2-0} - A_{2-3}$
3 - DIGESTOR	$0 = A_{2-3} - A_{3-4} - A_{3-5} - A_{3-6} - A_{3-0}$
4 - CHP	$0 = A_{3-4} + A_{0-4} - A_{4-01} - A_{4-02}$
5 - PURIFICATION	$0 = A_{3-5} - A_{5-01} - A_{5-02} - A_{5-03} - A_{5-04}$
6 - SORTING	$0 = A_{3-6} - A_{6-0} - A_{6-7}$
7 – PHASE SEPARATION	$0 = A_{6-7} - A_{7-01} - A_{7-02} - A_{7-03}$

Table 8: Mass balance equations of the Norwegian Mass Layer

We now have 7 equations; we need 18 more to resolve the system. To do so, we consider model approach equations.

EQ N°	EQUATION LABEL	EQUATION
8	Amount of agricultural residues available for biogas production	$A_{0-11} = AR$
9	Amount of sewage sludge available for biogas production	$A_{0-12} = SS$
10	Amount of industrial waste available for biogas production	$A_{0-13} = IW$
11	Amount of municipal waste available for biogas production	$A_{0-14} = MW$
12	Amount of aquaculture waste available for biogas production	$A_{0-15} = AW$
13	Deconditioning rate	$A_{1-0} = k_{1-0} * (A_{0-11} + A_{0-12} + A_{0-13} + A_{0-14})$
14	Losses during thermal pre-treatment	$A_{2-0} = k_{2-0} * A_{1-2}$
15	Mass of biogas going to CHP from energy layer	$*A_{3-4} = \frac{DB}{PCS} * B_{3-4}$
16	Mass of biogas going to Purification from energy layer	$*A_{3-5} = \frac{DB}{PCS} * B_{3-5}$
17	Share of mush becoming waste	$A_{3-6} = PM * A_{2-3}$
18	Stoichiometric equation for oxygen	$A_{0-4} = k_{3-41} * A_{3-4}$
19	Stoichiometric equation for water	$A_{4-01} = k_{3-43} * A_{3-4}$
20	Amount of carbon dioxide removed	$A_{5-02} = \frac{COC * DCO}{DB} * A_{3-5}$
21	Amount of water removed	$A_{5-03} = \frac{HOC * DHO}{DB} * A_{3-5}$
22	Amount of hydrogen sulfide removed	$A_{5-04} = HSC * EHSC * A_{3-5}$
23	Share of digestate for direct spreading	$A_{6-0} = PDS * A_{3-6}$

24	Share of liquid phase after phase separation	$A_{7-01} = PLP * A_{6-7}$
25	Share of solid phase sent to post treatment after phase separation	$A_{7-03} = PPT * A_{6-7}$

**Variables B_{3-4} and B_{3-5} are from the energy layer detailed later.*

Table 9: Model Approach equations of the Norwegian Mass Layer

Here is the parameter table:

PARAMETERS	LABELS	VALUE
AR	Agricultural residues	630 ktons
SS	Sewage-sludge	123 ktons
IW	Industrial waste	117 ktons
MW	Municipal waste	300 ktons
AW	Aquaculture waste	78 ktons
$\mathbf{k_{1-0}}$	Deconditioning rate	5%
$\mathbf{k_{2-0}}$	Losses during thermal pre-treatment	5%
DB	Density of biogas	1.15 kg/m^3
PCS	PCS of biogas	7 kWh/m^3
PM	Share of mush becoming digestate	85%
$\mathbf{k_{3-41}}$	Mass of oxygen per mass of biogas	1.19 kg_{O2}/kg_{biogas}
$\mathbf{k_{3-43}}$	Mass of water per mass of biogas	0.56 kg_{H2O}/kg_{biogas}
COC	CO2 content in biogas (volume)	0.26 m^3_{CO2}/ m^3_{biogas}
DCO	Density of CO2	1.87 kg/m^3
HOC	H2O content in biogas (volume)	0.06 m^3_{H2O}/ m^3_{biogas}
DHO	Density of H2O (gas)	0.59 kg/m^3
HSC	H2S content in biogas	0.005 m^3_{H2S}/ m^3_{biogas}
EHSC	Efficiency of H2S cleaning	95%
PDS	Share of digestate for direct spreading	55%
PLP	Share of liquid phase after phase separation	10%
PPT	Share sent to post treatment after phase separation	85%

Table 10: List of parameters of the Norwegian Mass Layer

The sources for all figures are available in the Appendix 2.

Thanks to these 25 equations and the parameters, I was able to determine every value of my system.

Here are the results for the mass layer in the Norwegian biogas production system:

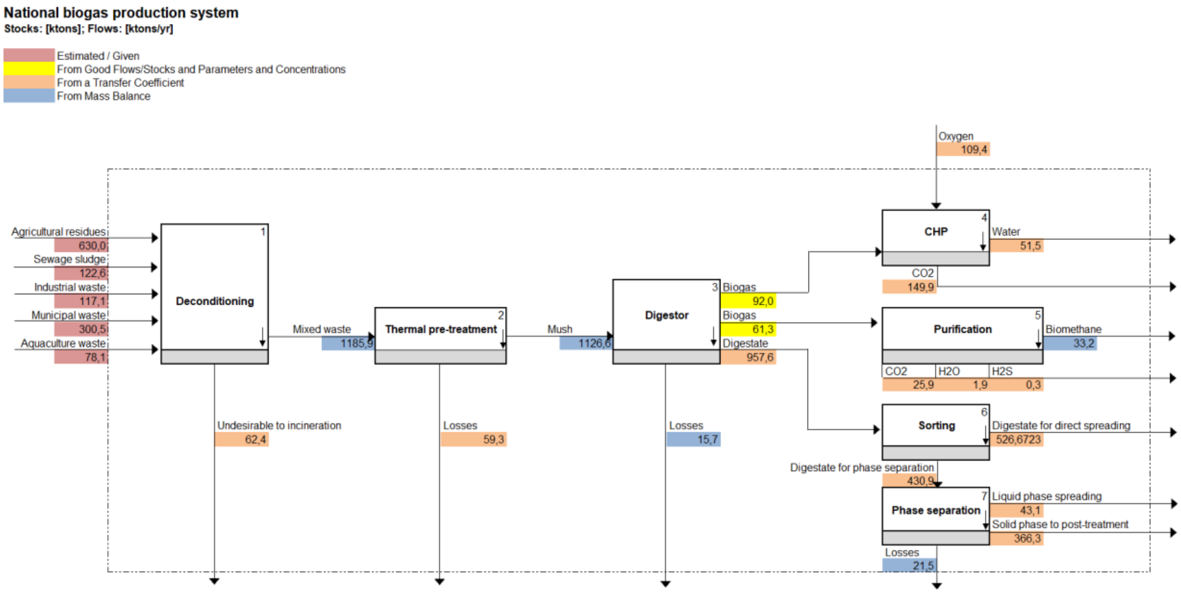

Figure 5: Mass Layer of the Norwegian biogas production MFA system

III.2. Energy Layer

To present the mathematical model of the mass layer, French and Norwegian MFA systems will be separated.

III.2.1. French system

We start by listing the processes.

PROCESS N°	PROCESS NAME
1	Deconditioning
2	Thermal pre-treatment
3	Digestor
4	CHP
5	Purification

Table 11: List of processes of the French Energy Layer

We are not considering the process dealing with the digestate as there is no interest to study the energy content of the digestate.

Then, we list all variables and unknowns.

VARIABLE N°	VARIABLE NAME	GOOD FLOW NAME	FROM	TO
1	B_{0-11}	Agricultural residues	0	1
2	B_{0-12}	Sewage sludge	0	1
3	B_{0-13}	Industrial waste	0	1
4	B_{0-14}	Municipal waste	0	1
5	B_{0-15}	Electricity	0	1
6	B_{1-0}	Undesirable to incineration	1	0
7	B_{1-2}	Mixed waste	1	2
8	B_{0-2}	Heating	0	2
9	B_{2-0}	Losses	2	0
10	B_{2-3}	Mush	2	3
11	B_{0-3}	Heating	0	3
12	B_{3-4}	Biogas	3	4
13	B_{3-5}	Biogas	3	5
14	B_{3-0}	Losses	3	0
15	B_{4-01}	Electricity	4	0
16	B_{4-02}	Heat	4	0
17	B_{4-03}	Losses	4	0
18	B_{5-01}	Biomethane	5	0
19	B_{5-02}	CO2	5	0

Table 12: List of variables and unknows of the French Energy Layer

We have 19 variables, so we need 19 equations. First, we define mass balance equation of every process. As a reminder, stocks and stock changes are not considered in the study.

PROCESS	MASS BALANCE EQUATIONS
1 - DECONDITIONING	$0 = B_{0-11} + B_{0-12} + B_{0-13} + B_{0-14} + B_{0-15} - B_{1-0} - B_{1-2}$
2 – THERMAL PRE-TREATMENT	$0 = B_{0-2} + B_{1-2} - B_{2-0} - B_{2-3}$
3 - DIGESTOR	$0 = B_{0-3} + B_{2-3} - B_{3-4} - B_{3-5} - B_{3-0}$
4 - CHP	$0 = B_{3-4} - B_{4-01} - B_{4-02} - B_{4-03}$
5 - PURIFICATION	$0 = B_{3-5} - B_{5-01} - B_{5-02}$

Table 13: Mass balance equations of the French Energy Layer

We now have 5 equations; we need 14 more to resolve the system. To do so, we consider model approach equations.

EQ N°	EQUATION LABEL	EQUATION
6	Energy content of agricultural residues	$B_{0-11} = A_{0-11} * ECA$
7	Energy content of sewage sludge	$B_{0-12} = A_{0-12} * ECS$
8	Energy content of industrial waste	$B_{0-13} = A_{0-13} * ECI$
9	Energy content of municipal waste	$B_{0-14} = A_{0-14} * ECMW$
10	Electricity input in the deconditioning process	$B_{0-15} = PED * B_{4-01}$
11	Heating input in the thermal pre-treatment process	$B_{0-2} = ECT * A_{1-2}$
12	Energy losses during thermal pre-treatment	$B_{2-0} = ECM * B_{2-3}$
13	Heating input for digestion	$B_{0-3} = (B_{3-4} + B_{3-5}) * PPE$
14	Energy content of biogas going into CHP	$B_{3-4} = (B_{4-01} + B_{4-02}) * \frac{1}{OE}$
15	Energy content of biogas going into Purification	$B_{3-5} = B_{5-01} * \frac{1}{EEP}$
16	Energy losses through the digestor wall	$B_{3-0} = ELD * B_{0-3}$
17	Electricity production from biogas	$B_{4-01} = EP$
18	Heat production from biogas	$B_{4-02} = HP$
19	Biomethane production from biogas	$B_{5-01} = BP$

Table 14: Model approach equations of the French Energy Layer

Here is the parameter table:

PARAMETERS	LABELS	VALUE
ECA	Energy content of agricultural residues	1.69 kWh/kg
ECS	Energy content of sewage sludge	0.54 kWh/kg
ECI	Energy content of industrial waste (mainly food-processing)	0.82 kWh/kg
ECMW	Energy content of municipal waste	0.99 kWh/kg
PED	Share of electricity produced required for deconditioning	5%
ECT	Energy consumption of the thermal pre-treatment process	66.58 kWh/tons
ECM	Energy content of the mush	0.446 kWh/kg
PPE	Share of primary energy produced required for digestor heating	11.5%
OE	CHP overall efficiency	79%
EEP	Energy efficiciency of the purification step	99.5%

ELD	Energy losses through the digestor walls (Share of heating input)	10%
EP	Electricity production from biogas	2.8 TWh
HP	Heat production from biogas	4.5 TWh
BP	Biomethane production from biogas	4.3 TWh

Table 15: List of parameters of the French Energy Layer

The sources for all figures are available in the Appendix 1.

Thanks to these 19 equations and the parameters, I was able to determine every value of my system.

Here are the results for the energy layer in the French biogas production system:

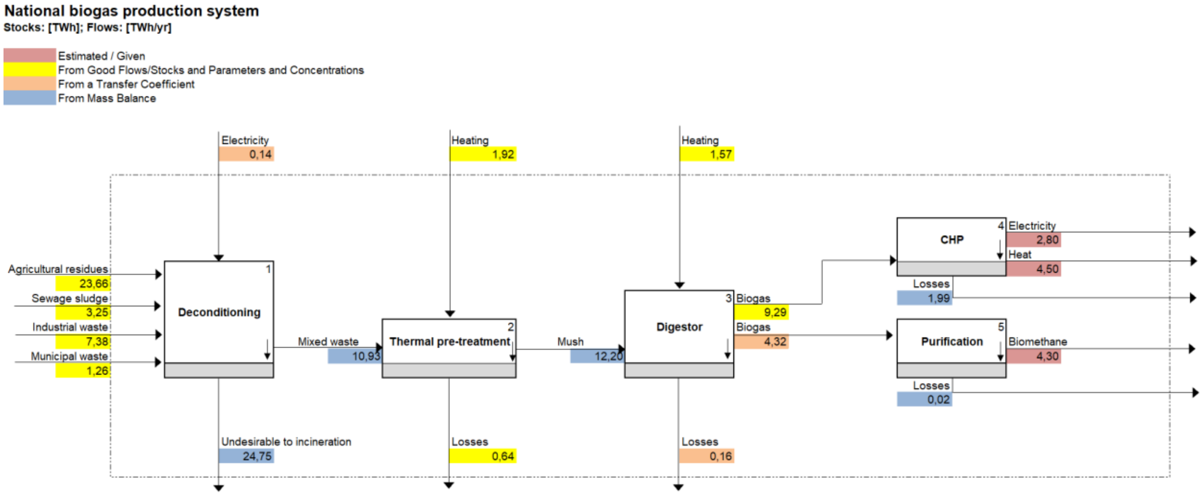

Figure 6: Energy Layer of the French biogas production MFA system

III.2.2 Norwegian system

We start by listing the processes.

PROCESS N°	PROCESS NAME
1	Deconditioning
2	Thermal pre-treatment
3	Digestor
4	CHP
5	Purification

Table 16: List of processes of the Norwegian Energy Layer

We are not considering the process dealing with the digestate as there is no interest to study the energy content of the digestate.

Then, we list all variables and unknowns.

VARIABLE N°	VARIABLE NAME	GOOD FLOW NAME	FROM	TO
1	B_{0-11}	Agricultural residues	0	1
2	B_{0-12}	Sewage sludge	0	1
3	B_{0-13}	Industrial waste	0	1
4	B_{0-14}	Municipal waste	0	1
5	B_{0-15}	Aquaculture waste	0	1
6	B_{0-16}	Electricity	0	1
7	B_{1-0}	Undesirable to incineration	1	0
8	B_{1-2}	Mixed waste	1	2
9	B_{0-2}	Heating	0	2
10	B_{2-0}	Losses	2	0
11	B_{2-3}	Mush	2	3
12	B_{0-3}	Heating	0	3
13	B_{3-4}	Biogas	3	4
14	B_{3-5}	Biogas	3	5
15	B_{3-0}	Losses	3	0
16	B_{4-01}	Electricity	4	0
17	B_{4-02}	Heat	4	0
18	B_{4-03}	Losses	4	0
19	B_{5-01}	Biomethane	5	0
20	B_{5-02}	CO2	5	0

Table 17: List of variables and unknows of the Norwegian Energy Layer

Again, the only difference is the adding of the energy content of aquaculture waste.

We have 20 variables, so we need 20 equations. First, we define mass balance equation of every process. As a reminder, stocks and stock changes are not considered in the study.

PROCESS	MASS BALANCE EQUATIONS
1 - DECONDITIONING	$0 = B_{0-11} + B_{0-12} + B_{0-13} + B_{0-14} + B_{0-15} + B_{0-16} - B_{1-0} - B_{1-2}$
2 – THERMAL PRE-TREATMENT	$0 = B_{0-2} + B_{1-2} - B_{2-0} - B_{2-3}$
3 - DIGESTOR	$0 = B_{0-3} + B_{2-3} - B_{3-4} - B_{3-5} - B_{3-0}$
4 - CHP	$0 = B_{3-4} - B_{4-01} - B_{4-02} - B_{4-03}$
5 - PURIFICATION	$0 = B_{3-5} - B_{5-01} - B_{5-02}$

Table 18: Mass balance equations of the Norwegian Energy Layer

We now have 5 equations; we need 15 more to resolve the system. To do so, we consider model approach equations.

EQ N°	EQUATION LABEL	EQUATION
6	Energy content of agricultural residues	$\mathrm{B}_{0-11} = \mathrm{A}_{0-11} * \mathrm{ECA}$
7	Energy content of sewage sludge	$\mathrm{B}_{0-12} = \mathrm{A}_{0-12} * \mathrm{ECS}$
8	Energy content of industrial waste	$\mathrm{B}_{0-13} = \mathrm{A}_{0-13} * \mathrm{ECI}$
9	Energy content of municipal waste	$\mathrm{B}_{0-14} = \mathrm{A}_{0-14} * \mathrm{ECMW}$
10	Energy content of aquaculture waste	$\mathrm{B}_{0-15} = \mathrm{A}_{0-15} * \mathrm{ECAW}$
11	Electricity input in the deconditioning process	$\mathrm{B}_{0-15} = \mathrm{PED} * \mathrm{B}_{4-01}$
12	Heating input in the thermal pre-treatment process	$\mathrm{B}_{0-2} = ECT * \mathrm{A}_{1-2}$
13	Energy losses during thermal pre-treatment	$\mathrm{B}_{2-0} = ECM * \mathrm{B}_{2-3}$
14	Heating input for digestion	$\mathrm{B}_{0-3} = (B_{3-4} + B_{3-5}) * PPE$
15	Energy content of biogas going into CHP	$B_{3-4} = BP * HP$
16	Energy content of biogas going into Purification	$B_{3-5} = BP * EP$
17	Energy losses through the digestor wall	$B_{3-0} = \mathrm{ELD} * \mathrm{B}_{0-3}$
18	Electricity production from biogas	$\mathrm{B}_{4-01} = B_{3-4} * PE$
19	Heat production from biogas	$\mathrm{B}_{4-02} = B_{3-4} * HE$
20	Biomethane production from biogas	$\mathrm{B}_{5-01} = B_{3-5} * EEP$

Table 19: Model approach equations of the Norwegian Energy Layer

Here is the parameter table:

PARAMETERS	LABELS	VALUE
ECA	Energy content of agricultural residues	1.69 kWh/kg
ECS	Energy content of sewage sludge	0.54 kWh/kg
ECI	Energy content of industrial waste (mainly food-processing)	0.82 kWh/kg
ECMW	Energy content of municipal waste	0.99 kWh/kg
ECAW	Energy content of aquaculture waste	0.928 kWh/kg
PED	Share of electricity produced required for deconditioning	5%
ECT	Energy consumption of the thermal pre-treatment process	66.58 kWh/tons
ECM	Energy content of the mush	0.446 kWh/kg
PPE	Share of primary energy produced required for digestor heating	11.5%
BP	Total biogas production in Norway	0.9 TWh
HP	Share of biogas to CHP Norway	60%
EP	Share of biogas to biofuel Norway	40%

ELD	Energy losses through the digestor walls (Share of heating input)	10%
PE	CHP Power efficiency	25%
HE	CHP Heat efficiency	60%
EEP	Energy efficiciency of the purification step	99.5%

Table 20: List of parameters of the Norwegian Energy Layer

The sources for all figures are available in the Appendix 2.

Thanks to these 20 equations and the parameters, I was able to determine every value of my system.

Here are the results for the energy layer in the Norwegian biogas production system:

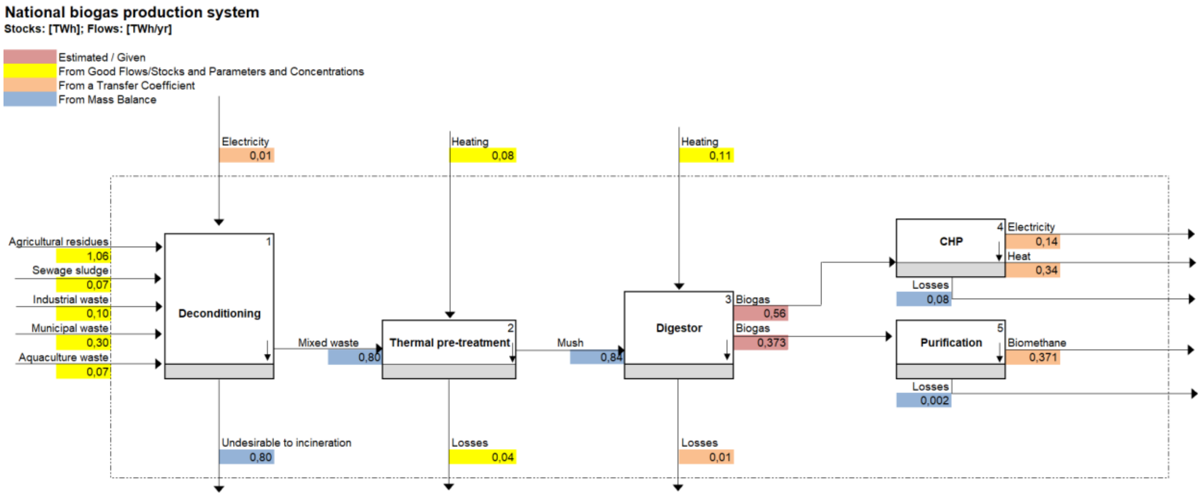

Figure 7: Energy Layer of the Norwegian biogas production MFA system

III.3. Nutrient Layer

For the nutrient layer, we will examine the three nutrients separately.

III.3.1. Nitrogen Layer

III.3.1.1. French Layer

We start by listing the processes.

PROCESS N°	PROCESS NAME
1	Deconditioning
2	Thermal pre-treatment
3	Digestor
4	Sorting
5	Phase separation

Table 21: List of processes of the French Nitrogen Nutrient Layer

We are not considering the processes dealing with the biogas as there is no interest to study the nutrient content of the biogas.

Then, we list all variables and unknowns.

VARIABLE N°	VARIABLE NAME	GOOD FLOW NAME	FROM	TO
1	$C_{0\text{-}11}$	Agricultural residues	0	1
2	$C_{0\text{-}12}$	Sewage sludge	0	1
3	$C_{0\text{-}13}$	Industrial waste	0	1
4	$C_{0\text{-}14}$	Municipal waste	0	1
5	$C_{1\text{-}0}$	Undesirable to incineration	1	0
6	$C_{1\text{-}2}$	Mixed waste	1	2
7	$C_{2\text{-}0}$	Losses	2	0
8	$C_{2\text{-}3}$	Mush	2	3
9	$C_{3\text{-}4}$	Digestate	3	4
10	$C_{3\text{-}0}$	Losses	3	0
11	$C_{4\text{-}0}$	For direct spreading	4	0
12	$C_{4\text{-}5}$	For phase separation	4	5
13	$C_{5\text{-}01}$	Liquid phase spreading	5	0
14	$C_{5\text{-}02}$	Solid phase spreading	5	0
15	$C_{5\text{-}03}$	To post-treatment	5	0
16	$C_{5\text{-}04}$	Losses	5	0

Table 22: List of variables and unknows of the French Nitrogen Nutrient Layer

We have 16 variables, so we need 16 equations. First, we define mass balance equation of every process. As a reminder, stocks and stock changes are not considered in the study.

PROCESS	MASS BALANCE EQUATIONS
1 - DECONDITIONING	$0 = C_{0-11} + C_{0-12} + C_{0-13} + C_{0-14} - C_{1-0} - C_{1-2}$
2 – THERMAL PRE-TREATMENT	$0 = C_{1-2} - C_{2-0} - C_{2-3}$
3 - DIGESTOR	$0 = C_{2-3} - C_{3-4} - C_{3-0}$
4 - SORTING	$0 = C_{3-4} - C_{4-0} - C_{4-5}$
5 – PHASE SEPARATION	$0 = C_{4-5} - C_{5-01} - C_{5-02} - C_{5-03} - C_{5-04}$

Table 23: Mass balance equations of the French Nitrogen Nutrient Layer

We now have 5 equations; we need 11 more to resolve the system. To do so, we consider model approach equations.

EQ N°	EQUATION LABEL	EQUATION
6	Nitrogen content of agricultural residues	$C_{0-11} = A_{0-11} * \mathrm{NAR}$
7	Nitrogen content of sewage sludge	$C_{0-12} = A_{0-12} * \mathrm{NSS}$
8	Nitrogen content of industrial waste	$C_{0-13} = A_{0-13} * \mathrm{NIW}$
9	Nitrogen content of municipal waste	$C_{0-14} = A_{0-14} * \mathrm{NMW}$
10	Nitrogen content of undesirable to incineration	$C_{1-0} = NUI * A_{1-0}$
11	Nitrogen content of the mush	$C_{2-3} = \frac{A_{2-3}}{A_{1-2}} * C_{1-2}$
12	Nitrogen content of the loss from digestor	$C_{3-0} = \frac{A_{3-0}}{A_{1-2}} * C_{1-2}$
13	Nitrogen content of the digestate spread directly after anaerobic digestion	$C_{4-0} = PDS * B_{3-4}$
14	Nitrogen content of the spread liquid phase	$C_{5-01} = (C_{4-5} - C_{5-04}) * NLP$
15	Nitrogen content of the spread solid phase	$C_{5-02} = (C_{4-5} - C_{5-04}) * NSPS$
16	Nitrogen content of the solid phase going to post-treatment	$C_{5-03} = (C_{4-5} - C_{5-04}) * NSPP$

Table 24: Model approach equations of the French Nitrogen Nutrient Layer

Here is the parameter table:

PARAMETERS	LABELS	VALUE
NAR	Nitrogen content in agricultural residues	5.23E-03 $\mathrm{ktons_N}$/ktons
NSS	Nitrogen content in sewage sludge	1.60E-03 $\mathrm{ktons_N}$/ktons
NIW	Nitrogen content in industrial waste	3.70E-03 $\mathrm{ktons_N}$ /ktons
NMW	Nitrogen content in municipal waste	7.62E-03 $\mathrm{ktons_N}$ /ktons
NUI	Nutrient content in undesirable to incineration	0 ktons/ktons
PDS	Percentage of digestate for direct spreading	55%
NLP	Share of N from digestate for phase separation to liquid phase	95%

NSPS	Share of N from digestate for phase separation to solid phase	0.4%
NSPP	Share of N from digestate for phase separation to post-treatment	4.6%

Table 25: List of parameters of the French Nitrogen Nutrient Layer

The sources for all figures are available in the Appendix 1.

For the nutrient content in undesirable to incineration, I assume that the materials removed during the deconditioning process do not contain nutrients.

Thanks to these 16 equations and the parameters, I was able to determine every value of my system.

Here are the results for the nutrient/nitrogen layer in the French biogas production system:

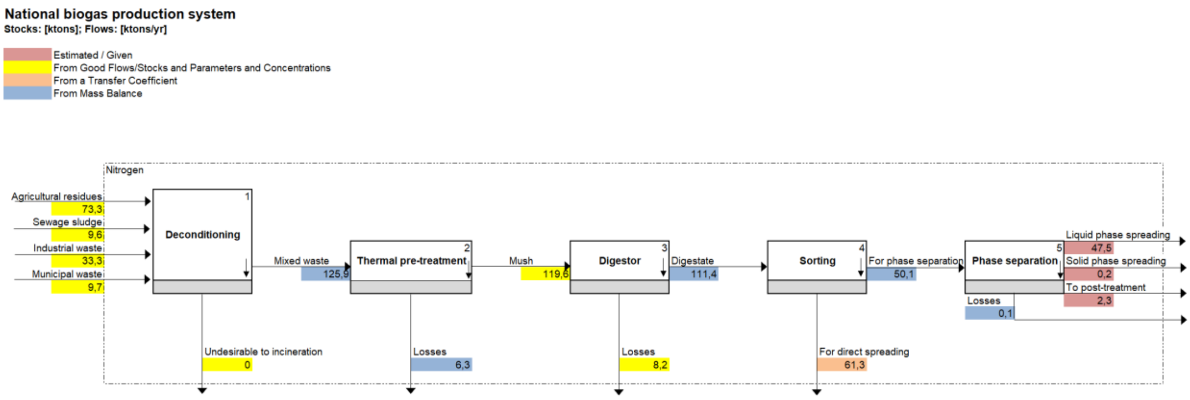

Figure 8: Nutrient/Nitrogen Layer of the French biogas production MFA system

III.3.1.2. Norwegian Layer

We start by listing the processes.

PROCESS N°	PROCESS NAME
1	Deconditioning
2	Thermal pre-treatment
3	Digestor
4	Sorting
5	Phase separation

Table 26: List of processes of the Norwegian Nitrogen Nutrient Layer

We are not considering the processes dealing with the biogas as there is no interest to study the nutrient content of the biogas.

Then, we list all variables and unknowns.

VARIABLE N°	VARIABLE NAME	GOOD FLOW NAME	FROM	TO
1	$C_{0\text{-}11}$	Agricultural residues	0	1
2	$C_{0\text{-}12}$	Sewage sludge	0	1
3	$C_{0\text{-}13}$	Industrial waste	0	1
4	$C_{0\text{-}14}$	Municipal waste	0	1
5	$C_{0\text{-}15}$	Aquaculture waste	0	1
6	$C_{1\text{-}0}$	Undesirable to incineration	1	0
7	$C_{1\text{-}2}$	Mixed waste	1	2
8	$C_{2\text{-}0}$	Losses	2	0
9	$C_{2\text{-}3}$	Mush	2	3
10	$C_{3\text{-}4}$	Digestate	3	4
11	$C_{3\text{-}0}$	Losses	3	0
12	$C_{4\text{-}0}$	For direct spreading	4	0
13	$C_{4\text{-}5}$	For phase separation	4	5
14	$C_{5\text{-}01}$	Liquid phase spreading	5	0
15	$C_{5\text{-}02}$	To post-treatment	5	0
16	$C_{5\text{-}03}$	Losses	5	0

Table 27: List of variables and unknows of the Norwegian Nitrogen Nutrient Layer

Same as in the mass layer, the difference compared to France is the adding of *aquaculture waste* as intrants and the removal of *Solid phase spreading*.

We have 16 variables, so we need 16 equations. First, we define mass balance equation of every process. As a reminder, stocks and stock changes are not considered in the study.

PROCESS	MASS BALANCE EQUATIONS
1 - DECONDITIONING	$0 = C_{0-11} + C_{0-12} + C_{0-13} + C_{0-14} + C_{0-15} - C_{1-0} - C_{1-2}$
2 – THERMAL PRE-TREATMENT	$0 = C_{1-2} - C_{2-0} - C_{2-3}$
3 - DIGESTOR	$0 = C_{2-3} - C_{3-4} - C_{3-0}$
4 - SORTING	$0 = C_{3-4} - C_{4-0} - C_{4-5}$
5 – PHASE SEPARATION	$0 = C_{4-5} - C_{5-01} - C_{5-02} - C_{5-03}$

Table 28: Mass balance equations of the Norwegian Nitrogen Nutrient Layer

We now have 5 equations; we need 11 more to resolve the system. To do so, we consider model approach equations.

EQ N°	EQUATION LABEL	EQUATION
6	Nitrogen content of agricultural residues	$C_{0-11} = A_{0-11} * NAR$
7	Nitrogen content of sewage sludge	$C_{0-12} = A_{0-12} * NSS$
8	Nitrogen content of industrial waste	$C_{0-13} = A_{0-13} * NIW$
9	Nitrogen content of municipal waste	$C_{0-14} = A_{0-14} * NMW$
10	Nitrogen content of aquaculture waste	$C_{0-15} = A_{0-14} * NAW$
11	Nitrogen content of undesirable to incineration	$C_{1-0} = NUI * A_{1-0}$
12	Nitrogen content of the mush	$C_{2-3} = \frac{A_{2-3}}{A_{1-2}} * C_{1-2}$
13	Nitrogen content of the loss from digestor	$C_{3-0} = \frac{A_{3-0}}{A_{1-2}} * C_{1-2}$
14	Nitrogen content of the digestate spread directly after anaerobic digestion	$C_{4-0} = PDS * B_{3-4}$
15	Nitrogen content of the spread liquid phase	$C_{5-01} = (C_{4-5} - C_{5-04}) * NLP$
16	Nitrogen content of the solid phase going to post-treatment	$C_{5-02} = (C_{4-5} - C_{5-04}) * NSPP$

Table 29: Model approach equations of the Norwegian Nitrogen Nutrient Layer

Here is the parameter table:

PARAMETERS	LABELS	VALUE
NAR	Nitrogen content in agricultural residues	5.23E-03 $ktons_N$/ktons
NSS	Nitrogen content in sewage sludge	1.60E-03 $ktons_N$/ktons
NIW	Nitrogen content in industrial waste	3.70E-03 $ktons_N$ /ktons
NMW	Nitrogen content in municipal waste	7.62E-03 $ktons_N$ /ktons
NAW	Nitrogen content in aquaculture waste	3.30E-03 $ktons_N$ /ktons
NUI	Nutrient content in undesirable to incineration	0 ktons/ktons
PDS	Percentage of digestate for direct spreading	55%
NLP	Share of N from digestate for phase separation to liquid phase	95%
NSPP	Share of N from digestate for phase separation to post-treament	5%

Table 30: List of parameters of the Norwegian Nitrogen Nutrient Layer

The sources for all figures are available in the Appendix 2.

For the nutrient content in undesirable to incineration, I assume that the materials removed during the deconditioning process do not contain nutrients.

Thanks to these 16 equations and the parameters, I was able to determine every value of my system.

Here are the results for the nutrient/nitrogen layer in the Norwegian biogas production system:

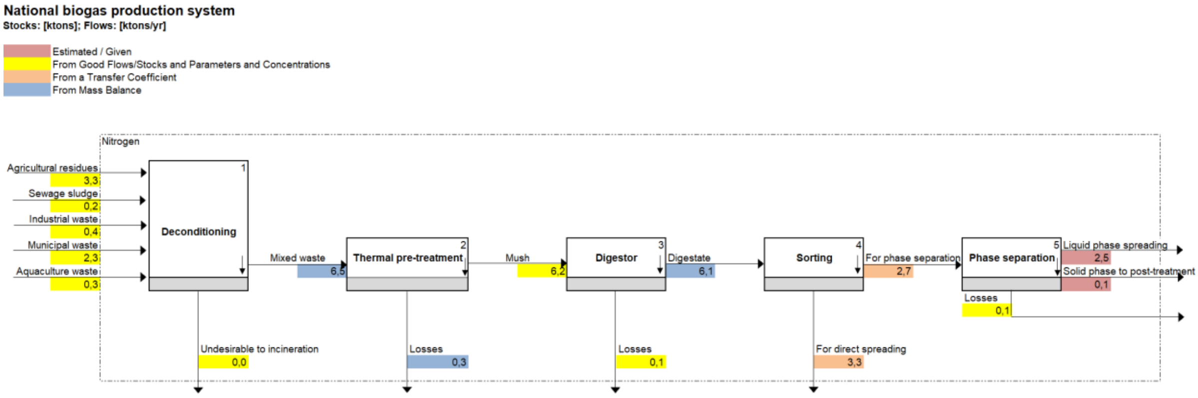

Figure 9: Nutrient/Nitrogen Layer of the Norwegian biogas production MFA system

III.3.2. Phosphorus Layer

III.3.2.1. French Layer

We start by listing the processes.

PROCESS N°	PROCESS NAME
1	Deconditioning
2	Thermal pre-treatment
3	Digestor
4	Sorting
5	Phase separation

Table 31: List of parameters of the French Phosphorus Nutrient Layer

We are not considering the processes dealing with the biogas as there is no interest to study the nutrient content of the biogas.

Then, we list all variables and unknowns.

VARIABLE N°	VARIABLE NAME	GOOD FLOW NAME	FROM	TO
1	D_{0-11}	Agricultural residues	0	1
2	D_{0-12}	Sewage sludge	0	1
3	D_{0-13}	Industrial waste	0	1
4	D_{0-14}	Municipal waste	0	1
5	D_{1-0}	Undesirable to incineration	1	0
6	D_{1-2}	Mixed waste	1	2
7	D_{2-0}	Losses	2	0
8	D_{2-3}	Mush	2	3
9	D_{3-4}	Digestate	3	4
10	D_{3-0}	Losses	3	0
11	D_{4-0}	For direct spreading	4	0
12	D_{4-5}	For phase separation	4	5
13	D_{5-01}	Liquid phase spreading	5	0
14	D_{5-02}	Solid phase spreading	5	0
15	D_{5-03}	To post-treatment	5	0
16	D_{5-04}	Losses	5	0

Table 32: List of variables and unknowns of the French Phosphorus Nutrient Layer

We have 16 variables, so we need 16 equations. First, we define mass balance equation of every process. As a reminder, stocks and stock changes are not considered in the study.

PROCESS	MASS BALANCE EQUATIONS
1 - DECONDITIONING	$0 = D_{0-11} + D_{0-12} + D_{0-13} + D_{0-14} - D_{1-0} - D_{1-2}$
2 – THERMAL PRE-TREATMENT	$0 = D_{1-2} - D_{2-0} - D_{2-3}$
3 - DIGESTOR	$0 = D_{2-3} - D_{3-4} - D_{3-0}$
4 - SORTING	$0 = D_{3-4} - D_{4-0} - D_{4-5}$
5 – PHASE SEPARATION	$0 = D_{4-5} - D_{5-01} - D_{5-02} - D_{5-03} - D_{5-04}$

Table 33: Mass balance equations of the French Phosphorus Nutrient Layer

We now have 5 equations; we need 11 more to resolve the system. To do so, we consider model approach equations.

EQ N°	EQUATION LABEL	EQUATION
6	Phosphorus content of agricultural residues	$D_{0-11} = A_{0-11} * PAR$
7	Phosphorus content of sewage sludge	$D_{0-12} = A_{0-12} * PSS$
8	Phosphorus content of industrial waste	$D_{0-13} = A_{0-13} * PIW$
9	Phosphorus content of municipal waste	$D_{0-14} = A_{0-14} * PMW$
10	Phosphorus content of undesirable to incineration	$D_{1-0} = NUI * A_{1-0}$
11	Phosphorus content of the mush	$D_{2-3} = \frac{A_{2-3}}{A_{1-2}} * D_{1-2}$
12	Phosphorus content of the loss from digestor	$D_{3-0} = \frac{A_{3-0}}{A_{1-2}} * D_{1-2}$
13	Phosphorus content of the digestate spread directly after anaerobic digestion	$D_{4-0} = PDS * B_{3-4}$
14	Phosphorus content of the spread liquid phase	$D_{5-01} = (D_{4-5} - D_{5-04}) * PLP$
15	Phosphorus content of the spread solid phase	$D_{5-02} = (D_{4-5} - D_{5-04}) * PSPS$
16	Phosphorus content of the solid phase going to post-treatment	$D_{5-03} = (D_{4-5} - D_{5-04}) * PSPP$

Table 34: Model approach equations of the French Phosphorus Nutrient Layer

Here is the parameter table:

PARAMETERS	LABELS	VALUE
PAR	Phosphorus content in agricultural residues	5.59E-04 $ktons_P$/ktons
PSS	Phosphorus content in sewage sludge	1.00E-03 $ktons_P$/ktons
PIW	Phosphorus content in industrial waste	4.00E-04 $ktons_P$ /ktons
PMW	Phosphorus content in municipal waste	8.88E-04 $ktons_P$ /ktons
NUI	Nutrient content in undesirable to incineration	0 ktons /ktons
PDS	Percentage of digestate for direct spreading	55%
PLP	Share of P from digestate for phase separation to liquid phase	25%
PSPS	Share of P from digestate for phase separation to solid phase	6%
PSPP	Share of P from digestate for phase separation to post-treatment	69%

Table 35: List of parameters of the French Phosphorus Nutrient Layer

The sources for all figures are available in the Appendix 1.

For the nutrient content in undesirable to incineration, I assume that the materials removed during the deconditioning process do not contain nutrients.

Thanks to these 16 equations and the parameters, I was able to determine every value of my system.

Here are the results for the nutrient/phosphorus layer in the French biogas production system:

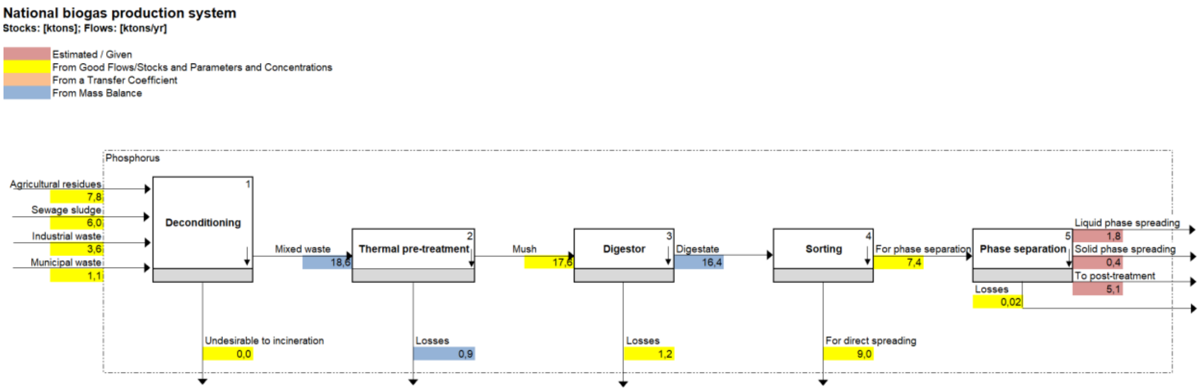

Figure 10: Nutrient/Phosphorus Layer of the French biogas production MFA system

III.3.2.2. Norwegian Layer

We start by listing the processes.

PROCESS N°	PROCESS NAME
1	Deconditioning
2	Thermal pre-treatment
3	Digestor
4	Sorting
5	Phase separation

Table 36: List of processes of the Norwegian Phosphorus Nutrient Layer

We are not considering the processes dealing with the biogas as there is no interest to study the nutrient content of the biogas.

Then, we list all variables and unknowns.

VARIABLE N°	VARIABLE NAME	GOOD FLOW NAME	FROM	TO
1	$D_{0\text{-}11}$	Agricultural residues	0	1
2	$D_{0\text{-}12}$	Sewage sludge	0	1
3	$D_{0\text{-}13}$	Industrial waste	0	1
4	$D_{0\text{-}14}$	Municipal waste	0	1
5	$D_{0\text{-}15}$	Aquaculture waste	0	1
6	$D_{1\text{-}0}$	Undesirable to incineration	1	0
7	$D_{1\text{-}2}$	Mixed waste	1	2
8	$D_{2\text{-}0}$	Losses	2	0
9	$D_{2\text{-}3}$	Mush	2	3
10	$D_{3\text{-}4}$	Digestate	3	4
11	$D_{3\text{-}0}$	Losses	3	0
12	$D_{4\text{-}0}$	For direct spreading	4	0
13	$D_{4\text{-}5}$	For phase separation	4	5
14	$D_{5\text{-}01}$	Liquid phase spreading	5	0
15	$D_{5\text{-}02}$	To post-treatment	5	0
16	$D_{5\text{-}03}$	Losses	5	0

Table 37: List of variables and unknows of the Norwegian Phosphorus Nutrient Layer

Same as in the mass layer, the difference compared to France is the adding of *aquaculture waste* as intrants and the removal of *Solid phase spreading*.

We have 16 variables, so we need 16 equations. First, we define mass balance equation of every process. As a reminder, stocks and stock changes are not considered in the study.

PROCESS	MASS BALANCE EQUATIONS
1 - DECONDITIONING	$0 = D_{0-11} + D_{0-12} + D_{0-13} + D_{0-14} + D_{0-15} - D_{1-0} - D_{1-2}$
2 – THERMAL PRE-TREATMENT	$0 = D_{1-2} - D_{2-0} - D_{2-3}$
3 - DIGESTOR	$0 = D_{2-3} - D_{3-4} - D_{3-0}$
4 - SORTING	$0 = D_{3-4} - D_{4-0} - D_{4-5}$
5 – PHASE SEPARATION	$0 = D_{4-5} - D_{5-01} - D_{5-02} - D_{5-03}$

Table 38: Mass balance equations of the Norwegian Phosphorus Nutrient Layer

We now have 5 equations; we need 11 more to resolve the system. To do so, we consider model approach equations.

EQ N°	EQUATION LABEL	EQUATION
6	Phosphorus content of agricultural residues	$D_{0-11} = A_{0-11} * PAR$
7	Phosphorus content of sewage sludge	$D_{0-12} = A_{0-12} * PSS$
8	Phosphorus content of industrial waste	$D_{0-13} = A_{0-13} * PIW$
9	Phosphorus content of municipal waste	$D_{0-14} = A_{0-14} * PMW$
10	Phosphorus content of aquaculture waste	$D_{0-15} = A_{0-14} * PAW$
11	Phosphorus content of undesirable to incineration	$D_{1-0} = NUI * A_{1-0}$
12	Phosphorus content of the mush	$D_{2-3} = \frac{A_{2-3}}{A_{1-2}} * D_{1-2}$
13	Phosphorus content of the loss from digestor	$D_{3-0} = \frac{A_{3-0}}{A_{1-2}} * D_{1-2}$
14	Phosphorus content of the digestate spread directly after anaerobic digestion	$D_{4-0} = PDS * B_{3-4}$
15	Phosphorus content of the spread liquid phase	$D_{5-01} = (D_{4-5} - D_{5-04}) * PLP$
16	Phosphorus content of the solid phase going to post-treatment	$D_{5-02} = (D_{4-5} - D_{5-04}) * PSPS$

Table 39: Model approach equations of the Norwegian Phosphorus Nutrient Layer

Here is the parameter table:

PARAMETERS	LABELS	VALUE
PAR	Phosphorus content in agricultural residues	5.59E-04 $ktons_P$/ktons
PSS	Phosphorus content in sewage sludge	1.00E-03 $ktons_P$/ktons
PIW	Phosphorus content in industrial waste	4.00E-04 $ktons_P$ /ktons
PMW	Phosphorus content in municipal waste	8.88E-04 $ktons_P$ /ktons
PAW	Phosphorus content in aquaculture waste	2.20E-03 $ktons_P$ /ktons
NUI	Nutrient content in undesirable to incineration	0 ktons /ktons
PDS	Percentage of digestate for direct spreading	55%
PLP	Share of P from digestate for phase separation to liquid phase	25%
PSPS	Share of P from digestate for phase separation to post-treatment	75%

Table 40: List of parameters of the Norwegian Phosphorus Nutrient Layer

The sources for all figures are available in the Appendix 2.

For the nutrient content in undesirable to incineration, I assume that the materials removed during the deconditioning process do not contain nutrients.

Thanks to these 16 equations and the parameters, I was able to determine every value of my system.

Here are the results for the nutrient/phosphorus layer in the Norwegian biogas production system:

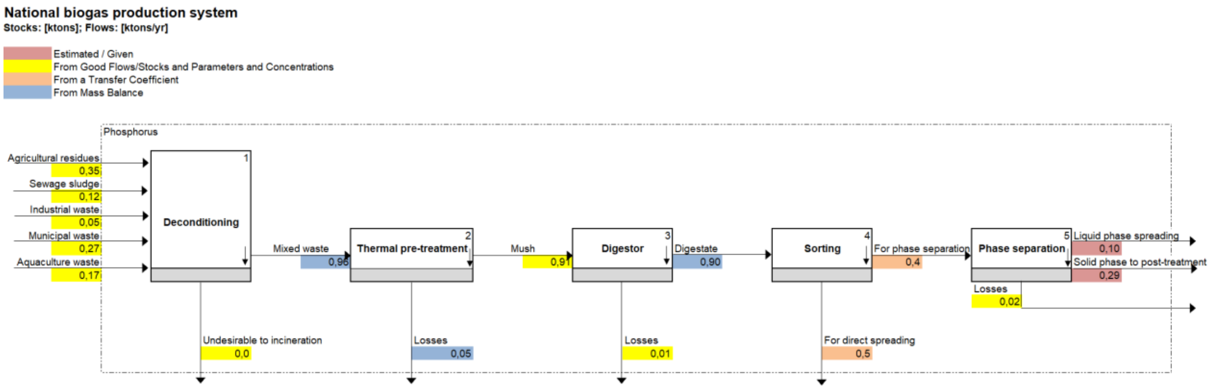

Figure 11: Nutrient/Phosphorus Layer of the Norwegian biogas production MFA system

III.3.3. Potassium Layer

III.3.3.1. French Layer

We start by listing the processes.

PROCESS N°	PROCESS NAME
1	Deconditioning
2	Thermal pre-treatment
3	Digestor
4	Sorting
5	Phase separation

Table 41: List of processes of the French Potassium Nutrient Layer

We are not considering the processes dealing with the biogas as there is no interest to study the nutrient content of the biogas.

Then, we list all variables and unknowns.

VARIABLE N°	VARIABLE NAME	GOOD FLOW NAME	FROM	TO
1	E_{0-11}	Agricultural residues	0	1
2	E_{0-12}	Sewage sludge	0	1
3	E_{0-13}	Industrial waste	0	1
4	E_{0-14}	Municipal waste	0	1
5	E_{1-0}	Undesirable to incineration	1	0
6	E_{1-2}	Mixed waste	1	2
7	E_{2-0}	Losses	2	0
8	E_{2-3}	Mush	2	3
9	E_{3-4}	Digestate	3	4
10	E_{3-0}	Losses	3	0
11	E_{4-0}	For direct spreading	4	0
12	E_{4-5}	For phase separation	4	5
13	E_{5-01}	Liquid phase spreading	5	0
14	E_{5-02}	Solid phase spreading	5	0
15	E_{5-03}	To post-treatment	5	0
16	E_{5-04}	Losses	5	0

Table 42: List of variables and unknows of the French Potassium Nutrient Layer

We have 16 variables, so we need 16 equations. First, we define mass balance equation of every process. As a reminder, stocks and stock changes are not considered in the study.

PROCESS	MASS BALANCE EQUATIONS
1 - DECONDITIONING	$0 = E_{0-11} + E_{0-12} + E_{0-13} + E_{0-14} - E_{1-0} - E_{1-2}$
2 – THERMAL PRE-TREATMENT	$0 = E_{1-2} - E_{2-0} - E_{2-3}$
3 - DIGESTOR	$0 = E_{2-3} - E_{3-4} - E_{3-0}$
4 - SORTING	$0 = E_{3-4} - E_{4-0} - E_{4-5}$
5 – PHASE SEPARATION	$0 = E_{4-5} - E_{5-01} - E_{5-02} - E_{5-03} - E_{5-04}$

Table 43: Mass balance equations of the French Potassium Nutrient Layer

We now have 5 equations; we need 11 more to resolve the system. To do so, we consider model approach equations.

EQ N°	EQUATION LABEL	EQUATION
6	Potassium content of agricultural residues	$E_{0-11} = A_{0-11} * KAR$
7	Potassium content of sewage sludge	$E_{0-12} = A_{0-12} * KSS$
8	Potassium content of industrial waste	$E_{0-13} = A_{0-13} * KIW$
9	Potassium content of municipal waste	$E_{0-14} = A_{0-14} * KMW$
10	Potassium content of undesirable to incineration	$E_{1-0} = NUI * A_{1-0}$
11	Potassium content of the mush	$E_{2-3} = \frac{A_{2-3}}{A_{1-2}} * E_{1-2}$
12	Potassium content of the loss from digestor	$E_{3-0} = \frac{A_{3-0}}{A_{1-2}} * E_{1-2}$
13	Potassium content of the digestate spread directly after anaerobic digestion	$E_{4-0} = PDS * B_{3-4}$
14	Potassium content of the spread liquid phase	$E_{5-01} = (E_{4-5} - E_{5-04}) * KLP$
15	Potassium content of the spread solid phase	$E_{5-02} = (E_{4-5} - E_{5-04}) * KSPS$
16	Potassium content of the solid phase going to post-treatment	$E_{5-03} = (E_{4-5} - E_{5-04}) * KSPP$

Table 44: Model approach equations of the French Potassium Nutrient Layer

Here is the parameter table:

PARAMETERS	LABELS	VALUE
KAR	Potassium content in agricultural residues	4.88E-03 $ktons_K$/ktons
KSS	Potassium content in sewage sludge	2.00E-04 $ktons_K$/ktons
KIW	Potassium content in industrial waste	7.00E-04 $ktons_K$ /ktons
KMW	Potassium content in municipal waste	2.40E-03 $ktons_K$ /ktons
NUI	Nutrient content in undesirable to incineration	0 ktons /ktons
PDS	Percentage of digestate for direct spreading	55%
KLP	Share of K from digestate for phase separation to liquid phase	80%
KSPS	Share of K from digestate for phase separation to solid phase	2%
KSPP	Share of K from digestate for phase separation to post-treatment	18%

Table 45: List of parameters of the French Potassium Nutrient Layer

The sources for all figures are available in the Appendix 1.

For the nutrient content in undesirable to incineration, I assume that the materials removed during the deconditioning process do not contain nutrients.

Thanks to these 16 equations and the parameters, I was able to determine every value of my system.

Here are the results for the nutrient/potassium layer in the French biogas production system:

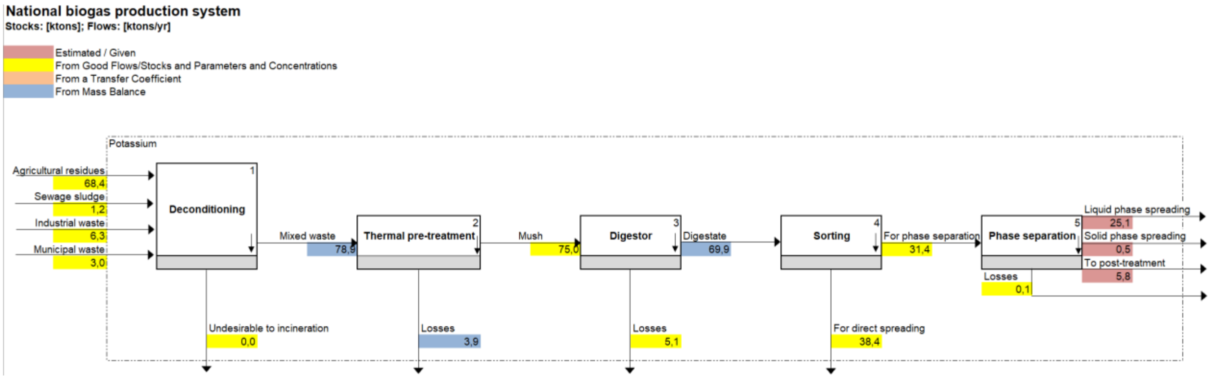

Figure 12: Nutrient/Potassium Layer of the French biogas production MFA system

III.3.3.2. Norwegian Layer

We start by listing the processes.

PROCESS N°	PROCESS NAME
1	Deconditioning
2	Thermal pre-treatment
3	Digestor
4	Sorting
5	Phase separation

Table 46: List of processes of the Norwegian Potassium Nutrient Layer

We are not considering the processes dealing with the biogas as there is no interest to study the nutrient content of the biogas.

Then, we list all variables and unknowns.

VARIABLE N°	VARIABLE NAME	GOOD FLOW NAME	FROM	TO
1	E_{0-11}	Agricultural residues	0	1
2	E_{0-12}	Sewage sludge	0	1
3	E_{0-13}	Industrial waste	0	1
4	E_{0-14}	Municipal waste	0	1
5	E_{0-15}	Aquaculture waste	0	1
6	E_{1-0}	Undesirable to incineration	1	0
7	E_{1-2}	Mixed waste	1	2
8	E_{2-0}	Losses	2	0
9	E_{2-3}	Mush	2	3
10	E_{3-4}	Digestate	3	4
11	E_{3-0}	Losses	3	0
12	E_{4-0}	For direct spreading	4	0
13	E_{4-5}	For phase separation	4	5
14	E_{5-01}	Liquid phase spreading	5	0
15	E_{5-02}	To post-treatment	5	0
16	E_{5-03}	Losses	5	0

Table 47: List of variables and unknows of the Norwegian Potassium Nutrient Layer

Same as in the mass layer, the difference compared to France is the adding of *aquaculture waste* as intrants and the removal of *Solid phase spreading*.

We have 16 variables, so we need 16 equations. First, we define mass balance equation of every process. As a reminder, stocks and stock changes are not considered in the study.

PROCESS	MASS BALANCE EQUATIONS
1 - DECONDITIONING	$0 = E_{0-11} + E_{0-12} + E_{0-13} + E_{0-14} + E_{0-15} - E_{1-0} - E_{1-2}$
2 – THERMAL PRE-TREATMENT	$0 = E_{1-2} - E_{2-0} - E_{2-3}$
3 - DIGESTOR	$0 = E_{2-3} - E_{3-4} - E_{3-0}$
4 - SORTING	$0 = E_{3-4} - E_{4-0} - E_{4-5}$
5 – PHASE SEPARATION	$0 = E_{4-5} - E_{5-01} - E_{5-02} - E_{5-03}$

Table 48: Mass balance equations of the Norwegian Potassium Nutrient Layer

We now have 5 equations; we need 11 more to resolve the system. To do so, we consider model approach equations.

EQ N°	EQUATION LABEL	EQUATION
6	Potassium content of agricultural residues	$E_{0-11} = A_{0-11} * KAR$
7	Potassium content of sewage sludge	$E_{0-12} = A_{0-12} * KSS$
8	Potassium content of industrial waste	$E_{0-13} = A_{0-13} * KIW$
9	Potassium content of municipal waste	$E_{0-14} = A_{0-14} * KMW$
10	Potassium content of aquaculture waste	$E_{0-15} = A_{0-14} * KAW$
11	Potassium content of undesirable to incineration	$E_{1-0} = NUI * A_{1-0}$
12	Potassium content of the mush	$E_{2-3} = \frac{A_{2-3}}{A_{1-2}} * E_{1-2}$
13	Potassium content of the loss from digestor	$E_{3-0} = \frac{A_{3-0}}{A_{1-2}} * E_{1-2}$
14	Potassium content of the digestate spread directly after anaerobic digestion	$E_{4-0} = PDS * B_{3-4}$
15	Potassium content of the spread liquid phase	$E_{5-01} = (E_{4-5} - E_{5-04}) * KLP$
16	Potassium content of the solid phase going to post-treatment	$E_{5-02} = (E_{4-5} - E_{5-04}) * KSPS$

Table 49: Model approach equations of the Norwegian Potassium Nutrient Layer

Here is the parameter table:

PARAMETERS	LABELS	VALUE
KAR	Potassium content in agricultural residues	4.88E-03 $ktons_K$/ktons
KSS	Potassium content in sewage sludge	2.00E-04 $ktons_K$/ktons
KIW	Potassium content in industrial waste	7.00E-04 $ktons_K$ /ktons
KMW	Potassium content in municipal waste	2.48E-03 $ktons_K$ /ktons
KAW	Potassium content in aquaculture waste	1.00E-04 $ktons_K$ /ktons
NUI	Nutrient content in undesirable to incineration	0 ktons /ktons
PDS	Percentage of digestate for direct spreading	55%
KLP	Share of K from digestate for phase separation to liquid phase	80%
KSPS	Share of K from digestate for phase separation to post-treatment	20%

Table 50: List of parameters of the Norwegian Potassium Nutrient Layer

The sources for all figures are available in the Appendix 2.

For the nutrient content in undesirable to incineration, I assume that the materials removed during the deconditioning process do not contain nutrients.

Thanks to these 16 equations and the parameters, I was able to determine every value of my system.

Here are the results for the nutrient/potassium layer in the Norwegian biogas production system:

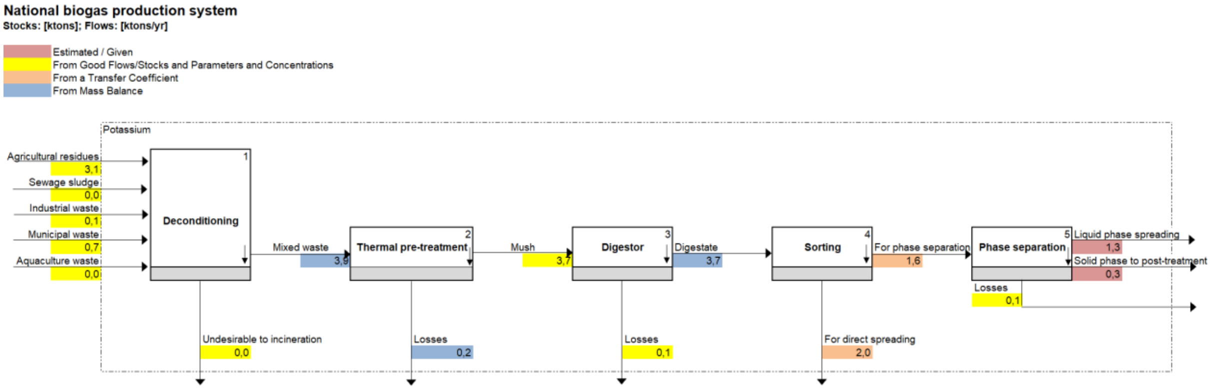

Figure 13: Nutrient/Potassium Layer of the Norwegian biogas production MFA system

IV. Uncertainty Analysis

With the mathematical approach, I was able to attribute a value to each flow. However, this value cannot be a real or true value. Indeed, all the calculations are based on parameters taken from the literature. These parameters have uncertainties as they cannot be hundred percent accurate.
Then, the next step, after the mathematical approach, is to determine the uncertainty of every flow based on the uncertainty of the parameters.

To do so, I used a Python program using the parameter uncertainties, dealing with all the equations of the mathematical approach, and using a Monte Carlo simulation. From parameter uncertainties and distribution as inputs, the Python program retrieves the mean and standard deviation of every flows.

IV.1. Parameters Uncertainties

First step of the uncertainty analysis is the assignment of relative error and distribution to every parameter.

Relative errors are between 5% and 20% depending on the uncertainty of the figures. For example, I assign a 5% relative error to the parameter *Density of biogas* as it is a number that is used by many scientists when they make calculations about biogas. Same goes for the PCS of biogas.

Conversely, I assign to the energy content of all intrants a 20% relative error as even if these figures are from serious scientific literatures, they come from estimations and/or calculations.

For the distribution, I mainly used the *normal* distribution but also the *truncated normal* distribution.

IV.1.1 Normal distribution

Normal distribution, also known as the Gaussian distribution, is a distribution that is symmetric and characterized by its mean and standard deviation. It is one of the most important and widely used probability distributions.

In a normal distribution, the data is symmetrically distributed around the mean.

In the table that will follow, all parameters assigned with a normal distribution present two columns, the first with dp1 representing the mean value and the second with dp2 representing the standard deviation.

IV.1.2. Truncated normal distribution

The truncated normal distribution is a variation of the normal distribution that is restricted to a certain range or interval. It is obtained by taking a standard normal distribution and truncating it at specific upper and lower limits.

The truncated normal distribution inherits some properties from the normal distribution, such as symmetry within the specified range. However, it differs in terms of its probability density being zero outside of the range.

Truncated normal distributions have various applications, particularly in situations where data is known to be bounded.

In this case, truncated distribution was useful with transfer coefficient or percentage, where the distribution needs to be between 0 and 1.

In the table that will follow, all parameters assigned with a truncated normal distribution present four columns, the first with dp1 representing the mean value, the second with dp2 representing the lower limit, the third with dp3 representing the upper limit and the last with dp4 representing the standard deviation.

When all these assignments were done, the following tables were created:

Parameters	Symbol	Observed value	Units	Rel. Err.	dp1	dp2	dp3	dp4	Distribution
Agricultural residues	AR	14000	ktons	10%	14000	1400			norm
Sewage-sludge	SS	6010	ktons	10%	6010	601			norm
Industrial waste	IW	9000	ktons	10%	9000	900			norm
Municipal waste	MW	1270	ktons	10%	1270	127			norm
Deconditioning rate	k_10	0,05		5%	0,05	0	1	2,50E-03	truncnorm
Losses during hygienisation/pasteurisation	k_20	0,05		5%	0,05	0	1	2,50E-03	truncnorm
Density of biogas	DB	1150	tons/m3	5%	1150	57,5			norm
PCS of biogas	PCS	7,00	kWh/m3	5%	7,00	0,35			norm
Mass of oxygen per mass of biogas	k_341	1,19	kgO2/kgbiogas	5%	1,19	0,0595			norm
Mass of carbon dioxyde per mass of biogas	k_342	1,63	kgCO2/kgbiogas	5%	1,63	0,0815			norm
Mass of water per mass of biogas	k_343	0,56	kgH2O/kgbiogas	5%	0,56	0,028			norm
H2S content in biogas	HSC	0,005		10%	0,005	0	1	0,0005	truncnorm
Efficiency of H2S cleaning	EHSC	0,95		10%	0,95	0	1	9,5%	truncnorm
H2O content in biogas (volume)	HOC	0,06	kgH2O/kgbiogas	10%	0,06	0	1	0,006	truncnorm
Density of H2O (gas)	DHO	0,59	kg/m3	5%	0,59	0,0295			norm
CO2 content in biogas (volume)	COC	0,26	kgCO2/kgbiogas	10%	0,26	0	1	0,026	truncnorm
Density of CO2	DCO	1,87	kg/m3	5%	1,87	0,0935			norm
Share of mush becoming digestate	PM	0,85		15%	0,85	0	1	0,1275	truncnorm
Share of digestate for direct spreading	PDS	0,55		15%	0,55	0	1	0,0825	truncnorm
Share of digestate for phase separation	PPS	0,45		15%	0,45	0	1	0,0675	truncnorm
Share of liquid phase after phase separation	SPLP	0,176		15%	0,18	0	1	0,0264	truncnorm
Share of solid phase after phase separation	PSP	0,066		15%	0,07	0	1	0,0099	truncnorm
Share sent to post treatment after phase separation	PPT	0,756		15%	0,76	0	1	0,113333	truncnorm
Energy content of agricultural residues	ECA	1,69E-03	TWh/ktons	20%	0,00	0,000338			norm
Energy content of sewage sludge	ECS	5,40E-04	TWh/ktons	20%	0,00	0,000108			norm
Energy content of industrial waste (mainly food-processing)	ECI	8,20E-04	TWh/ktons	20%	0,00	0,000164			norm
Energy content of municipal waste	ECMW	9,90E-04	TWh/ktons	20%	0,00	0,000198			norm
Share of electricity produced required for deconditioning	PED	0,05		20%	0,05	0	1	0,01	truncnorm
Energy consumption of the thermal pre-treatment process	ECT	6,66E-05	TWh/ktons	20%	0,00	1,33E-05			norm
Energy content of the mush	ECM	0,446	kWh/kg	15%	0,446	0,0669			norm
Share of primary energy produced required for digestor heating	PPE	0,115		20%	0,115	0,023			norm
Energy losses through the digestor walls (Share of heating input)	ELD	0,10		10%	0,100	0	1	0,01	truncnorm
Biomethane production from biogas	BP	4,3	TWh	10%	4,3	0,43			norm
Electricity production from biogas	EP	2,8	TWh	10%	2,8	0,28			norm
Heat production from biogas	HP	4,5	TWh	10%	4,5	0,45			norm
CHP Heat efficiency	HE	0,60		5%	0,6	0	1	0,03	truncnorm
CHP Power efficiency	PE	0,25		5%	0,3	0	1	0,0125	truncnorm
CHP overall efficiency	OE	0,79		10%	0,8	0	1	0,07857	truncnorm
Energy efficiciency of the purification step	EEP	0,995		20%	0,995	0	1	0,199	truncnorm
Nitrogen content in agricultural residues	NAR	5,23E-03	ktonsN/ktons	20%	5,23E-03	1,05E-03			norm
Nitrogen content in sewage sludge	NSS	1,60E-03	ktonsN/ktons	20%	1,60E-03	3,20E-04			norm
Nitrogen content in industrial waste	NIW	3,70E-03	ktonsN/ktons	20%	3,70E-03	7,40E-04			norm
Nitrogen content in municipal waste	NMW	7,62E-03	ktonsN/ktons	20%	7,62E-03	1,52E-03			norm
Phosphorus content in agricultural residues	PAR	5,59E-04	ktonsP/ktons	20%	5,59E-04	1,12E-04			norm
Phosphorus content in sewage sludge	PSS	1,00E-03	ktonsP/ktons	20%	1,00E-03	2,00E-04			norm
Phosphorus content in industrial waste	PIW	4,00E-04	ktonsP/ktons	20%	4,00E-04	8,00E-05			norm
Phosphorus content in municipal waste	PMW	8,88E-04	ktonsP/ktons	20%	8,88E-04	1,78E-04			norm
Potassium content in agricultural residues	KAR	4,88E-03	ktonsK/ktons	20%	4,88E-03	9,77E-04			norm
Potassium content in sewage sludge	KSS	2,00E-04	ktonsK/ktons	20%	2,00E-04	4,00E-05			norm
Potassium content in industrial waste	KIW	7,00E-04	ktonsK/ktons	20%	7,00E-04	1,40E-04			norm
Potassium content in municipal waste	KMW	2,40E-03	ktonsK/ktons	20%	2,40E-03	4,80E-04			norm
Share of N from digestate for phase separation to liquid phase	NLP	0,95		20%	0,95	0	1	0,19	truncnorm
Share of N from digestate for phase separation to solid phase	NSPS	0,004		20%	0,004	0	1	0,0008	truncnorm
Share of N from digestate for phase separation to post-treament	NSPP	0,05		20%	0,05	0	1	0,0092	truncnorm
Share of P from digestate for phase separation to liquid phase	PLP	0,25		20%	0,25	0	1	0,05	truncnorm
Share of P from digestate for phase separation to solid phase	PSPS	0,06		20%	0,06	0	1	0,012	truncnorm
Share of P from digestate for phase separation to post-treament	PSPP	0,69		20%	0,69	0	1	0,138	truncnorm
Share of K from digestate for phase separation to liquid phase	KLP	0,80		20%	0,80	0	1	0,16	truncnorm
Share of K from digestate for phase separation to solid phase	KSPS	0,02		20%	0,02	0	1	0,0032	truncnorm
Share of K from digestate for phase separation to post-treatment	KSPP	0,18		20%	0,18	0	1	0,0368	truncnorm

Table 51: Uncertainty analysis of the French MFA system parameters

Parameters	Symbol	Observed value	Units	Rel. Err.	dp1	dp2	dp3	dp4	Distribution
Agricultural residues	AR	630	ktons	10%	630	63,0029			norm
Sewage-sludge	SS	123	ktons	10%	123	12,2574			norm
Industrial waste	IW	117	ktons	10%	117	11,7078			norm
Municipal waste	MW	300	ktons	10%	300	30,0473			norm
Aquaculture waste	AW	78	ktons	10%	78	7,8125			norm
Deconditioning rate	k_10	0,05		5%	0,05	0	1	2,50E-03	truncnorm
Losses during hygienisation/pasteurisation	k_20	0,05		5%	0,05	0	1	2,50E-03	truncnorm
Density of biogas	DB	1150	tons/m3	5%	1150	57,5			norm
PCS of biogas	PCS	7,00	kWh/m3	5%	7,00	0,35			norm
Mass of oxygen per mass of biogas	k_341	1,19	kgO2/kgbiogas	5%	1,19	0,0595			norm
Mass of carbon dioxyde per mass of biogas	k_342	1,63	kgCO2/kgbiogas	5%	1,63	0,0815			norm
Mass of water per mass of biogas	k_343	0,56	kgH2O/kgbiogas	5%	0,56	0,028			norm
H2S content in biogas	HSC	0,005		10%	0,005	0	1	0,0005	truncnorm
Efficiency of H2S cleaning	EHSC	0,95		10%	0,95	0	1	9,5%	truncnorm
H2O content in biogas (volume)	HOC	0,06	kgH2O/kgbiogas	10%	0,06	0	1	0,006	truncnorm
Density of H2O (gas)	DHO	0,59	kg/m3	5%	0,59	0,0295			norm
CO2 content in biogas (volume)	COC	0,26	kgCO2/kgbiogas	10%	0,26	0	1	0,026	truncnorm
Density of CO2	DCO	1,87	kg/m3	5%	1,87	0,0935			norm
Share of mush becoming digestate	PM	0,85		15%	0,85	0	1	0,1275	truncnorm
Share of digestate for direct spreading	PDS	0,55		15%	0,55	0	1	0,0825	truncnorm
Share of digestate for phase separation	PPS	0,45		15%	0,45	0	1	0,0675	truncnorm
Percentage of liquid phase after phase separation	SPLP	0,10		15%	0,10	0	1	0,015	truncnorm
Percentage of solid phase sent to post treatment after phase separation	PPT	0,85		15%	0,85	0	1	0,1275	truncnorm
Energy content of agricultural residues	ECA	1,69E-03	TWh/ktons	20%	0,00	0,000338			norm
Energy content of sewage sludge	ECS	5,40E-04	TWh/ktons	20%	0,00	0,000108			norm
Energy content of industrial waste (mainly food-processing)	ECI	8,20E-04	TWh/ktons	20%	0,00	0,000164			norm
Energy content of municipal waste	ECMW	9,90E-04	TWh/ktons	20%	0,00	0,000198			norm
Energy content of aquaculture waste	ECAW	9,28E-04	TWh/ktons	20%	0,00	0,000186			norm
Share of electricity produced required for deconditioning	PED	0,05		20%	0,05	0	1	0,01	truncnorm
Energy consumption of the thermal pre-treatment process	ECT	6,66E-05	kWh/ktons	20%	0,00	1,33E-05			norm
Energy content of the mush	ECM	0,446	kWh/kg	15%	0,446	0,0669			norm
Share of primary energy produced required for digestor heating	PPE	0,115		20%	0,115	0,023			norm
Energy losses through the digestor walls (Share of heating input)	ELD	0,10		10%	0,100	0	1	0,01	truncnorm
Total biogas production in Norway	BP	0,9	TWh	10%	0,9	0,0933			norm
Share of biogas to biofuel Norway	EP	0,40		15%	0,40	0	1	0,06	truncnorm
Share of biogas to CHP Norway	HP	0,60		15%	0,60	0	1	0,09	truncnorm
CHP Heat efficiency	HE	0,60		5%	0,6	0	1	0,03	truncnorm
CHP Power efficiency	PE	0,25		5%	0,3	0	1	0,0125	truncnorm
Energy efficiency of the purification step	EEP	0,995		20%	0,995	0	1	0,199	truncnorm
Nitrogen content in agricultural residues	NAR	5,23E-03	ktonsN/ktons	20%	5,23E-03	1,05E-03			norm
Nitrogen content in sewage sludge	NSS	1,60E-03	ktonsN/ktons	20%	1,60E-03	3,20E-04			norm
Nitrogen content in industrial waste	NIW	3,70E-03	ktonsN/ktons	20%	3,70E-03	7,40E-04			norm
Nitrogen content in municipal waste	NMW	7,62E-03	ktonsN/ktons	20%	7,62E-03	1,52E-03			norm
Nitrogen content in aquaculture waste	NAW	3,30E-03	ktonsN/ktons	20%	3,30E-03	6,60E-04			norm
Phosphorus content in agricultural residues	PAR	5,59E-04	ktonsP/ktons	20%	5,59E-04	1,12E-04			norm
Phosphorus content in sewage sludge	PSS	1,00E-03	ktonsP/ktons	20%	1,00E-03	2,00E-04			norm
Phosphorus content in industrial waste	PIW	4,00E-04	ktonsP/ktons	20%	4,00E-04	8,00E-05			norm
Phosphorus content in municipal waste	PMW	8,88E-04	ktonsP/ktons	20%	8,88E-04	1,78E-04			norm
Phosphorus content in aquaculture waste	PAW	2,20E-03	ktonsP/ktons	20%	2,20E-03	4,40E-04			norm
Potassium content in agricultural residues	KAR	4,88E-03	ktonsK/ktons	20%	4,88E-03	9,77E-04			norm
Potassium content in sewage sludge	KSS	2,00E-04	ktonsK/ktons	20%	2,00E-04	4,00E-05			norm
Potassium content in industrial waste	KIW	7,00E-04	ktonsK/ktons	20%	7,00E-04	1,40E-04			norm
Potassium content in municipal waste	KMW	2,40E-03	ktonsK/ktons	20%	2,40E-03	4,80E-04			norm
Potassium content in aquaculture waste	KAW	1,00E-04	ktonsK/ktons	20%	1,00E-04	2,00E-05			norm
Share of N from digestate for phase separation to liquid phase	NLP	0,95		20%	0,95	0	1	0,19	truncnorm
Share of N from digestate for phase separation to solid phase	NSPP	0,05		20%	0,05	0	1	0,01	truncnorm
Share of P from digestate for phase separation to liquid phase	PLP	0,25		20%	0,25	0	1	0,05	truncnorm
Share of P from digestate for phase separation to solid phase	PSPS	0,75		20%	0,75	0	1	0,15	truncnorm
Share of K from digestate for phase separation to liquid phase	KLP	0,80		20%	0,80	0	1	0,16	truncnorm
Share of K from digestate for phase separation to solid phase	KSPS	0,20		20%	0,20	0	1	0,04	truncnorm

Table 52: Uncertainty analysis of the Norwegian MFA system parameters

Once I determine all the parameter uncertainties, I used the Python program.

IV.2. Python program

The entire Python program is in the Appendix 3 & 4. It is inspired by a Python code created by Nils Dittrich from NTNU in 2022.

After importing all necessary modules from Python, the first step is to import all the parameters with relative error and distribution thanks to the upper tables and then initialize them. Then, through the Python code, every parameter has been sampled. Before quantifying the mathematical model in Python, it was important to be sure that each parameter was independent from another. To do so, I plot the sample of any parameter as function of another.

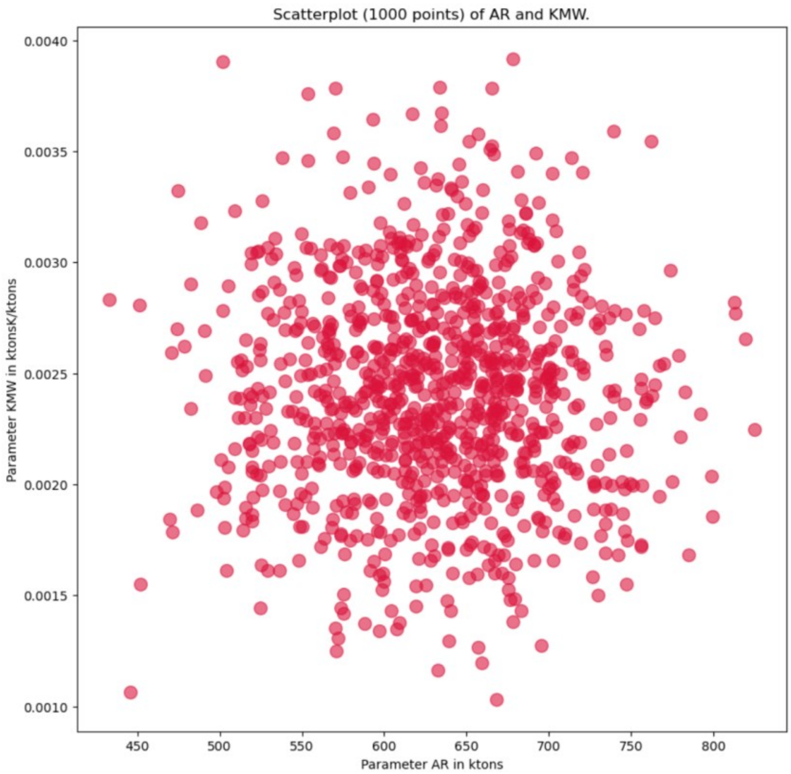

Figure 14: Scatterplot of a parameter as function of another

As visible, there is no relation between the two parameters so we can conclude that there are independent. It was the same results for every other parameter.

Next step is quantifying the system in Python thanks to a specific function. The function takes the list of parameters as input and gives the list of flows as outputs. Equations of every flow are filled in the function.

The outputs contain a list of values corresponding to the values of each flow. The aim was then to use these values to determine mean and standard deviation of every flow. That is why I perform a Monte Carlo Simulation at this stage.

IV.3. Monte-Carlo Simulation

Monte Carlo simulation is a computational technique that utilizes random sampling to model and analyze the behavior of complex systems or processes.

In a Monte Carlo simulation, a problem or system is simulated multiple times using random inputs or parameters. Each simulation run represents a possible outcome, and by conducting a large number of simulations, statistical patterns and trends can be observed.

I conduct 10^4 simulations in the code to have clear and visible outcomes for the flows. As outputs, histograms of the distribution of every flow were plotted.

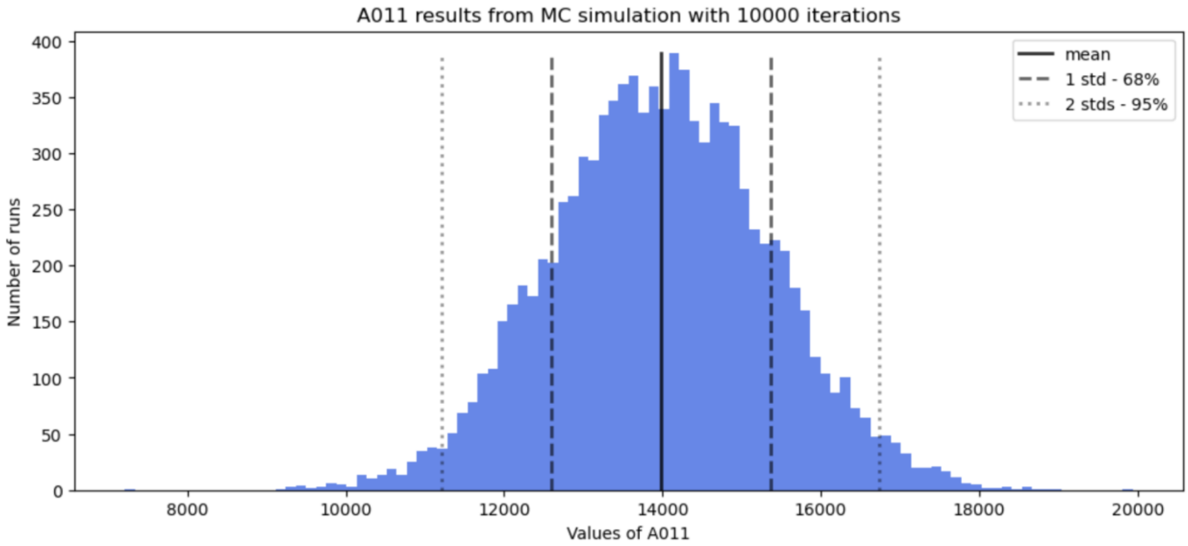

Figure 15: Example of histogram plotted after Monte-Carlo Simulation

Several information can be read on the graph. First the mean value in the middle of the graph, then the distribution of the flow, with the key values of one standard deviation containing 68% of the values and two standard deviations containing 95% of the values.

Thanks to the Monte-Carlo simulation, from the parameters uncertainties, I determined the uncertainties of every flow of the MFA systems.

The result and comments on this uncertainty analysis will be presented later, after the presentation of data reconciliation.

IV.4. Data reconciliation

Even if I now have more accurate values for every flow, the study is not complete yet. In the Python program, I never define basic equations of MFA, the mass balance equations. Consequently, even if flow values are closer to real values, they do not respect mass balance principle.
The final step of the study is to perform data reconciliation to use the mean value and standard deviation calculated in the Python program and make them abide the mass balance principle.

Data reconciliation is a process that involves comparing and reconciling different sources of data related to the flow of materials within a system.

The goal of data reconciliation is to identify and resolve inconsistencies or errors in the data to obtain a more accurate and reliable representation of the flows.

To perform data reconciliation, I use the software STAN (subSTance flow ANalysis) 2.6.801.

STAN is a probabilistic programming language and software tool used for realizing data reconciliation of MFA systems.

The software allows to specify the models using a high-level modeling language similar to mathematical notation.

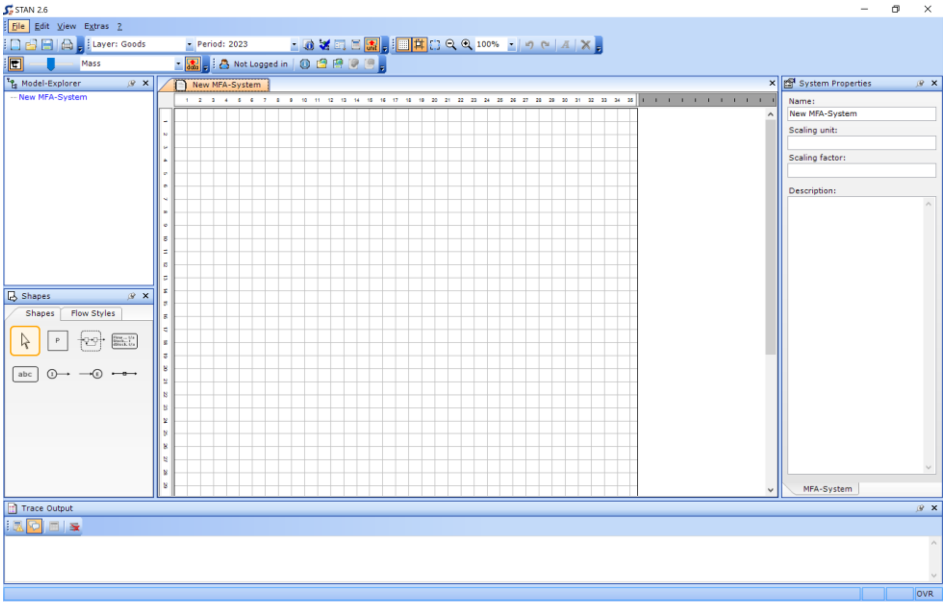

Figure 16: Interface of the STAN software

After drawing the systems and allocating to every flow the mean value and standard deviation calculated in Python, the software reconciled the data and calculated the best estimated value and the best standard deviation regarding mass balance principle.

After data reconciliation, values of every flow are accurate and abide by the mass balance principle.

We can replace the original value by the reconciled value in the MFA systems to be as close as possible to reality.

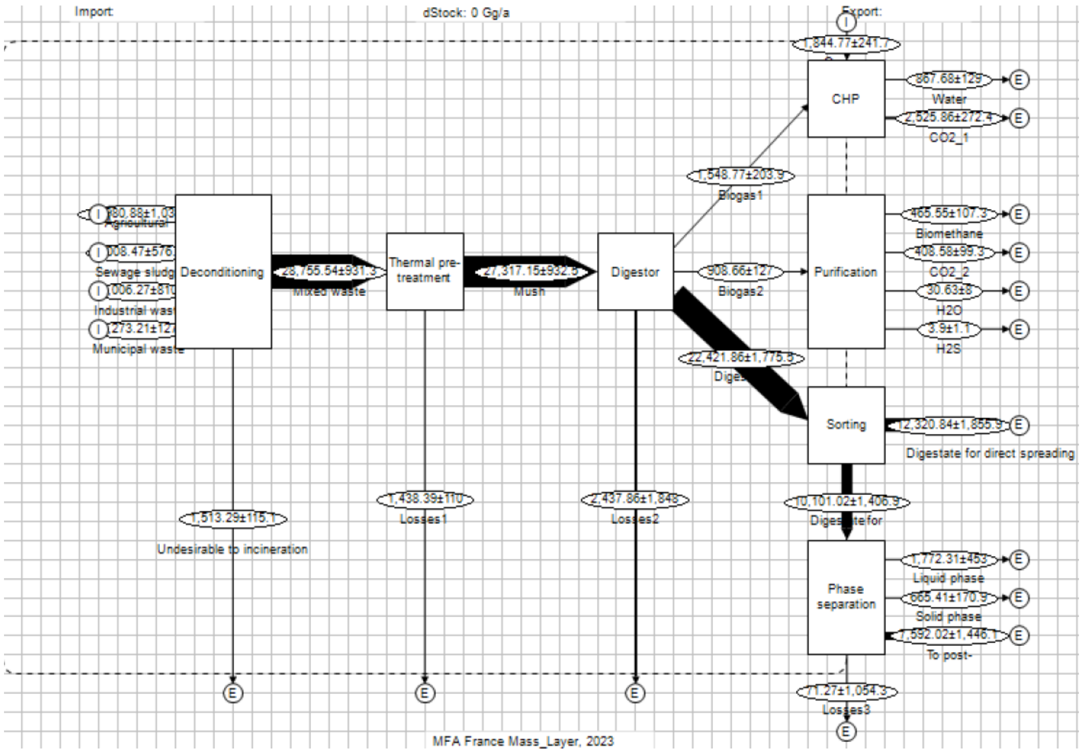

Figure 17: Example of the before/after STAN calculations for the French Mass Layer (before with values from Monte-Carlo Simulation)

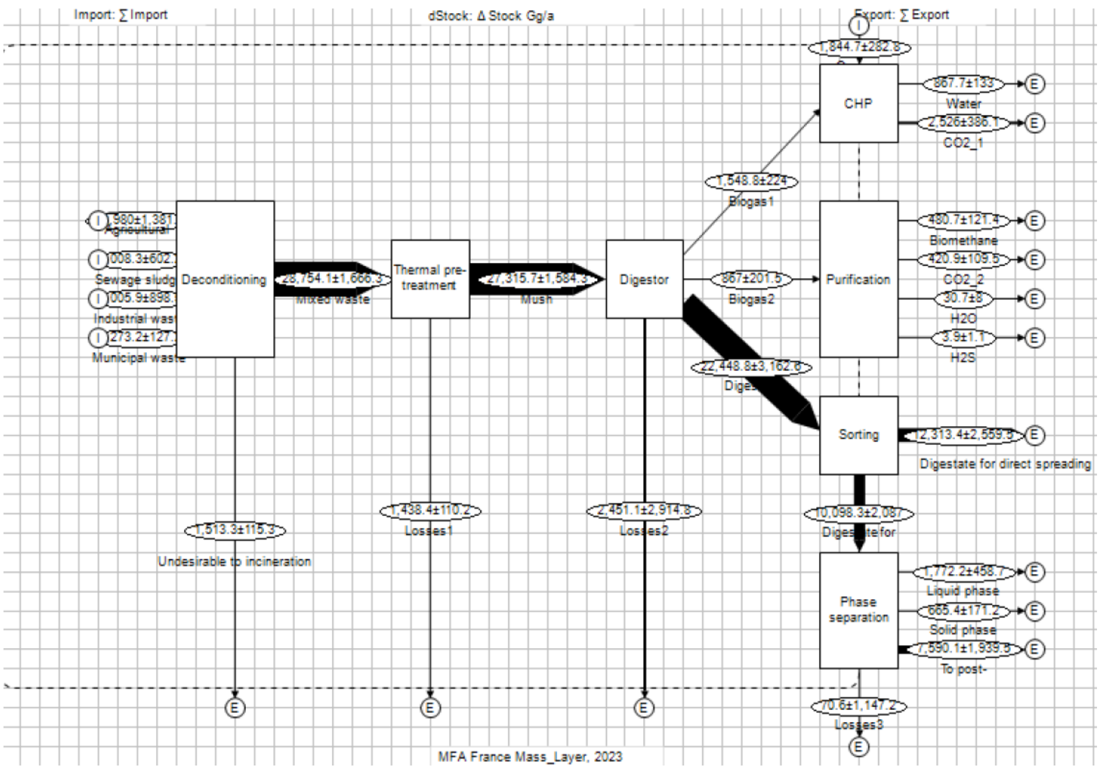

Figure 18: Example of the before/after STAN calculations for the French Mass Layer (after with values calculated with STAN)

IV.5. Results of uncertainty analysis and data reconciliation

The aim of this part is to analyze and interpret the results of uncertainty analysis and data reconciliation presented above.

IV.5.1. French biogas production MFA systems

The tables below sum up the different stages of the study for the French biogas production system.

Flow name	Original value	MC value	MC Stand Dev	MC relative error	Best estimate value	Best estimate Stand Dev
Agricultural residues	14000,0	13980,0	1381,5	10%	13980,9	1031,3
Sewage sludge	6010,0	6008,3	602,2	10%	6008,5	576,3
Industrial waste	9000,0	9005,9	898,5	10%	9006,3	810,0
Municipal waste	1270,0	1273,2	127,2	10%	1273,2	127,0
Mixed waste	28766,0	28754,1	1666,3	6%	28755,5	931,3
Undesirable to incineration	1514,0	1513,3	115,3	8%	1513,3	115,1
Mush	27327,7	27315,7	1584,3	6%	27317,2	932,5
Losses	1438,3	1438,4	110,2	8%	1438,4	110,0
Biogas	1526,4	1548,8	224,0	14%	1548,8	203,9
Biogas	710,0	867,0	201,5	23%	908,7	127,0
Digestate	23228,5	22448,8	3162,6	14%	22421,9	1775,5
Losses	1862,8	2451,1	2914,8	**119%**	2437,9	1848,0
Oxygen	1816,4	1844,7	282,8	15%	1844,8	241,7
Water	854,8	867,7	133,0	15%	867,7	129,0
CO2	2488,0	2526,0	386,1	15%	2525,9	272,4
Biomethane	384,6	480,7	121,4	25%	465,6	107,3
CO2	300,2	420,9	109,5	26%	408,6	99,3
H2O	21,9	30,7	8,0	26%	30,6	8,0
H2S	3,4	3,9	1,1	27%	3,9	1,1
Digestate for direct spreading	12775,7	12313,4	2559,5	21%	12320,8	1855,9
Digestate for separation	10452,8	10098,3	2087,0	21%	10101,0	1406,9
Liquid phase spreading	1839,7	1772,2	458,7	26%	1772,3	453,0
Solid phase spreading	689,9	665,4	171,2	26%	665,4	170,9
To post-treatment	7897,7	7590,1	1939,5	26%	7592,0	1446,1
Losses	25,6	70,6	1147,2	**1624%**	71,3	1054,3

*MC stands for Monte-Carlo simulation

* Best estimate values are values calculated after data reconciliation

Table 53: Results of the uncertainty analysis and data reconciliation for the French Mass Layer

After Monte-Carlo simulation, the relative error is between 6% and 27% for most of the flows. As it is under 30%, we can consider that the uncertainties are quite reasonable and that the calculations are precise.

However, two flows have a very high relative error, superior to 100% and even 1000%. Going back to the mathematical approach, the two flows are calculated with mass balance equation. As the mass balance equation is an accumulation of terms, it is logical to have a very high uncertainty, as all uncertainties are accumulating. That is why relative errors are of no interest for flows determined through mass balance.

We can also notice that the flows from the purification process (*biomethane*, *CO2*, *H2O* and *H2S*) and the phase separation process (*Liquid phase spreading*, *solid phase spreading* and *to post-treatment*) have higher uncertainties than others. It means that they are calculated from parameters with high uncertainties or from a high number of parameters. For both processes, it is the second reason, back to the mathematical modeling, the flows are calculated with more than ten parameters. Even if these parameters are highly certain, uncertainties are accumulating.

Consequently, we need to be cautious interpreting these values, keeping in mind that they are more uncertain than the others.

After data reconciliation, there is some differences between flows. Whereas values of most of the flows do not change much, less than one percent compared to the Monte-Carlo results, the value of the biogas flow from *Digestor* to *Purification* varies more, around 5%. It can be explained by the fact that this flow has the more important uncertainty compared to other flows of the *Purification* process. Then, during data reconciliation, this value was the easiest to modify.

Flow name	Original value	MC value	MC Stand Dev	MC relative error	Best estimate value	Best estimate Stand Dev
Agricultural residues	23,7	23,6	5,2	22%	22,0	4,0
Sewage sludge	3,2	3,3	0,7	23%	3,3	0,7
Industrial waste	7,4	7,4	1,7	51%	7,2	1,7
Municipal waste	1,3	1,3	0,3	9%	1,3	0,3
Electricity	0,1	0,1	0,0	1%	0,1	0,0
Mixed waste	10,9	11,9	1,6	50%	12,0	0,9
Undesirable to incineration	24,8	19,9	5,7	**176%**	21,9	4,0
Heating	1,9	1,9	0,4	12%	1,9	0,4
Mush	12,2	13,2	1,5	46%	13,2	0,8
Losses	0,6	0,7	0,1	3%	0,7	0,1
Heating	1,6	1,7	0,4	12%	1,7	0,4
Biogas	9,3	9,4	1,2	36%	9,4	0,7
Biogas	4,3	5,3	1,2	36%	5,3	0,7
Losses	0,2	0,2	0,0	1%	0,2	0,0
Electricity	2,8	2,8	0,3	9%	2,8	0,3
Heat	4,5	4,5	0,4	14%	4,5	0,4
Losses	2,0	2,1	1,0	30%	2,1	0,7
Biomethane	4,3	4,3	0,4	13%	4,3	0,4
Losses	0,02	1,0	1,0	**109%**	1,0	0,7

Table 54: Results of the uncertainty analysis and data reconciliation for the French Energy Layer

For the energy layer, standard deviations of every flow are higher compared to mass layer. It is logical as back to mathematical model; energy layer equations consist of more parameters than mass layer ones. For example, equation of agricultural residues energy content consists of two terms while equation of agricultural residues mass only consists of one. It is the same for all flows.

Same observation for flows from mass balance equations, standard deviation is of no interest.

As standard deviations are higher, the gap between the Monte-Carlo mean value and the best estimate value is a little bit higher too but the correction stays relatively small.

Flow name	Original value	MC value	MC Stand Dev	MC relative error	Best estimate value	Best estimate Stand Dev
Agricultural residues	73,3	73,3	16,4	22%	73,3	16,4
Sewage sludge	9,6	9,6	2,2	22%	9,6	2,2
Industrial waste	33,3	33,3	7,5	23%	33,3	7,5
Municipal waste	9,7	9,8	2,2	22%	9,8	2,2
Mixed waste	125,9	125,9	18,4	15%	125,37	10,4
Undesirable to incineration	0,0	0,0	0,0	0%	0%	0%
Mush	119,6	119,6	17,4	15%	119,1	10,4
Losses	6,3	6,3	1,0	15%	6,3	1
Digestate	111,4	108,9	20,2	19%	107,8	10,5
Losses	8,2	10,7	13,0	**121%**	11,3	10,6
For direct spreading	61,3	59,7	14,4	24%	60,9	10,7
For phase separation	50,1	49,0	11,8	24%	46,9	8,1
Liquid phase spreading	47,5	40,4	12,3	30%	43,6	8,3
Solid phase spreading	0,2	0,2	0,1	33%	0,2	0,1
To post-treatment	2,3	2,2	0,8	34%	2,2	0,8
Losses	0,1	0,3	5,1	**1627%**	0,9	4,9

Table 55: Results of the uncertainty analysis and data reconciliation for the French Nitrogen Nutrient Layer

Flow name	Original value	MC value	MC Stand Dev	MC relative error	Best estimate value	Best estimate Stand Dev
Agricultural residues	7,8	7,8	1,7	22%	7,8	1,3
Sewage sludge	6,0	6,0	1,4	23%	6,0	1,2
Industrial waste	3,6	3,6	0,8	23%	3,6	0,8
Municipal waste	1,1	1,1	0,3	23%	1,1	0,3
Mixed waste	18,6	18,6	2,3	13%	18,5	1,3
Undesirable to incineration	0,0	0,0	0,0	0,0	0,0	0,0
Mush	17,6	17,6	2,2	13%	17,6	1,2
Losses	0,9	0,9	0,1	14%	0,9	0,1
Digestate	16,4	16,1	2,7	17%	16,0	1,4
Losses	1,2	1,6	1,9	**120%**	1,6	1,5
For direct spreading	9,0	8,8	2,0	23%	8,9	1,5
For phase separation	7,4	7,2	1,7	23%	7,2	1,4
Liquid phase spreading	1,8	1,7	1,4	81%	1,7	1,3
Solid phase spreading	0,4	0,4	0,3	81%	0,4	0,3
To post-treatment	5,1	4,7	3,8	81%	5,0	1,9
Losses	0,02	0,05	0,74	**1580%**	0,1	0,7

Table 56: Results of the uncertainty analysis and data reconciliation for the French Phosphorus Nutrient Layer

Flow name	Original value	MC value	MC Stand Dev	MC relative error	Best estimate value	Best estimate Stand Dev
Agricultural residues	68,4	68,2	15,2	22%	68,0	7,2
Sewage sludge	1,2	1,2	0,3	23%	1,2	0,3
Industrial waste	6,3	6,3	1,4	23%	6,3	1,4
Municipal waste	3,0	3,1	0,7	22%	3,1	0,7
Mixed waste	78,9	78,8	15,3	19%	78,6	7,1
Undesirable to incineration	0,0	0,0	0,0	0,0	0,0	0,0
Mush	75,0	74,8	14,5	19%	74,7	7,1
Losses	3,9	3,9	0,8	20%	3,9	0,8
Digestate	69,9	68,1	15,3	23%	67,9	7,4
Losses	5,1	6,7	8,2	**122%**	6,8	6,9
For direct spreading	38,4	37,4	10,2	27%	37,7	7,6
For phase separation	31,4	30,6	8,3	27%	30,3	5,7
Liquid phase spreading	25,1	23,3	8,6	37%	23,9	5,9
Solid phase spreading	0,5	0,5	0,2	38%	0,5	0,2
To post-treatment	5,8	5,6	2,1	39%	5,6	2,1
Losses	0,1	0,2	3,2	**1643%**	0,3	3,1

Table 57: Results of the uncertainty analysis and data reconciliation for the French Potassium Nutrient Layer

Observations are like the previous layers. Uncertainties are higher as equations consist of more terms and standard deviations of flows from mass balance equations are of no interest.

However, we can notice that uncertainties are quite reasonable and will permit an interpretation of the data in the following parts.

For data reconciliation part, best estimate values are close to Monte-Carlo mean values.

The only issue in this part is the 81% of relative errors for flows *Liquid phase spreading, Solid phase spreading* and *to post-treatment* in the phosphorus. I am not able to explain the difference of relative errors between the three nutrient layers as they are built in a similar way.

IV.5.2. Norwegian biogas production MFA systems

The tables below sum up the different stages of the study for the Norwegian biogas production system. The analyzes of the results are the same as for the French system.

Flow name	Original value	MC value	MC Stand Dev	MC relative error	Best estimate value	Best estimate Stand Dev
Agricultural residues	630,0	629,9	62,8	10%	630,1	42,4
Sewage sludge	122,6	122,4	12,2	10%	122,4	12,1
Industrial waste	117,1	117,1	11,8	10%	117,1	11,7
Municipal waste	300,5	300,2	29,9	10%	300,2	28,0
Aquaculture waste	78,1	78,1	7,8	10%	78,1	7,8
Mixed waste	1185,9	1185,3	68,2	6%	1185,5	38,2
Undesirable to incineration	62,4	62,4	4,7	8%	62,4	4,7
Mush	1126,6	1126,0	64,9	6%	1126,2	38,2
Losses	59,3	59,3	4,5	8%	59,3	4,5
Biogas	92,0	91,7	17,8	19%	91,7	16,1
Biogas	61,3	61,2	12,0	20%	64,1	7,7
Digestate	957,6	922,3	130,2	14%	921,7	73,7
Losses	15,7	50,8	122,2	**241%**	48,8	77,1
Oxygen	109,4	109,2	21,9	20%	109,2	18,8
Water	51,5	51,3	10,3	20%	51,3	10,0
CO2	149,9	149,6	30,0	20%	149,6	21,2
Biomethane	33,2	33,9	7,5	22%	32,8	6,6
CO2	25,9	29,7	6,7	23%	28,8	6,1
H2O	1,9	2,2	0,5	23%	2,2	0,5
H2S	0,3	0,3	0,1	23%	0,3	0,1
Digestate for direct spreading	526,7	507,7	105,2	21%	506,6	76,7
Digestate for phase separation	430,9	415,5	86,1	21%	415,1	58,3
Liquid phase spreading	43,1	41,5	10,6	26%	41,5	10,6
Solid phase to post-treatment	366,3	340,7	84,0	25%	340,4	60,5
Losses	21,5	33,3	46,1	**139%**	33,2	42,6

*MC stands for Monte-Carlo simulation

* Best estimate values are values calculated after data reconciliation

Table 58: Results of the uncertainty analysis and data reconciliation for the Norwegian Mass Layer

Flow name	Original value	MC value	MC Stand Dev	MC relative error	Best estimate value	Best estimate Stand Dev
Agricultural residues	1,06	1,06	0,24	22%	1,01	0,2
Sewage sludge	0,07	0,07	0,02	23%	0,07	0,02
Industrial waste	0,10	0,10	0,02	23%	0,06	0,18
Municipal waste	0,30	0,30	0,07	23%	0,3	0,07
Aquaculture waste	0,07	0,07	0,02	22%	0,07	0,02
Electricity	0,01	0,02	0,01	25%	0,02	0,01
Mixed waste	0,80	0,80	0,13	17%	0,79	0,06
Undesirable to incineration	0,80	0,66	0,28	**43%**	0,73	0,21
Heating	0,08	0,08	0,02	21%	0,08	0,02
Mush	0,84	0,83	0,12	15%	0,83	0,06
Losses	0,04	0,04	0,01	16%	0,04	0,01
Heating	0,11	0,11	0,03	25%	0,11	0,03
Biogas	0,56	0,56	0,10	18%	0,56	0,05
Biogas	0,37	0,37	0,07	18%	0,37	0,05
Losses	0,01	0,01	0,00	27%	0,01	0
Electricity	0,14	0,14	0,03	19%	0,14	0,03
Heat	0,34	0,33	0,06	19%	0,34	0,05
Losses	0,08	0,08	0,02	29%	0,08	0,02
Biomethane	0,37	0,31	0,07	24%	0,31	0,05
Losses	0,00	0,06	0,05	**78%**	0,06	0,04

Table 59: Results of the uncertainty analysis and data reconciliation for the Norwegian Energy Layer

Flow name	Original value	MC value	MC Stand Dev	MC relative error	Best estimate value	Best estimate Stand Dev
Agricultural residues	3,30	3,29	0,74	23%	3,27	0,52
Sewage sludge	0,20	0,20	0,04	22%	0,2	0,04
Industrial waste	0,43	0,43	0,10	22%	0,43	0,1
Municipal waste	2,29	2,29	0,51	22%	2,28	0,45
Aquaculture waste	0,26	0,26	0,06	22%	0,26	0,06
Mixed waste	6,48	6,46	0,90	14%	6,45	0,45
Undesirable to incineration	0,00	0,00	0,00	0,00	0,00	0,00
Mush	6,15	6,14	0,86	14%	6,13	0,45
Losses	0,32	0,32	0,05	15%	0,32	0,05
Digestate	6,07	5,86	1,04	18%	5,81	0,53
Losses	0,09	0,28	0,67	**243%**	0,31	0,53
Digestate for direct spreading	3,34	3,23	0,76	23%	3,29	0,55
Digestate for phase separation	2,73	2,64	0,62	23%	2,52	0,41
Liquid phase spreading	2,48	2,04	0,61	30%	2,2	0,42
Solid phase to post-treatment	0,13	0,12	0,04	33%	0,12	0,04
Losses	0,12	0,18	0,25	**140%**	0,21	0,24

Table 60: Results of the uncertainty analysis and data reconciliation for the Norwegian Nitrogen Nutrient Layer

Flow name	Original value	MC value	MC Stand Dev	MC relative error	Best estimate value	Best estimate Stand Dev
Agricultural residues	0,35	0,35	0,08	23%	0,35	0,06
Sewage sludge	0,12	0,12	0,03	22%	0,12	0,03
Industrial waste	0,05	0,05	0,01	23%	0,05	0,01
Municipal waste	0,27	0,27	0,06	23%	0,27	0,05
Aquaculture waste	0,17	0,17	0,04	22%	0,17	0,04
Mixed waste	0,96	0,96	0,11	12%	0,96	0,06
Undesirable to incineration	0,00	0,00	0,00	0,00	0,00	0,00
Mush	0,91	0,91	0,11	12%	0,91	0,06
Losses	0,05	0,05	0,01	13%	0,05	0,01
Digestate	0,90	0,87	0,14	16%	0,87	0,07
Losses	0,01	0,04	0,10	**243%**	0,04	0,08
Digestate for direct spreading	0,49	0,48	0,11	22%	0,48	0,08
Digestate for phase separation	0,40	0,39	0,09	22%	0,39	0,06
Liquid phase spreading	0,10	0,09	0,03	32%	0,09	0,03
Solid phase to post-treatment	0,29	0,27	0,08	31%	0,27	0,06
Losses	0,02	0,03	0,04	**139%**	0,03	0,04

Table 61: Results of the uncertainty analysis and data reconciliation for the Norwegian Phosphorus Nutrient Layer

Flow name	Original value	MC value	MC Stand Dev	MC relative error	Best estimate value	Best estimate Stand Dev
Agricultural residues	3,08	3,08	0,69	23%	3,08	0,36
Sewage sludge	0,02	0,02	0,01	22%	0,02	0,01
Industrial waste	0,08	0,08	0,02	22%	0,08	0,02
Municipal waste	0,72	0,72	0,16	23%	0,72	0,16
Aquaculture waste	0,01	0,01	0,00	22%	0,01	0,00
Mixed waste	3,91	3,91	0,71	18%	3,91	0,34
Undesirable to incineration	0,00	0,00	0,00	0,00	0,00	0,00
Mush	3,72	3,72	0,68	18%	3,71	0,34
Losses	0,20	0,20	0,04	19%	0,2	0,04
Digestate	3,66	3,55	0,75	21%	3,54	0,36
Losses	0,05	0,16	0,41	**252%**	0,17	0,34
Digestate for direct spreading	2,02	1,95	0,51	26%	1,96	0,37
Digestate for phase separation	1,65	1,60	0,42	26%	1,58	0,27
Liquid phase spreading	1,26	1,14	0,38	33%	1,16	0,28
Solid phase to post-treatment	0,32	0,30	0,10	35%	0,30	0,10
Losses	0,07	0,11	0,15	**139%**	0,11	0,14

Table 62: Results of the uncertainty analysis and data reconciliation for the Norwegian Potassium Nutrient Layer

V. Sensitivity Analysis

Final step of the MFA study, sensitivity analysis is a technique used to assess the impact of variations or uncertainties in input parameters on the results of the analysis. It helps to understand how sensitive the outcomes or conclusions are to changes in the data or assumptions used.

Sensitivity analysis involves systematically varying one or more input parameters while keeping other parameters constant and observing the corresponding changes in the outputs or results.
The goal is to evaluate the robustness of the MFA model and identify which parameters have the most significant influence on the outcomes.

There are two types of sensitivity, absolute and relative sensitivity. The main difference lies in how they express and measure the sensitivity of the model.

Absolute sensitivity measures the absolute change in the output corresponding to a unit change in the input parameter. It represents the impact of a parameter change on the output, regardless of the initial value or scale of the parameter. Absolute sensitivity is expressed in the units of the output variable.

Relative sensitivity measures the proportional change in the output due to a relative change in the input parameter. It represents the percentage change in the output relative to the initial value of the parameter. Relative sensitivity is dimensionless and expressed as a percentage or ratio.

The key distinction between absolute and relative sensitivity is how they quantify the impact of parameter changes. Absolute sensitivity focuses on the actual change in the output variable, while relative sensitivity considers the proportional change relative to the initial value of the parameter.

The most interesting sensitivity to analyze and interpret is the relative sensitivity as it gives a result in percentage. But to determine relative sensitivity, it is necessary to determine the absolute one.

I led a sensitivity analysis for the two systems, French and Norwegian.

First, I express every flow only function of parameters. Then, I derive the mathematical equation function of the parameter I wanted to study to determine the absolute sensitivity. Then, I multiplied the absolute sensitivity by the ratio between the value of the parameter and the value of the flow, to determine the relative sensitivity.

I repeat these calculations for every key flow, the ones that are the most critical to the MFA systems.

The results of this sensitivity analysis are presented through histogram graphs.

V.1. Sensitivity analysis on the French biogas production system

Sensitivity analyses have been conducted on certain flows of the MFA systems; the ones considered as key flows.

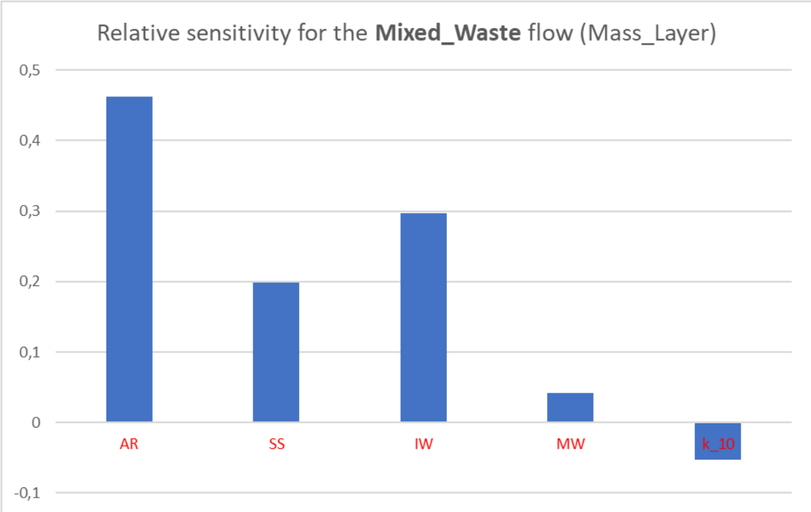

Figure 19: Relative sensitivity for the Mixed waste flow (Mass_Layer)

In the Mass Layer, the mixed waste, representing the total volume of waste going to the digestor, is mainly sensitive to agricultural residues and then industrial waste. It means that French mainly relies on agriculture to furnish intrants to biogas facilities. It also means that if the French State want to increase the production of biogas, the most effective way to do it is to increase the volume of agriculture residues first. Indeed, if volume of agricultural residue increases of 1%, volume of mixed waste increases of 0.46%.

The fact that no relative sensitivity overcomes 1% means that the system is well balanced.

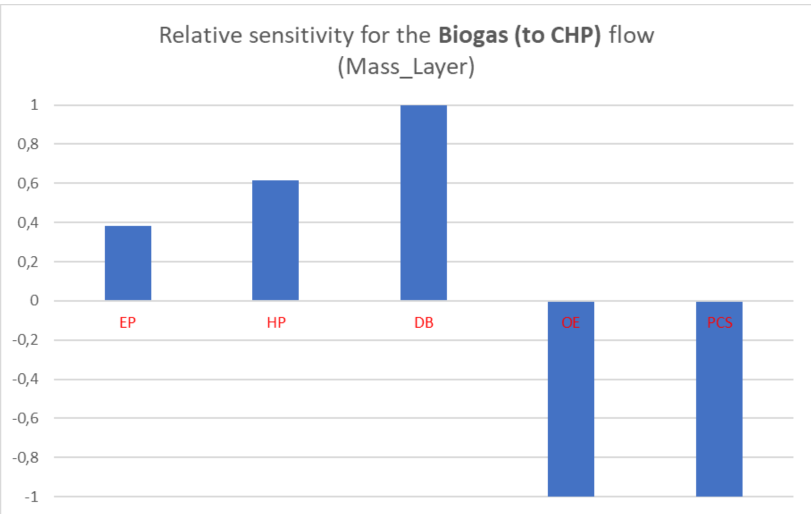

Figure 20: Relative sensitivity for the Biogas (to CHP) flow (Mass_Layer)

The biogas production, in mass, is highly sensitive to three parameters, the density of biogas, the PCS of biogas and the overall efficiency of the CHP. As the first two parameters are limited by the laws of physics, it is possible to play on the overall efficiency of the CHP. It means that if engineers can increase of 1% the efficiency of the CHP, the biogas production will increase of 1%. If this seems interesting, it should be difficult to perform such an innovation as current CHP technologies are already cutting-edge technologies.

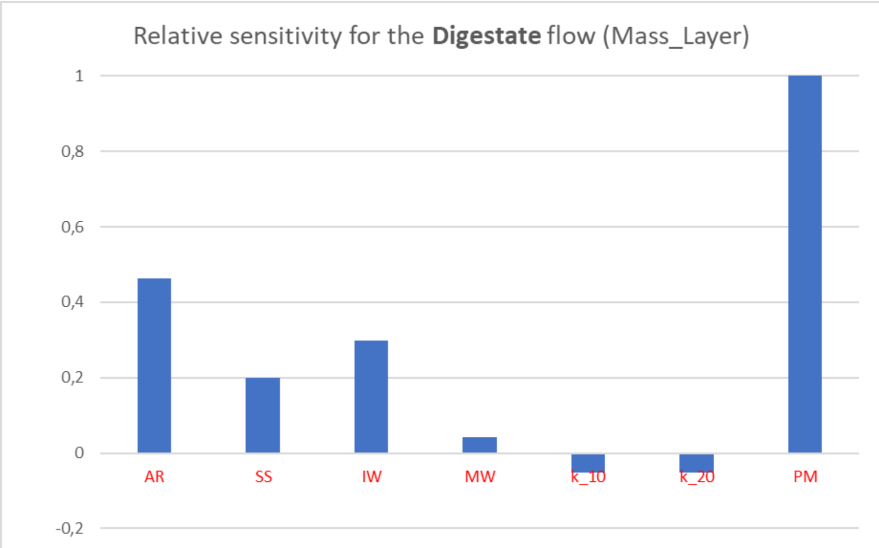

Figure 21: Relative sensitivity for the Digestate flow (Mass_Layer)

The production of digestate is one of the key factors of biogas production. In France, before biogas, it is the most valuable by-products for farmers.

The sensitivity analysis shows that the digestate production is quite sensitive to agricultural residue. Increasing the volume of this type of waste could have an important impact on the production of biogas.

But the largest sensitivity for digestate production is to the parameter PM representing the share of mush, input of the digestor, becoming digestate. This parameter represents a sort of efficiency for the digestor. Currently, 85% of the mush entering the digestor ends up as digestate. By limiting the number of losses at the bottom of the tank and increasing the amount of agricultural residues, digestate production would increase the most significatively.

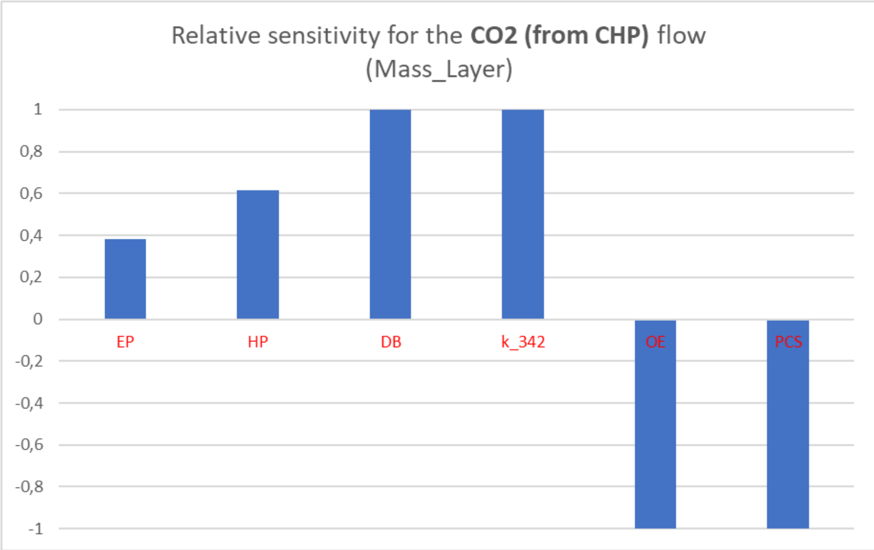

Figure 22: Relative sensitivity for the CO2 (from CHP) flow (Mass_Layer)

Carbon dioxide is one of the primary greenhouse gases responsible for climate change. Biogas is considered as a green energy, aiming to generate energy alongside reducing the burden on climate change. The aim is then to reduce as much as possible the production of CO_2 during biogas production, even if it is considered as “green” CO_2 as it comes from waste.

CO_2 production from CHP is highly sensitive so four parameters. Three of them are limited by laws of physics and cannot be increase or decrease. The only parameter we can modify is again the overall efficiency of the CHP. Even if it will be difficult, increasing the efficiency would lead to a reduction in CO_2 production in a significant way.

As expected, increasing electricity production (EP) or heat production (HP) would lead to more CO_2.

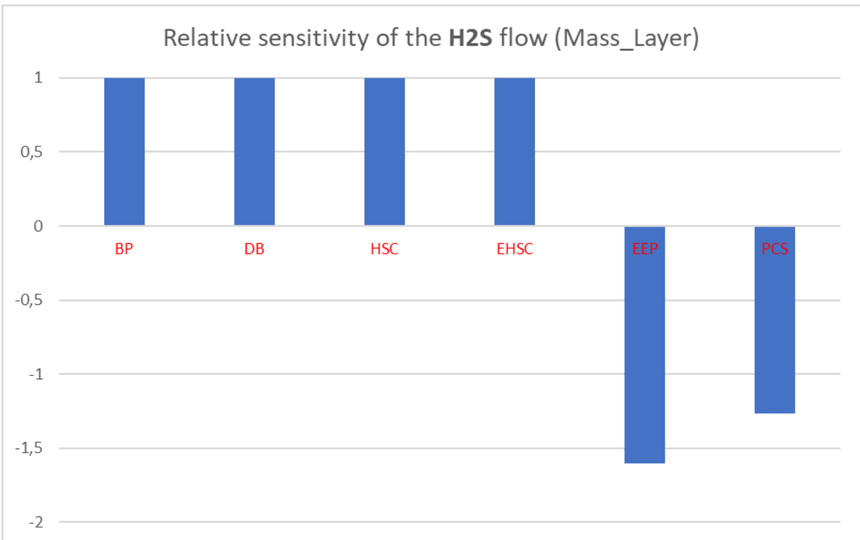

Figure 23: Relative sensitivity for the H2S flow (Mass_Layer)

H_2S is a corrosive component of biogas that needs to be eliminate during the purification process of biomethane production.

H_2S production is highly sensitive to some parameters, sometimes even higher than 1%. If most of parameters are limited by laws of physics (density of biogas DB or PCS), some others can be modified.

It is the case for parameter EEP, energy efficiency of the purification process, the one H_2S is the most sensitive to. If this efficiency could increase, the H_2S production would drastically diminish. Problem, this efficiency is already very high, close to 100%.

Another possibility, a bit less effective, is to reduce the H_2S content in biogas (HSC).

Yet, hydrogen sulfide is produced during the decomposition of organic matter in anaerobic environment when bacteria break down organic materials. This is what is happening inside the digestor, so it is quite impossible to reduce the H_2S content as it would mean reducing biogas production.

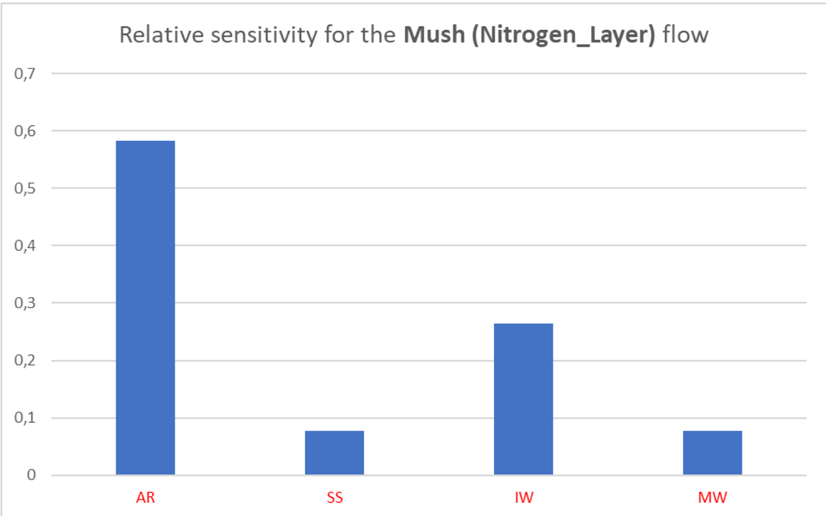

Figure 24: Relative sensitivity for the Mush flow (Nitrogen_Layer)

To increase the volume of nitrogen in the mush and so after anaerobic digestion in the digestate, it is the agricultural residues that have the largest influence, followed by industrial waste. It means that if the producer wants a more nitrogen concentrated digestate (or less concentrated), he/she needs to increase the share of agricultural residues and industrial waste in its intrants mix.

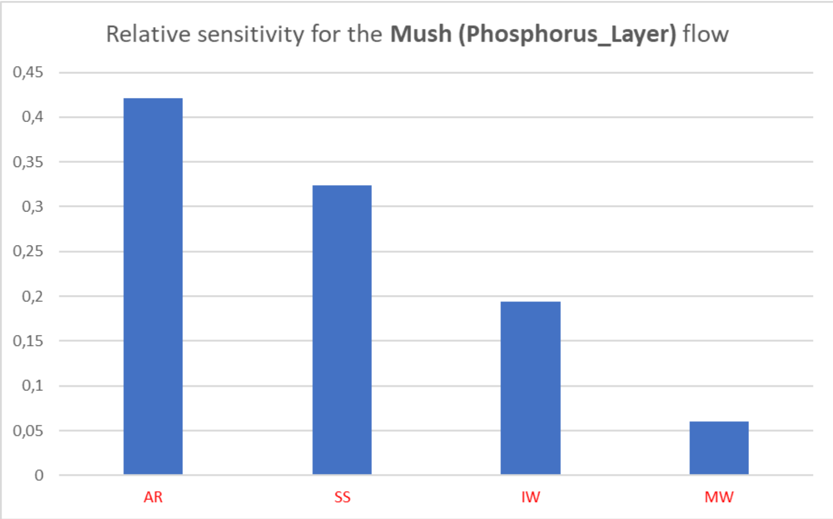

Figure 25: Relative sensitivity for the Mush flow (Phosphorus_Layer)

For the phosphorus, agricultural residues have again the largest influence but closely followed by sewage sludge. It is shares of these two intrants that the producer must increase if more phosphorus is required for the soils.

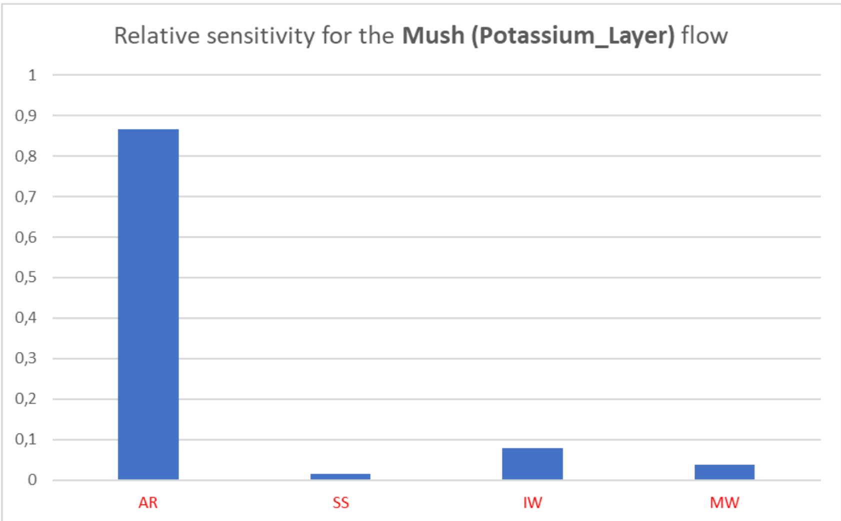

Figure 26: Relative sensitivity for the Mush flow (Potassium_Layer)

For potassium, agricultural residue is the only intrant having an influence. If potassium content needs to be increased or reduced, it is on the share of agricultural residue in the intrants mix that the producer will play.

V.2. Sensitivity analysis on the Norwegian biogas production system

Here will only be interpreted the sensitivity analysis presenting differences with the analysis of the French system.

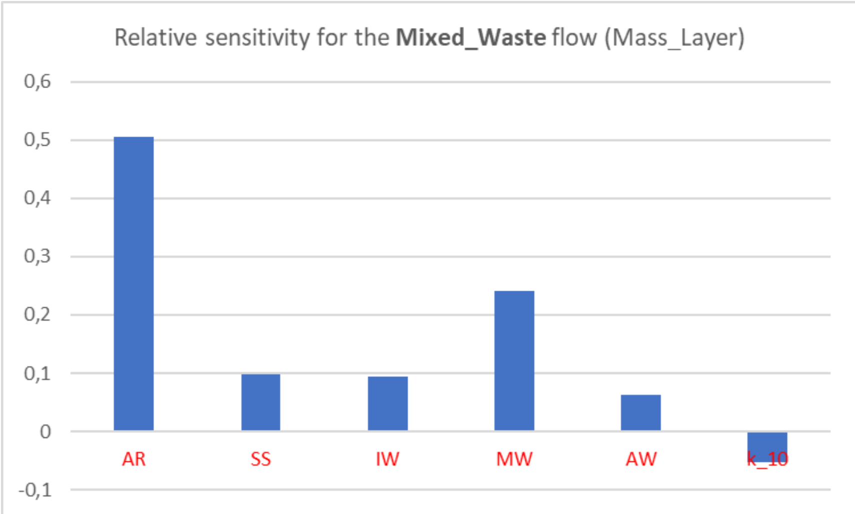

Figure 27: Relative sensitivity for the Mixed waste flow (Mass_Layer)

The main difference between France and Norway is the influence of municipal waste on the number of intrants. Municipal waste presents a more important share on the intrants mix in Norway than in France, leading to a larger sensitivity for this parameter. This is one of the most considerable differences between the two countries strategies regarding biogas production. In both countries, volume of intrants is highly sensitive to the volume of agricultural residues.

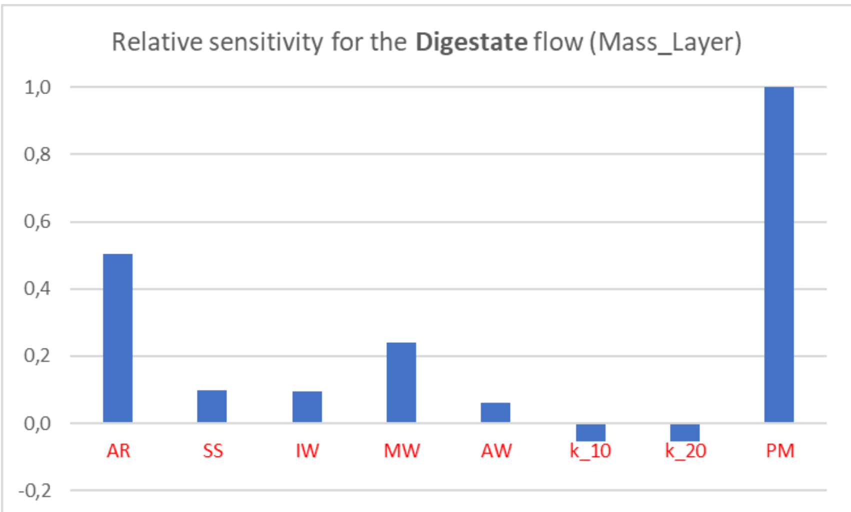

Figure 28: Relative sensitivity for the Digestate flow (Mass_Layer)

Again, the difference between France and Norway is the impact of Municipal waste. In Norway, increasing the share of municipal waste in the intrants mix could increase significantly the digestate production.

As increasing volume of municipal waste dedicated to biogas production relies more on social and political decisions than scientific innovations, it is an interesting opportunity and advantage for Norway compared to France.

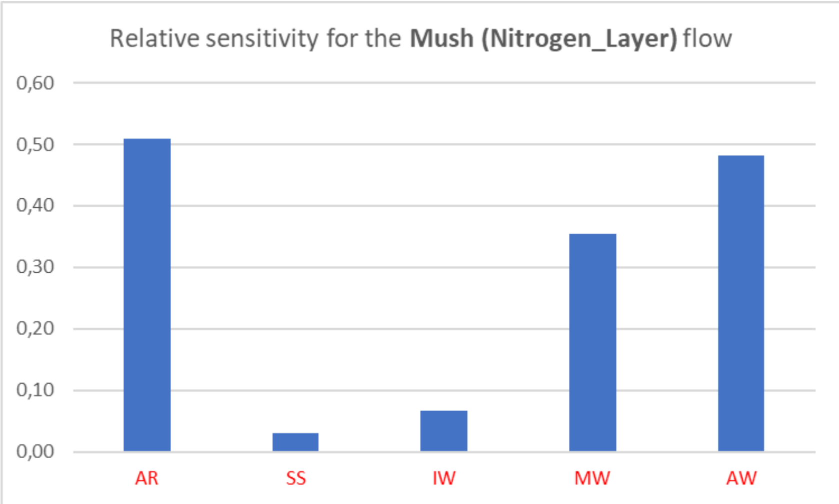

Figure 29: Relative sensitivity for the Mush flow (Nitrogen_Layer)

Alongside agricultural residue, it is interesting to notice that the amount of nitrogen in the digestate is highly sensitive to municipal waste and even more to aquaculture waste. Again, it appears as a huge advantage for Norway which has two more strategic levers to increase the nitrogen content of its digestate.

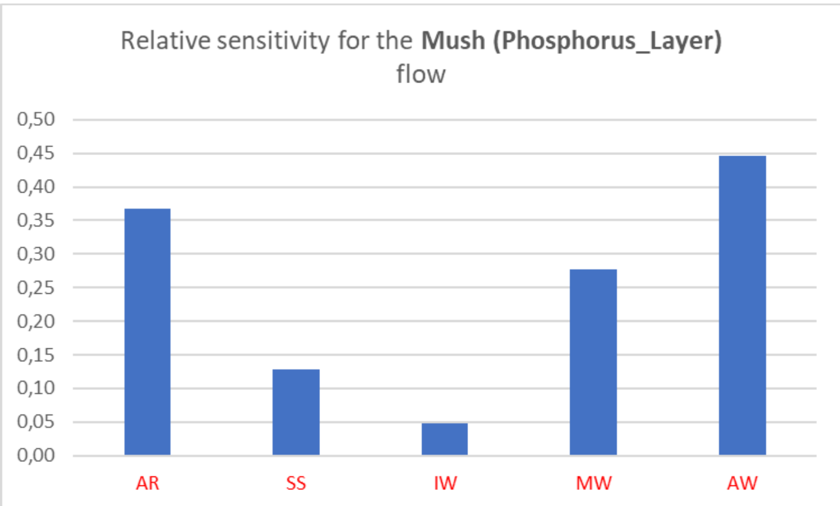

Figure 30: Relative sensitivity for the Mush flow (Phosphorus_Layer)

Same goes for phosphorus, as municipal and aquaculture waste have a significant influence on phosphorus content in the mush and later in the digestate. As expected, phosphorus content is highly sensitive to aquaculture waste.

Indeed, fishes like salmons, farmed in aquaculture, are considered as ones of the most important sources of phosphorus in the biodiversity. Then, increasing aquaculture waste share in the intrants mix would increase the phosphorus content of digestate.

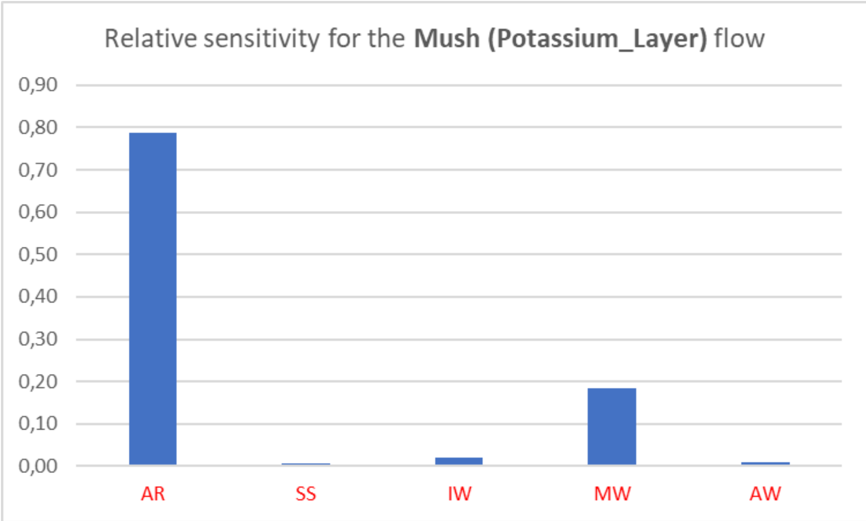

Figure 31: Relative sensitivity for the Mush flow (Potassium_Layer)

For the potassium, the only difference with the French model is the influence of municipal waste which appears as another source of potassium, still far away from agricultural residue. While increasing agricultural residue of 1% would cause a 0,8% surge in potassium content, an increase of 1% of municipal waste would cause a small 0,2% surge.

Agriculture residues is still the parameter potassium content is the most sensitive to, but municipal waste must be considered.

VI. Discussions

In this part, I am going to analyze and discuss the results of the MFA study I present in the first ones.

The analysis and interpretation will be led on absolute and relative figures, considering population of the two countries. Indeed, as French is twelve time more populated than Norway, it would be biased to conclude only on raw figures.. Both visions will be presented and will help to the conclusion.

VI.1. Mass Layer

In the mass layer, the aim is to compare the volume of materials treated and produced. The results of the study will focus on the intrants as they define the political strategies adopted by the two countries to promote biogas production.

Mass layer also shows how many digestate is produced and how it is used. It underlines the interests and issues of digestate production and utilization.

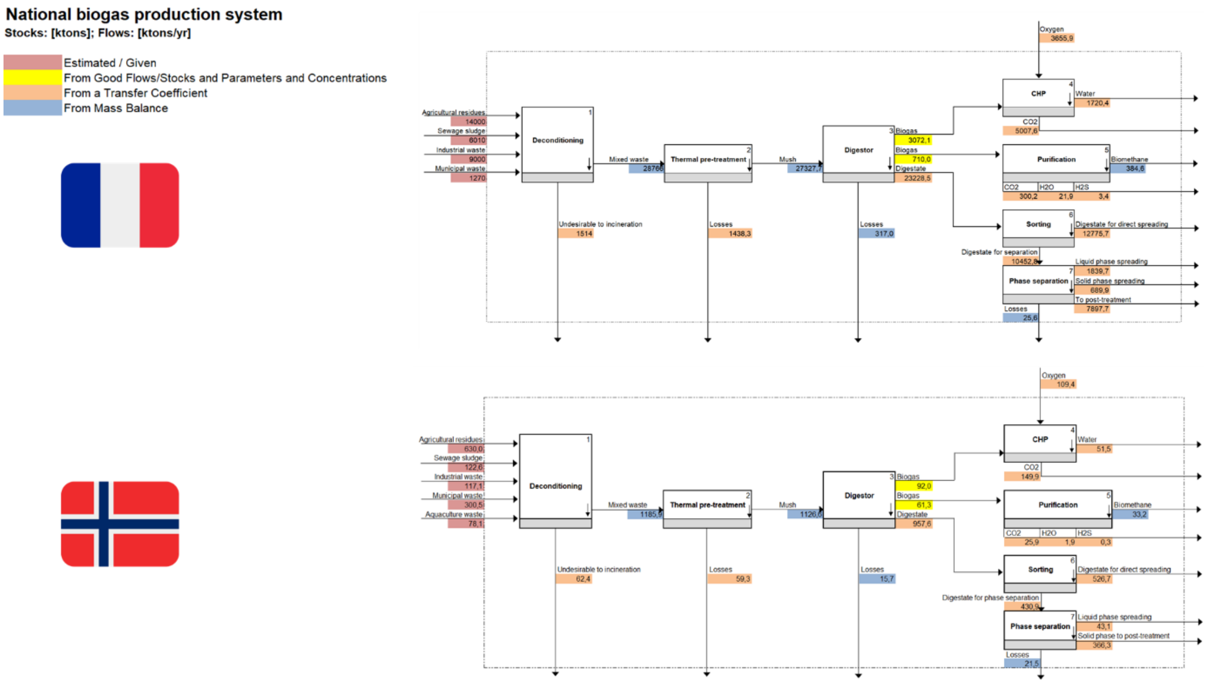

Figure 32: Comparison between the MFA French and Norwegian biogas production system on Mass Layer

VI.1.1. Intrants

Biogas production typically requires various inputs or substrates to generate gas through anaerobic digestion. The choice of inputs depends on the specific biogas plant and its objectives.

As intrants, I decided to consider five different categories:

- Agricultural residues
- Sewage sludge
- Industrial waste
- Municipal waste
- Aquaculture waste, specific to Norway

VI.1.1.1. Agricultural residues

In agricultural residues, animal manure from livestock produces a significant volume of biogas and digestate, rich in organic matter. Manure from cows, pigs, poultry, and other animals is commonly used in biogas production.

There are also crop residues, which are agricultural residues left after the harvest, such as stalks, stems, husks, and straw and which can be utilized for biogas production. Energy crops are also under this category. These are dedicated energy crops such as corn, grasses and other biomass crops that can be cultivated specifically for biogas production. These crops have high biomass content and can be grown sustainably. They are often used in the form of silage, which preserves the organic matter.

In France, such crops are limited in number by the law to avoid competition between energy and alimentation. Energy crops can be harvested if they represent a maximum of 15% of the intrants of the biogas plant in weight per year.

Finally, intermediate crops are also considered. Intermediate crops are temporary crops grown between the main crops in an agricultural rotation system. These crops are primarily cultivated to improve soil health and enhance fertility. Unlike cash crops that are grown for harvest and economic gain, intermediate crops are primarily used for their positive effects on the soil and subsequent crops. But these crops can also be used as intrants in a biogas facility as they present a high methanogenic potential. For example, there are oats, phacelia, ray-grass, field peas, corn, rye, clover, or mustard.

VI.1.1.2. Sewage sludge

Sewage sludge from municipal WWTP contain organic matter and can be used in biogas production. The biogas from sewage sludge is often richer in methane compared to other inputs.

There are two types of sewage sludge:

- Primary sludge from sieving in WWTE and fat in sedimentation ponds. They present high contents of mineral and organic materials.
- Secondary sludge, also called biological sludge from clarification of water (final step in WWTP).

Both sludges can be mixed to enhance biogas production, then it is called mixed sludge.

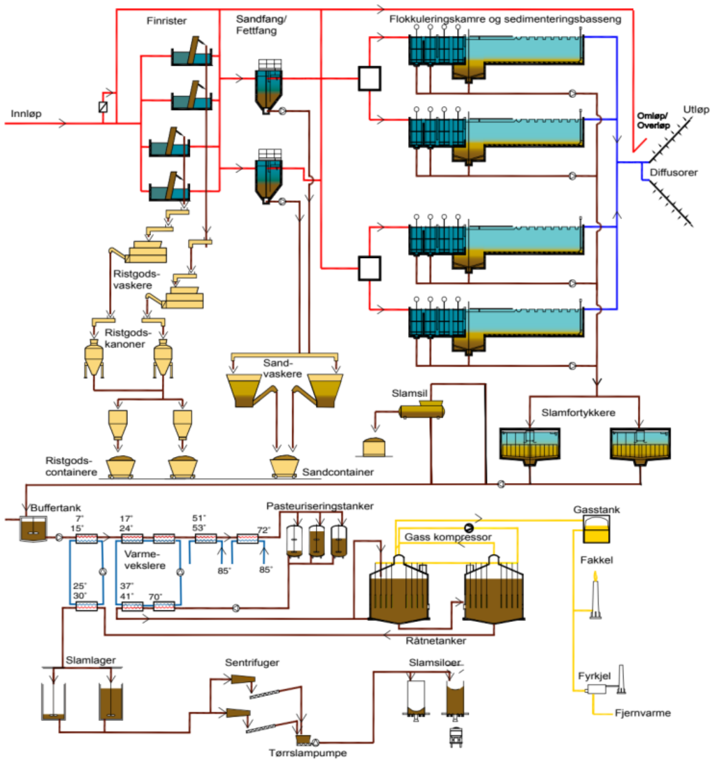

Figure 33: Blueprint of a WWTP linked to a biogas plant in Norway

There are some advantages with the use of sewage sludge as intrants:

- 40% reduction in the volume of sewage sludge treated directly in WWTP
- Elimination of odors
- Production of digestate largely free of pathogens
- Reducing the content of volatile organic compounds
- Recovering nutrients such as nitrogen or phosphorus from wastewater (as otherwise sewage sludge is sent to incineration)

When sewage sludge is used as intrants in a biogas plant, there are some additional regulations for the digestate to kill all pathogens. Sewage sludge must undergo anaerobic digestion in a mesophilic state at 37°C.

Digestate from sewage sludge is not considered as a product but as a waste. It means that the valuable parts can be used in agriculture but under strict regulations. A spreading plan needs to be completed. This plan requires information on the agronomic values, metal trace element and pathogen content of the digestate as long as a soil analysis few years after spreading. Digestate from sewage sludge often presents a higher content in nitrogen and phosphorus than casual digestate.

VI.1.1.3. Industrial waste

Under industrial waste, there are mainly food processing residues. These are residues generated from food processing industries, including fruit and vegetable processing, breweries, distilleries, and dairy plants which can serve as a substrate for biogas production.

There are also waste from certain industries generating organic waste or by-products that can be suitable for biogas production. For instance, there are food manufacturing waste, paper, and pulp industry residues.

For biogas production, stress has been put recently on slaughterhouse waste. They produce animal by-products, such as blood, fat, and bones. The volume is huge, in European Union about 20 million of tons are produced each year.

Considering ABP, Animal By-Products, and their use for biogas production, regulations are clear.
There are three categories of ABP:

- Category 1: consists of materials that pose the highest risk to animal and public health due to the potential presence of transmissible diseases (for instance brain, spinal cord, or intestines).
- Category 2: consists of materials that are considered lower risk than Category 1, but they still require proper handling and processing to ensure animal and public health (for instance fallen stock).
- Category 3: consists of materials that pose the lowest risk to animal and public health, including by-products that are considered safe for specific uses after appropriate processing (for instance skins, blood, or feathers).

Only ABP from categories 2 and 3 can be used to produce biogas but with strict thermal treatment.

ABP from category 2 needs to be sterilized at 133°C, under 3 bars of pressure and for 20 minutes.
ABP from category 3 needs to be pasteurized at 70°C for 60 minutes.

VI.1.1.4. Municipal waste

Under the category municipal waste, are gathered:

- Food waste: generated from households, restaurants, cafeterias, and supermarkets, is a significant component of municipal waste. It includes leftovers, spoiled or expired food, food trimmings, and other organic materials.
- Yard waste: includes green waste, such as grass clippings, leaves, branches, and other yard trimmings and green waste from household gardens, parks, and public spaces.
- Organic Residues: generated in urban areas, such as bio-based packaging materials, coffee grounds or tea bags.

Sewage sludge could also be included in the category of municipal waste, but I decided to create a special category to treat them separately.

Municipal waste can require more treatment and attention from biogas producers as the composition can vary a lot based on local practices and waste management systems. In addition, proper sorting, separation, and pre-treatment of municipal waste may be necessary to optimize biogas production and ensure the quality of the digestate.

VI.1.1.5. Aquaculture waste

This category is specific to Norway, one of the leading countries in aquaculture globally, which has a significant focus on salmon farming.

Aquaculture waste rounds up several types of marine waste such as:

- Fish sludge: accumulated in fish farm sedimentation basins or fish waste collected during cleaning and harvesting processes. It contains fish excreta or uneaten feed.
- Fish processing waste: such as fish heads, tails, bones, or viscera.
- Effluents: such as water used for cleaning, fish growing or circulation of feed.
- Algae: in some aquaculture systems, algae are cultivated as feed or to mitigate nutrient loads in fish farm effluents

As aquaculture waste are often throw into the water and barely treated, using it as intrants in the biogas production process presents a sustainable way to deal with such type of waste.

All in all, the optimal composition and ratio of inputs can vary depending on the desired biogas output, local availability, environmental considerations, and specific technology used in the biogas plant.

In addition, all types of intrants do not have the same methanogenic potential. If intrants with high methanogenic potential are of course interesting to produce the largest volume of biogas possible, intrants with poor methanogenic potential can be useful to keep a good physico-chemical balance into the digestor.

For every biogas plant, it is important to find the most efficient intrant mix to produce as much biogas as possible while maintaining control over the quality of by-products, especially the digestate.

VI.1.2. Analysis of the intrant mix

Back to the MFA study, here are the comparison of the intrants mix between France and Norway.

Intrants (ktons/yr)	France	Norway
Agricultural residues	14 000	630
Sewage sludge	6 010	123
Industrial waste	9 000	117
Municipal waste	1 270	300
Aquaculture waste	0	78
Total	**30 280**	**1 248**

Table 63: Table with the mass of every intrant in the French and Norwegian models

As expected, in each category, excepted aquaculture waste, France used far more materials than Norway to produce biogas. In average, France uses 24 times more materials than Norway.

To be able to compare, these numbers have been divided by the population of each country to give a mass of intrants per capita.

Intrants (kg/cap)	France	Norway
Agricultural residues	209	115
Sewage sludge	90	22
Industrial waste	134	21
Municipal waste	19	55
Aquaculture waste	0	14
Total	**452**	**227**

Table 64: Table with the mass of every intrant per capita in the French and Norwegian models

In the table, it appears that per capita, French is still ahead of Norway in terms of mass of intrants.

VI.1.2.1. Agricultural residues

The gap is important for agricultural residues. In fact, France mainly relies on farming biogas facilities to produce biogas.

Almost 90% of the biogas facilities in France are farming facilities where farmers use their own organic waste alongside neighbor organic waste. They also buy some waste to food-processing industries to improve their plants' efficiency.

Only small number of facilities are managed by specialized companies using different categories of intrants.

In addition, French and Norwegian agriculture have distinct characteristics due to differences in geography, climate, agricultural practices, and policies.

First, France has a diverse agricultural landscape with a wide range of climates, including Mediterranean, continental, and oceanic regions. That is why France develops the cultivation of various and numerous crops at large-scale. France is known to be a major producer of cereals, sugar beets, potatoes, wine grapes, fruits, and vegetables.

Conversely, Norway's geography is characterized by rugged terrain, fjords, and a long coastline. The climate is colder and challenging for agriculture, particularly in the northern regions even if coastal areas and sheltered valleys provide better conditions for farming. For these reasons, Norwegian agriculture is heavily focused on livestock farming. Because of climatic limitations, crop cultivation is more challenging, with a primary focus on hardy crops such as barley, oats, and root vegetables.

Thus, the geographic and climate differences between the two countries contribute to the variation in agricultural practices and outputs. That is why the number of agricultural residues per capita is higher in France compared to Norway and the gap will be hard to tighten.

VI.1.2.2. Sewage sludge

The gap between the two countries regarding sewage sludge can be explained by differences in regulations. While Norway restricted the use of digestate from sewage sludge, France reduces the constraints to encourage farmers developing their own facilities.

In Norway, only few WWTP have the authorization to transform sewage sludge into biogas and digestate. Indeed, strict regulations and guidelines are in place to ensure that the sludge meets quality standards and does not pose risks to the environment or human health. Different organizations govern the rules regarding digestate use from sewage sludge.

- The Norwegian Food Safety Authority has guidelines in place to ensure that the use of digestate as a fertilizer does not pose risks to food safety or human health. These guidelines cover aspects such as application rates, timing, methods, and potential limitations based on the quality and composition of the digestate.
- The Norwegian Environment Agency ensures that the utilization of digestate does not result in negative impacts on soil, water, or ecosystems. The agency sets standards for nutrient content, heavy metal concentrations, and other parameters to safeguard the environment.
- The Norwegian Water Resources and Energy Directorate regulates digestate impact on water resources. They establish guidelines for the management of liquid effluents from digestate and ensure compliance with regulations related to wastewater discharge and environmental protection.

Furthermore, digestate from sewage sludge abides by waste management regulations in Norway. These regulations ensure that the handling, transport, and storage of digestate comply with waste management practices and prevent environmental contamination. It addresses issues such as containment, odor control, and proper documentation of waste handling.

Because of all these regulations and requirements, many biogas producers refuse to use sewage sludge as intrants.

In France, regulations have been lightened to encourage biogas producers using sewage sludge. Since 2014, it is mainly the Environmental Code in France that addresses aspects such as storage, transport, application practices, and environmental protection. The code ensures that the use of digestate is carried out in compliance with waste management regulations, minimizing risks to soil, water, and ecosystems.

Since that year, biomethane from sewage sludge can be injected into the national gas network, allowing producers to sell the biogas at relative high prices. That decision is one of the most important turning points when it comes to sewage sludge in the French biogas production system.

Reducing the regulation load on biogas producer could be a tool for Norwegian authorities to stimulate sewage sludge treatment in Norway and increase its proportion on intrants mix.

VI.1.2.3. Industrial waste

The gap between the two countries regarding industrial waste is the most important one. It was hard for me to find literature explaining such a gap, but I have some ideas of factors that could explain why France is using more industrial waste for biogas production compared to Norway.

First, France and Norway have different industrial landscapes. France appears as more industrialized with a more diverse manufacturing sector. Consequently, there is a greater availability of industrial waste in France compared to Norway.

Then, because France is more industrialized, it may have a more comprehensive waste management policies or incentives that encourage the use of industrial waste for biogas production. As landfilling or incineration is yet high for that kind of waste compared to Norway, French policies promote energy and nutrient recovery of industrial waste. France also implemented specific support mechanisms such as feed-in tariffs or subsidies for renewable energy projects.

In its Multiannual Energy Plan, France and its president, Emmanuel Macron, puts the stress on industry sustainability and biogas production. Then, France places industrial waste as part of its renewable energy strategy. In Norway, because industry is not so harmful for the environment, this emphasis may be not so important.

Finally, differences in research, funding, and collaborations in the field of biogas production can impact the adoption of innovative technologies and the use of different waste streams. France may have invested more in research and development related to industrial waste utilization for biogas production than Norway.

Neither of these assumptions are verified facts but they could explain why France relies more on industrial waste than Norway to produce biogas.

VI.1.2.4. Municipal waste

Municipal waste is the only intrant category where Norway uses more materials than France correlated to the population (excepted aquaculture waste).

This is one the most considerable difference between the two countries' strategies to produce biogas, handling of biowaste. As a reminder, municipal waste gathers biowaste and yard waste. However, the use of yard waste is very limited as it does not degrade so well. Municipal waste mainly consists of biowaste.

While Norway relies a lot on biowaste, with source sorting in most of cities all around the country, France does not collect separately biowaste at all (I would study deeper this aspect on a separate part).

Norway has implemented some waste management regulations, incentives, and policies to support the use of biowaste for biogas production. These measures aim to increase waste recycling rates, reduce greenhouse gas emissions, and achieve renewable energy targets.

Needless to say that the use of biowaste for biogas production in Norway varies a lot depending on regional practices, waste management infrastructure and tools for collection and handling of that kind of waste.

VI.1.2.5. Aquaculture waste

As explained before, France does not have any aquaculture industry while Norway is one of the leading countries. If I decided to consider aquaculture waste as part of industrial waste, it could have tightened a bit the gap between the two countries.

Aquaculture waste represents around 6% of the intrants in the Norwegian biogas production system. It is an important number as the collection of aquaculture waste is in its infancy. Indeed, many aquaculture farmers or producers still do not collect at all the waste. To mitigate the environmental impacts of aquaculture waste, Norway has implemented various measures and regulations.

When a fish farm is already in place, the Norwegian Environment Agency analyzes and sets guidelines for the discharge of organic waste, nutrients, and other pollutants from fish farms.

Before building an aquaculture facility, there is a careful site selection and determination of loading capacity to prevent excessive accumulation of aquaculture waste and plan the collection. Impact assessments are always conducted to determine the sustainability of potential fish farming locations and ensure that the ecosystem can assimilate the waste that cannot be handled.

To collect the waste, regular cleaning is carried out to prevent waste accumulation around fish farm cages. Vacuum systems and other methods are employed to remove organic waste and transferred it into biogas facilities. For the sludge, which consists of settled organic particles and fish feces, some fish farms use sedimentation tanks or sludge dewatering techniques, to separate and handle the sludge efficiently.

To stay on the cutting edge of technology and sustainability, Norway invests in research and innovation to develop new technologies for effective aquaculture waste management.

Let's focus on the common threads and differences between the intrant mix of the two countries.

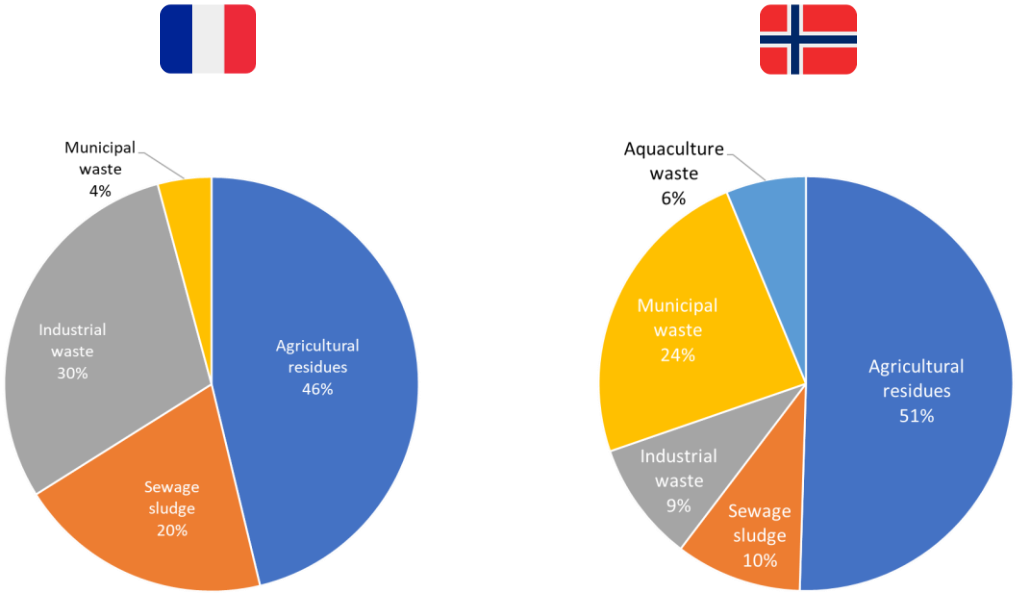

Figure 34: The French and Norwegian intrant mix for biogas production

One of the only common threads between France and Norway is the predominance of agricultural residues in the intrants mix. In both countries, they represent about the half of the intrants in term of mass.

In France it is industrial waste the second most important intrants while Norway relies mostly on municipal waste after agricultural residues. In France, municipal waste accounts for less than 5%, underlining the problem of biowaste handling in the country.

Sewage sludge is the third most important intrant in both countries but in different proportions. In France, it represents 20% of the intrants, the half in Norway.

Considering industrial and aquaculture waste together, they represent 15% of the intrants in Norway, more than sewage sludge.

These two mixes underline the differences between the two countries' strategies and the specificities of each country.

France is more industrialized and look for solutions regarding energy and carbon transition. Norway is already virtuous and looks for the participation of their citizen, especially for biowaste source sorting and use for biogas production and tries to capitalize on its specificity through aquaculture. For all these reasons, intrant mixes are the images of both countries' place on the energy transition and global strategies.

VI.1.3. Issues and opportunities of biowaste in France

Biowaste sorting, collection and treatment is one the most considerable difference between France and Norway regarding waste strategy.

While in Norway, biowaste sorting and treatment follow a well-established process, in France, there are mainly disposed in residuals.

Norwegian authorities actively promote and support biowaste sorting and treatment through different tools such as legislation, incentives, and public awareness campaigns. The aim is to minimize waste sent to landfills, reduce greenhouse gas emissions, and maximize resource recovery.

In most of Norwegian cities, every household is given a designated bin or bag to collect biowaste separately from other types of waste. Then, several collection systems are taking place like individual or collective collections.

Once collected, the biowaste is taken to specialized treatment facilities. The most common method is anaerobic digestion for biogas production, but composting is also promoted.

The implemented system is efficient, and every citizen understands that he/she has a key role to play.

In France, there are two different types of bins. The first one is for plastic, cardboard, paper, and metal while the other one is for residuals. The only solution is to put all the biowaste into the residuals going mainly to incineration without sorting. Both energy and nutrient potentials are lost.

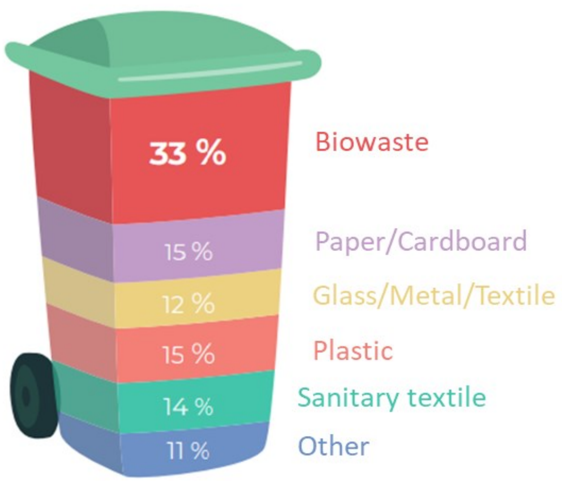

Figure 35: Average French residual bins content

Biowaste is by far the largest component, in term of mass, in the French average residual bin and the only component without another sorting and treatment solution. Indeed, paper and cardboard are recycled in a separate bin, same for metal and plastic and glass has specific containers same as sanitary textile.

It has become clear that biowaste is one of the only waste types without any treatment chain, it is sent directly to incineration without any potential consideration.

However, in 2018, the EU decided to make compulsory biowaste separate sorting by 31 December 2023:

“By 31 December 2023, bio-waste must either be separated and recycled at source or collected separately and not mixed with other types of waste” (EU, 2018b).

This legislation became an opportunity for France to operate a transition on its biowaste management and start implementing recovery process.

While deadline is set for the end of this year, pathway is still immature and will not be efficient yet.

In what follows, I wanted to determine what were the potentials of an efficient biowaste treatment sector.

The aim is to calculate the energy recovery potential from biowaste sorting and treatment in France and compare it with other waste types.

The figures used in the calculations are raw sources. In other words, it is the global annual biowaste production in France without considering the sorting rate or the different use for biowaste. It is like every biowaste is fully sorted and went for biogas production.

Here are the figures used in the study per type of producers:

- Households: 83 kg/capita
- Restaurants: 130 g/meal
- Market: 2 tons/seller
- Food retail: 20 kg/m² (of supermarket)
- Garden waste: 130 tons/city
- Food industry: 3 tons

To determine the total volume of biowaste produced, the following figures have been used:

- Population of France: 67.75 million
- Total number of meals served at restaurants: 12.3 billions
- Total number of sellers on markets: 450 000 sellers
- Total supermarket surface for food: 30 million m²
- Number of cities in France: 36 529 cities

	Quantity	Unit
Households	5,6E+06	tons
Restaurants	1,6E+06	tons
Market	9,0E+05	tons
Food retail	6,0E+05	tons
Garden waste	4,7E+06	tons
Food industry	3,00E+06	tons
Total	**1,6E+07**	**tons**

Table 65: Global annual amount of biowaste in France per year per producers

Considering that the average size of a biogas plant is around 20 000 tons/year, this volume of biowaste would require 800 biogas plants.

To compare, nowadays in France only 10 biogas plants are treating biowaste.

There is still a long way to go until France have an efficient and viable biowaste treatment process.

VI.1.3.1. Degraded part

Biowaste is made of a lot of water which will not be converted into biogas. In the literature, the average dry matter content of organic waste is 30%. In addition, there are many components that will not be degraded during the anaerobic digestion. Around 80% of the dry matter is degradable (i.e. volatile solids, VS) and will be converted to CH_4 and CO_2 during fermentation of all intrants, excepted for garden waste where it is 75%.

Then, the degraded part of biowaste can be determined.

	Quantity	Unit	Dry matter		Degradable DM	Degraded
			%DM	tonsDM/yr	%VS	tonsVS/yr
Households	5,6E+06	tons	30%	1,7E+06	80%	1,3E+06
Restaurants	1,6E+06	tons	30%	4,8E+05	80%	3,8E+05
Market	9,0E+05	tons	30%	2,7E+05	80%	2,2E+05
Food retail	6,0E+05	tons	30%	1,8E+05	80%	1,4E+05
Garden waste	4,7E+06	tons	30%	1,4E+06	75%	1,1E+06
Food industry	3,00E+06	tons	30%	9,0E+05	80%	7,2E+05
Total	**1,6E+07**	**tons**				

Table 66: Global annual amount of degraded biowaste

VI.1.3.2. Theoretical Methane Potential

To determine the theoretical methane potential of biowaste, the chemical equation of anaerobic digestion needs to be considered:

$$C_n\,H_aO_b\,+\left(n-\frac{a}{4}-\frac{b}{2}\right)H_2O\;\rightarrow\left(\frac{n}{2}+\frac{a}{8}-\frac{b}{4}\right)CH_4+\left(\frac{n}{2}-\frac{a}{8}+\frac{b}{4}\right)CO_2$$

To make the calculations, we consider that the conditions are optimal:

- We know the exact composition of the feedstock
- All the organic material is converted to biogas
- Water is the only external source (under strictly anaerobic conditions)
- Biomethane is the only use of the biogas produced

Then, we can determine the specific methane yield, B, in liter$_{CH4}$/g$_{VS}$, (at standard temperature and pressure):

$$B=\frac{\left(\frac{n}{2}+\frac{a}{8}-\frac{b}{4}\right)*22.4}{12n+a+16b}$$

22.4 is the volume in liters of one mole of gas at standard conditions.

To simplify, scientists often consider an average composition of organic waste: $\boldsymbol{C_{30}\,H_{50}O_{25}}$

Then, the equation becomes:

$C_{30}\,H_{50}O_{25}\;+5H_2O\;\rightarrow 15CH_4+15\;CO_2$

For B:

- n = 30
- a = 50
- b = 25

➔ B = 0.415 liter$_{CH4}$/g$_{VS}$

VI.1.3.3. Energy recovery

With this parameter and the energy density of methane, which is 0.01 kWh/liter$_{CH4}$, the annual energy recovery from biowaste in France can be determined.

	Quantity	Unit	Dry matter		Degradable DM	Degraded	CH4 yield	CH4 yield	Energy density	Energy produced
			%DM	tonsDM/yr	%VS	tonsVS/yr	liter/gramVS	liter/yr	kWh/liter	TWh
Households	5,6E+06	tons	30%	1,7E+06	80%	1,3E+06	0,415	5,6E+11	0,01	5,6E+00
Restaurants	1,6E+06	tons	30%	4,8E+05	80%	3,8E+05	0,415	1,6E+11	0,01	1,6E+00
Market	9,0E+05	tons	30%	2,7E+05	80%	2,2E+05	0,415	9,0E+10	0,01	9,0E-01
Food retail	6,0E+05	tons	30%	1,8E+05	80%	1,4E+05	0,415	6,0E+10	0,01	6,0E-01
Garden waste	4,7E+06	tons	30%	1,4E+06	75%	1,1E+06	0,415	4,4E+11	0,01	4,4E+00
Food industry	3,00E+06	tons	30%	9,0E+05	80%	7,2E+05	0,415	3,0E+11	0,01	3,0E+00
Total	**1,6E+07**	**tons**							**Total**	**16,1**

Table 67: Calculations of the annual energy recovery from biowaste in France

All in all, in perfect conditions, the maximum energy available from biowaste in France every year is **16.1 TWh**.

As the French annual natural gas consumption is around 500 TWh, it could cover around 3% of it.

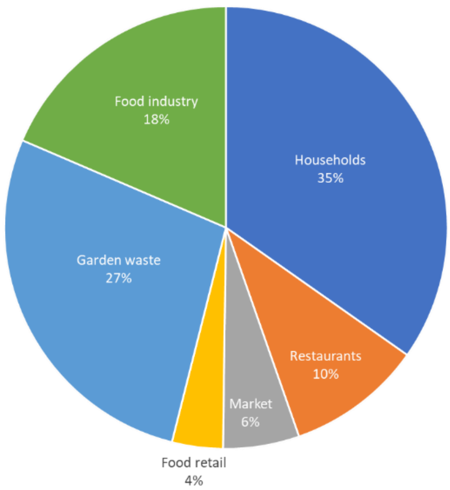

Figure 36: Share of biowaste producer in the global energy recovery

As expected, households are the largest energy producer when it comes to biowaste.

Thanks to this graph, priorities can be set. Household, garden, food industry and even restaurants biowaste need to be sorted separately as they represent a huge input source of energy production.

However, food retail and market biowaste, often consisting of just expired or “ugly” products should better be redistributed to charitable associations for the needed.

VI.1.3.4. Results analysis

According to a study from 2020 on 3.26 million people (5.7% of the population in France) where source separation was implemented, the sorting efficiency was about **43%**. The rest was composted or not sorted at all.

It means that from the 16.1 TWh, we could only recover $16.1 * 0.43 = \mathbf{7.8\ TWh}$

Now, the energy recovery potential represents 1.6% of the French annual natural gas consumption.

However, comparing this energy recovery volume to:

- Volume of biomethane injected in 2021: **4.6 TWh**
- Global production of **biogas** last year in France: **10 TWh**

These figures shows that the energy recovery potential from biowaste in France is quite interesting and could take part in the rise of the biogas production.

In addition, energy production from biowaste will be helpful to meet the objectives set up by the French government to encourage biowaste treatment and recovery through biogas production.

These objectives are distributed in time:

- 2023: **6 TWh** of biomethane injected
- 2028: between **14 and 22 TWh** of biomethane injected
- 2030: between **7 and 10 %** of the national natural gas consumption injected as biomethane

VI.1.3.5. Conclusion

France has a significant potential for energy recovery from biowaste due to its large population and food industry.

To make use of this potential, France has implemented various incentives and policies to promote biowaste energy recovery. For instance, the country has established feed-in prices and other financial incentives to support the development of biogas projects. The government has also set renewable energy targets and implemented regulations to encourage separate collection and treatment of biowaste.

In addition, France has implemented a ban on food waste in supermarkets. Now, they need to donate unsold food or send it for energy recovery. This measure helps to reduce food waste landfilling and facilitates energy recovery.

Thus, if compared to the annual French gas consumption, the potential energy recovery from biowaste may seem rather small or even insignificant, but it is still a step forward to fossil fuel free energy consumption.

VI.1.4. Biogas by-products

If biogas production will be analyzed in the Energy Layer part, biogas by-products production will be discussed here.

In the MFA systems studied, there are four different biogas by-products:

- CO_2 from *CHP* process
- CO_2 from *purification* process
- H_2O from *purification* process
- H_2S from *purification* process

There are of course other by-products appearing during biogas production but only the most common and relevant are considered here.

They are considered as by-products as they do not have any utility in the biogas production. They come from chemical and/or physical transformations taking place during the process and leaving the system at the end.

Here is the annual production of these by-products in the two countries.

(ktons/yr)	France	Norway
CO_2 from CHP	5 000	150
CO_2 from purification	300	26
H_20 from purification	22	2
H_2S from purification	3,4	0,3

Table 68: Annual production of by-products during biogas production

VI.1.4.1. CO_2

CO_2 is released during the production of biogas. When organic matter is under anaerobic digestion, decomposition is taking place in the absence of oxygen and it emits CO2. However, it is important to consider the overall carbon balance.

CO_2 released during biogas production is considered as part of the biogenic carbon cycle. Biogenic carbon is derived from recently living sources, such as plant and animal waste, in opposition to fossil fuel-derived carbon.

When biogas is produced, the CO2 emitted is considered as carbon neutral as organic matter would have naturally decomposed, releasing CO_2 into the atmosphere anyway.

In addition, biogas production contributes to greenhouse gas emissions reduction by replacing fossil fuel in several uses. When biogas is used to produce electricity, it replaces gas, coal, or petroleum. Same goes for heat and biomethane.

However, CO_2 emissions during biogas production depend on several factors such as:

- Type and quality of the feedstock
- Efficiency of the anaerobic digestion process
- End-use of the biogas

Optimizing these factors could minimize emissions and maximize the environmental benefits of biogas production.

For France, CO_2 emissions during biogas production represents 12% of the energy industry emissions. If 12% is a huge share, it is important to notice that energy industry in France does not generate as much carbon as for other countries. Indeed, as electricity is mainly from nuclear energy, its carbon content is low. In addition, there is only one coal-fired power station still in use and few gas-fired power station.

Even if gas and petroleum are still massively used, the French energy industry is not the largest European (and international) CO_2 emitter. That is why CO_2 emissions from biogas production presents such an important share.

However, it is important to say that most of French biogas facilities do not have any Carbon Capture and Storage (CCS) system as they are mainly farming plants. CO_2 is consequently released in the atmosphere most of the time. Equipping a few facilities with CCS could be a tool to reduce even more biogas carbon footprint.

In Norway, CO_2 generation from biogas represents 1.2% of the energy industry emissions. If it seems unsignificant, many Norwegian scientists are working on recovering this CO_2 and recycling it.

It is the case in the Magic Factory (Den Magiske Fabrikken) in Tönsberg, Norway. Built in 2016, it is the largest food waste treatment plant in Norway, covering around 1.2 million people.

As intrants, there are:

- 60 000 tons food waste
- 70 000 tons cow manure
- 5 550 tons other organic liquids (commercial waste)

They produce:

- 70 GWh biomethane (8.2 million Nm3), mainly transformed into bioLNG for transport)
- 126 000 tons liquid biofertilizer

In addition of producing biogas, they recover every by-product and recycle it for other purposes. It is the case for CO_2 as they use it alongside the digestate to produce tomatoes.

The aim is to scale-up the installation to industrial plants to normalize the technology.

If CO_2 can be captured, it can have other uses.

In drinking water production plant, CO_2 is used to maintain calco-carbonic balance of the water. CO_2 is already used in 99% of drinking water production plant.

In cooling towers and hot water grids, CO_2 can be used as anti-limescale. It is better than strong acids for safety reasons and because it does not provoke corrosion.

Finally, it can also be used to produce urea, a widely spread fertilizer that also enters in the composition of plastics.

As there are a lot of possibilities and potential uses for CO_2, developing CCS in French biogas plants but also in every Norwegian one is a solution to minimize carbon footprint of biogas even if it is considered as "green" carbon.

VI.1.4.2. H_2S

Quantities of hydrogen sulfide are produced during biogas production when sulfur-rich compounds are broken down in the absence of oxygen. Before cleaning, biogas contains between 0 and 0.5% of H_2S.

The production of H_2S can be influenced by various factors:

- Composition of the feedstock
- pH level in the digestor
- Retention time
- Operating conditions.

Hydrogen sulfide is a toxic gas, harmful for human health in high concentrations as it can penetrate the respiratory tract. It is also corrosive and can damage equipment, pipelines, and gas engines. That is why cleaning, called desulphurization, is necessary to reduce between 90 and 99% H_2S content.

Legislation regarding H_2S is strict, there are regulated limit values of H_2S in the biogas when it goes out of the plant.

Once captured, H_2S has two common uses:

- In chemical industry to produce sulfuric acids
- In metallurgy to remove impurities from certain minerals

To reduce H_2S production, there are two technics:

- Pre-treatment: Reducing sulfur-containing compounds in the intrants
- pH control: Maintaining an optimal pH level (over 7) in the digestor will optimize the activity of sulfur-reducing bacteria

VI.1.5. Digestate

When it comes to biogas production, the element always associated is digestate. In France, it is even digestate demand that is driving the biogas production.

Digestate is the residual material resulting from anaerobic digestion. It is a nutrient-rich substance that is used as an organic fertilizer or soil amendment. Because of its composition, it contributes to enhance soil fertility, nutrient cycling, and overall soil health.

Digestate has approximately the same fertilizing effect as manure, but the nutrient mix might be different, and plants can potentially absorb the nutrients better.

The three major nutrients contained in the digestate are nitrogen, phosphorus, and potassium. It also contains micro-elements and fibers, useful for soil health.

For French farmers, digestate is the most important element of the biogas production chain, even more than biogas itself. It is considered as the main reason why farmers are building biogas plants.

Two reasons are driving their decisions:

- It replaces mineral fertilizers that are destroying biodiversity and taking part to climate change.
- It helps them to become independent to fertilizer producers. In the current international situation, being autonomous regarding fertilizers has becoming a key aspect. Indeed, since Russian war in Ukraine, there have been many fertilizer shortages and some farmers lost a lot of their production. Having a local and organic fertilizer directly on site is becoming a powerful asset.

In Norway, the situation is completely different as the agricultural activity is significantly lower and so the organic fertilizer requests lower too. In addition, digestate must undergo additional treatments, compared to France. It means that farmers need to invest in infrastructure to store and treat the digestate.

Consequently, the digestate represents a cost for centralized biogas facilities, as there is no willingness to pay for the digestate. Biogas plant must pay the farmer to accept the digestate. Because there are no incentives targeting recycling of nutrients, it is hard to predict whether the demand for digestate as a fertilizer will increase and represent an income rather than a cost in the future.

However, as manure input for biogas production is expecting to increase in the future, the use of digestate in agriculture is likely to increase too, as most farmers that supply manure to a biogas plant would expect to receive the digestate in return.

VI.1.5.1. Digestate treatment

As presented in the MFA study, if digestate can be spread directly out of the digestor, it can also undergo phase separation (before maybe post-treatment).

Liquid and solid phases are different in the composition. They have specific uses but are complementary.

The liquid phase is a fertilizer. It is rich in nitrogen and potassium. It allows a fast nutrition of the plants, like a liquid manure for example.

The solid phase is a soil amendment. It improves the quality of the soil as it is rich in phosphorus and organic material. Compared to the liquid phase, it will feed the soil with a rather long-term action.

In France, both phases are used together and in large quantities. In Norway, digestate is dewatered and composted in many plants, and the dry digestate is used as a soil improvement product. The experience related to use of liquid digestate as a fertilizer is limited to a few, recently built plants.

VI.1.5.2. Result analysis

The aim of this subpart is to analyze the results of the MFA study regarding digestate. Figures are gathered in the following table.

ktons/yr (kg/cap)	France	Norway
Raw digestate	23 230 (347)	960 (175)
Digestate for direct spreading	12 780	530
Digestate for phase separation	10 450	430
Liquid phase for spreading	1840	43
Solid phase for spreading	690	ø
Solid phase to post-treatment	7 900	370

Table 69: Annual production of digestate during biogas production

As expected, the main difference between the two countries is the quantity of digestate produced per capita. In France, it is almost the double of the quantity per capita of Norway. It is explained by the reasons mentioned above. There are more sanitary regulations in Norway and agricultural sector is less developed.

Biogas producers then do not focus on an efficient nutrient recovery and focus on energy efficiency.

Another difference is the share of liquid phase after phase separation. In France, 18% of the digestate undergoing phase separation finish in liquid phase while only 10% in Norway. As mentioned above, liquid phase use is not common in Norway where the stress is put on solid-phase composting (*Post-treatment* in the MFA systems) to dewater it and use it as a soil improvement product.

At the opposite, France is using the two phases together to maximize the efficiency of soil treatment and insure the best productivity possible.

That's why post-treatment is more common in Norway with 86% of the digestate entering phase separation, compared to 75% for France.

VI.2. Energy Layer

The aim of the energy layer is, of course, to determine the energy produced from anaerobic digestion of organic waste. Comparing this production to the national consumption is also an objective, in order to analyze the impact of biogas production on the energy mix.

In addition, the energy layer allows to compare energy content of various intrants, to determine which ones are important to produce energy and which one are more to insure digestate production.

In parallel, the energy layer allows to determine global and specific efficiencies of the biogas production system for the two countries to find similarities and differences and have some hints to propose improvements.

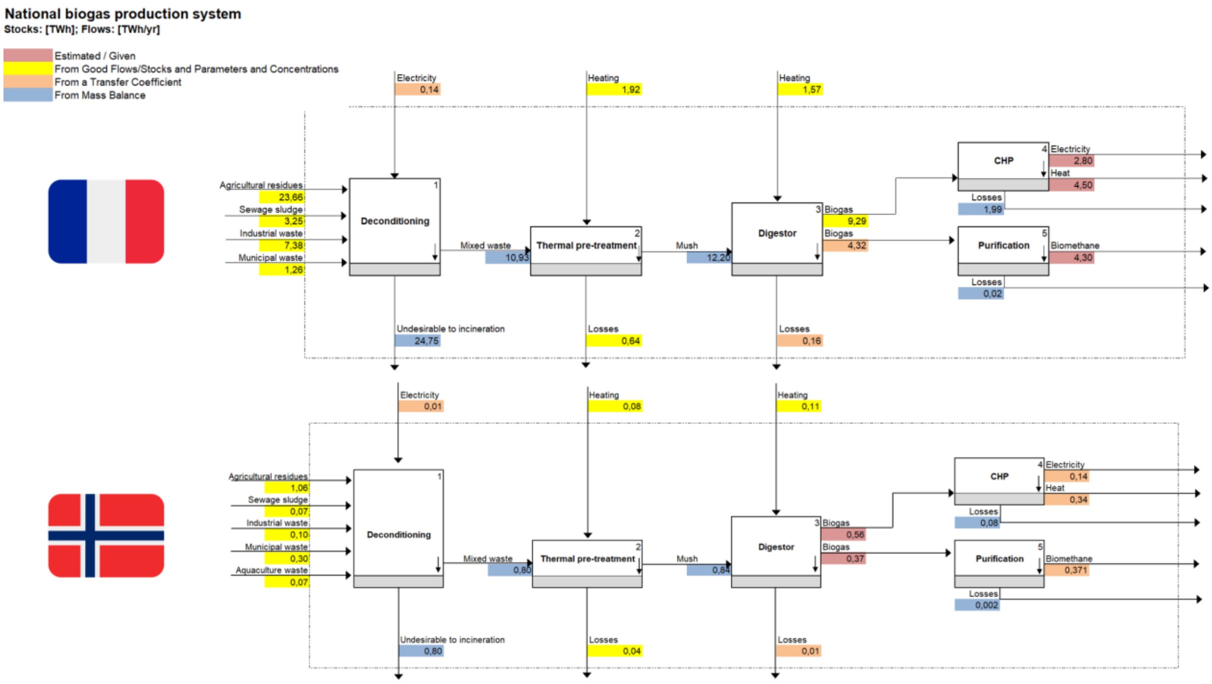

Figure 37: Comparison between the MFA French and Norwegian biogas production system on Energy Layer

VI.2.1. Intrants

The intrants considered have different energy content, from the highest, 1.69 kWh/kg for agricultural residues, to the lowest, 0.54 kWh/kg for sewage sludge.

Multiplied by the volume of each intrant, global energy inputs per intrants can be determined.

Intrants (TWh/yr)	France	Norway
Agricultural residues	23.4	1.1
Sewage sludge	3.3	0.07
Industrial waste	7.4	0.1
Municipal waste	1.3	0.3
Aquaculture waste	0	0.07
Total	**35.4**	**1.64**

Figure 38: Energy inputs per intrant

As expected, agricultural residues are by far the largest energy contributors for both countries. They bring 66% of the intrant's energy input in France and 67% in Norway.

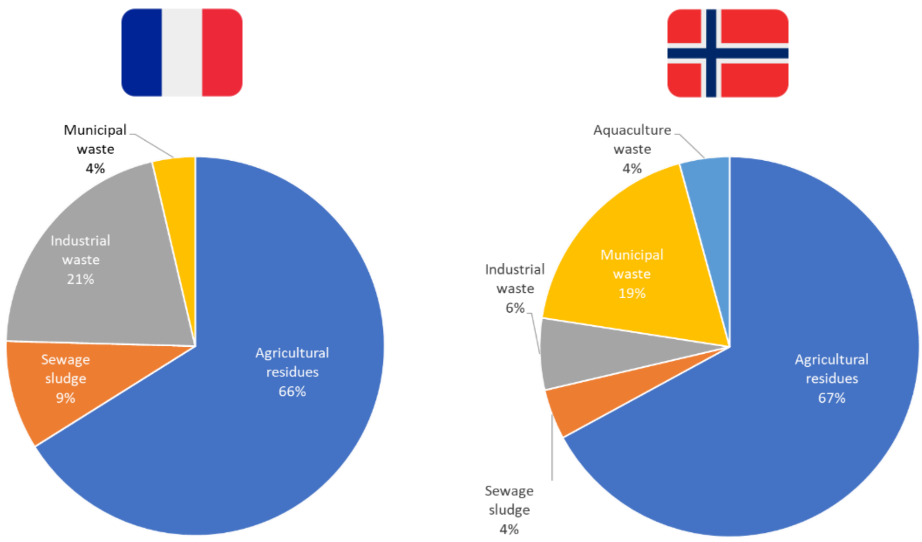

Figure 39: Share of every intrant regarding energy inputs

If agricultural residues prevail in both countries, this is the only similarity in the energy mix. France relies about a quarter on industrial waste in terms of energy inputs while it is limited to 6% in Norway. It is explained by the more important industrialization of France.

For sewage sludge, France also relies more on it compared to Norway. This is because of regulations and laws that are more restrictive in the Scandinavian country. In France, as wastewater and sewage sludge become significant issues, government is lightening the regulation to find new solutions of treatment.

At the opposite, municipal waste has a larger place in the energy mix in Norway than in France, almost 20% against only 4%. As explained earlier, Norway relies a lot on biowaste from municipalities to produce biogas. They develop an important collection system through the entire countries to collect and bring all biowaste to few existing plants. These plants are treating important quantities of biowaste which present a high energy content, almost the double of sewage sludge one.

As presented in the study on biowaste potential above, France could increase the share of municipal waste on the energy inputs mix but many infrastructure investments are required.

It is important to notice that aquaculture waste in the Norwegian energy mix and municipal waste in the French energy mix have the same share. However, in the mass layer, municipal waste inputs are 16 times more important. It shows that municipal waste is used inefficiently in the French biogas production model.

VI.2.2. Energy production

Most obvious reason for building a biogas plant is producing energy. As it contains mainly the methane molecule, biogas can be used as a substitute of natural gas.

Natural gas is used worldwide for heating, cooking and in the transport sector. Its advantage is that it can be stored and used to adjust electricity production during winter. Its major inconvenient is that it is a fossil fuel with extraction, transport and combustion processes emitting a lot of greenhouse gases like CO_2 among others. Another inconvenient, natural gas is a not renewable at human scale, peak of production seems already behind us. In addition, the resource is very limited in term of space. Russia has on its territory about a quarter of global resources, posing dependency issues. The war in Ukraine provokes the energy crises taking place since the beginning of 2022.

That is why biogas can be interesting, as a counter power of the natural gas supremacy. Biogas can be used for several energy purposes:

- **Heat production**: In a CHP, it presents interesting energy performances if the maximum of heat can be used directly on site or very close to the production source to avoid thermal losses.
- **Electricity production**: In a CHP, the efficiency is lower, 37% below heat production, because of the limited yield of the engine, under 33%, but benefits for the producers when sold are higher.
- **Biomethane**: After undergoing purification to remove all particles excepted methane, biomethane can be injected into the gas network or transformed into bioLNG. If benefits are important, there are many additional cleaning steps, sometimes too heavy for producers.
    - **BioLNG**: After undergoing additional steps of cleaning and compression, biomethane can be transformed into liquid fuel to replace traditional oil a fuel for vehicles

Below is the energy production and energy requirements for the two countries per type of outcomes determined in the MFA study.

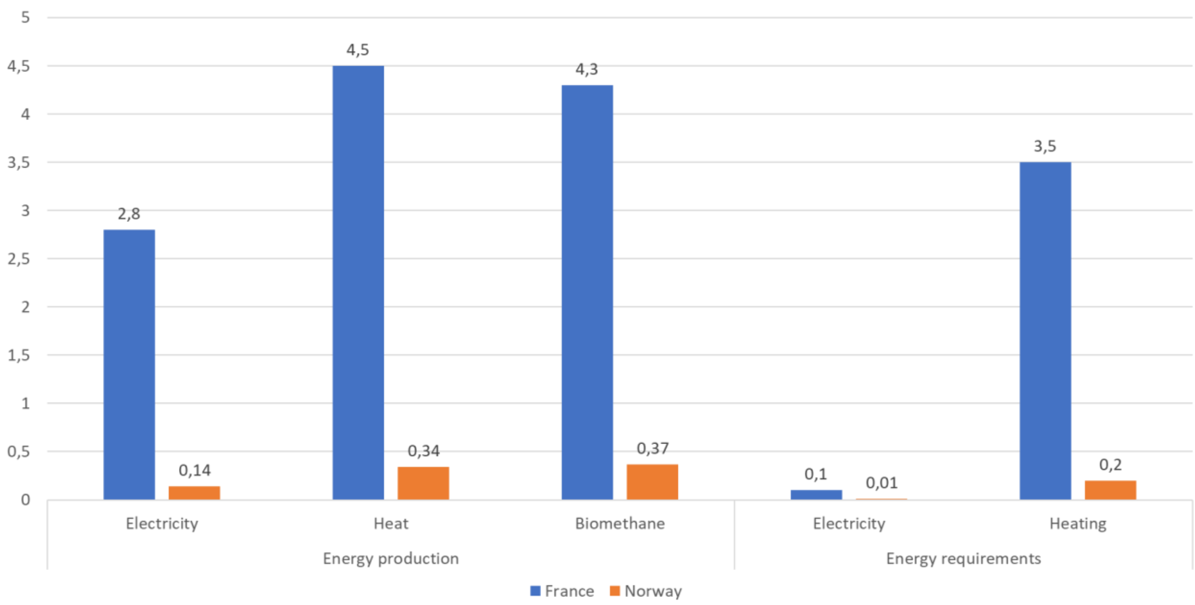

Figure 40: Energy production and requirements per type of outcomes for the two countries (in TWh)

VI.2.2.1. France

In France, as expected, heat production is the first source of energy in the biogas production system. Indeed, heat production is the cheapest option to produce energy with biogas. It does not require complex installations and technologies and so investments are lower. Combined with the fact that ninety percent of the French biogas facilities are farming facilities managed by one or more farmers and not professional ones, heat production is predominant option for energy production. In addition, as there are mainly farming facilities, producers can easily use the heat produced on site, just nearby the plants. So, there are few energy losses, huge economic benefits, and no interaction with potential customers.

The other reason is that heat production has a better efficiency in a CHP compared to electricity production. If biogas is implemented into a CHP, more heat would be produced than electricity.

The second outcome regarding energy production in France is biomethane. Its production is very close to heat production, 4.3 TWh for biomethane against 4.5 TWh for heat.

In both countries, biomethane production is more complex and expensive for biogas producers. Indeed, there are additional treatment processes compared to the use of a CHP to remove all useless particles. It requires more installations and cutting-edge technologies, so investments are higher.

However, the benefits of biomethane are very interesting compared to the ones of heat. In France, around 95% of biomethane is injected into the natural gas grid. Indeed, French natural gas grid is very developed all around the country and gas can be distributed from North to South thanks to kilometers of pipelines.

Once purified, biomethane can be sold to energy providers who will take in charge the injection on the network and distribution to their customers.

As France is trying to develop its independency regarding fossil fuel and to reduce greenhouse gas emissions, biomethane appears as an interesting opportunity.

That is why several incentives to promote biomethane injection have been implemented:

- **Feed-in Tarif**: The French State implemented feed-in tariff to provide financial support to producers. In other words, this incentive guarantees a fixed price for the biomethane sold in a long period. The tariff rates depend on the size on the facility and are set for a period of around 15 years. It is similar to the Power Purchase Agreement, implemented for renewable electricity.
- **Simplified connection process to the grid**: Administrative procedures to connect biomethane plants have been reduced and lightened. The aim is to diminish time and effort required for producers to obtain authorizations.
- **Investment Support**: The French Environment and Energy Management Agency (ADEME) provides financial support to biomethane facility investments through its construction and operation. This support often covers a significant share of the project costs.

- **Green Gas Certificates**: The French State implemented a system entitled "Certificats de Garantie d'Origine". These certificates are allocated to each biomethane producers, certifying a renewable origin. Once obtained, they can be traded and sold to gas suppliers to offset their carbon footprint.
- **Tax incentives**: There are some tax incentives for the producers, for instance the VAT, Value-Added Tax, is on a reduce rate for the sale of biomethane compared to natural gas.

Thus, the French State provides a financial and regulatory support to encourage investment in biomethane injection, in order to reduce greenhouse gases emissions and its dependency to fossil fuel.

Electricity is the lowest energy provider of the biogas production system in France. First, because of the lower efficiency of the electricity production system in CHP but also because electricity production is complex and expansive.

In addition, regarding electricity, France already relies mainly on a decarbonated electricity thanks to its numerous nuclear power plants. About 70% of French electricity comes from nuclear power plants. France also relies a lot on hydraulic power production and is developing wind power turbine and solar electricity. For all these reasons, France does not need extra volume of renewable and decarbonated electricity and so does not put the stress on electricity production for biogas facilities. However, it is important to notice that some incentives exist for electricity produced from biogas like the subvention entitled "Prime à l'efficacité énergétique". It gives a bonus to producers for every kWh of electricity sold to providers.

Looking to the energy requirements of biogas production in France, the process requires a lot of heat but very small volume of electricity. Around 78% of the heat production is required for heating the process against 4% for electricity.

It can be very interesting to reuse a share of the heat produce in CHP for heating the system and use the rest to heat buildings near the biogas facilities. Indeed, selling heat produced is not financially interesting as the more heat is transported, the more losses are going to happened. At the end, the customer will only recover a small part of the production.

For producers, operating costs would be reduced as no natural gas would be necessary for heating, and incomes would be generated by the production of electricity or biomethane.

VI.2.2.2. Norway

In Norway, the overview is a bit different. For heat and electricity, it is like France. More heat is produced because of a better efficiency than electricity. Heat is reused at around 60% into the heating process of the system and the rest is mainly used for heating buildings around the facilities.

The difference between the two countries regards biomethane production. In Norway, biomethane production is higher than heat and electricity production.

In Norway, almost every biogas plants are professional facilities managed by companies and not by farmers. As they are managed by companies looking, energy production is oriented to what makes more money, in this case biomethane.

However, biomethane is not injected into the Norwegian gas grid like in France. First, because the natural gas grid is quite inexistant in Norway, at least it is not very developed or very old and not so efficient. Other reason and difference with France, Norway produces plenty of natural gas. The country has deposits all other the place. After the war of Ukraine and the cessation of Russian gas exportations, Norway became the first exporter of gas in Europe, generating historically high incomes for the countries. That is why biomethane injection is not common, because there is no use of it.

Nevertheless, biomethane is still produced a lot in Norway, to be transformed into bioLNG, used for transport instead of petroleum.

Thanks to its incomes for gas and crude oil exportations, Norway developed for many years incentive programs to make the transport sector more sustainable. The two main levers are electric vehicles and bioLNG.

BioLNG is considered a renewable source as it is produced from organic waste. Replacing fossil-based LNG with bioLNG contributes to meeting renewable energy objectives and reducing global carbon footprint. In addition, as it is from agricultural residues, sewage sludge, municipal, industrial and aquaculture waste, producing bioLNG promotes circular economy and abides by the waste pyramid with recycling, waste minimization and energy recovery.

The Norwegian strategy for transforming its transport sector into a sustainable sector is replacing small and compact fossil fuel-based vehicles by electric vehicles. For other types of vehicles like trucks and buses, they rather develop financial support to bioLNG facilities. Indeed, for these vehicles, weight of batteries is too high, and electricity is not a viable solution. BioLNG appears as an opportunity to decarbonize the heavy transportation sector to align with country’s objectives regarding global warming.

VI.2.3. Energy efficiency

Analyzing the energy layer also gives the opportunity to determine the efficiency of the two biogas production systems thanks to the MFA models.

For the global efficiency, we use the formula below:

$$Global\ efficiency = \frac{Energy\ produced}{Energy\ entering\ the\ biogas\ facility}$$

For global efficiency, numerator consists of the energy produced through electricity, heat and biomethane. Denominator consists of all energy inputs, energy content of intrants but also energy required for processes, namely electricity for *deconditioning*, heating for *thermal pre-treatment* and *digestor*.

Doing the calculations, the results are:

- France: 29.6 %
- Norway: 47.3 %

If Norway seems to have a higher efficiency than France, figures are relatively low compared to casual biogas system efficiencies. That is why we may wonder if this efficiency is the most appropriate one and if results are relevant.

In the denominator, we consider the energy content of organic waste before undergoing deconditioning. When waste is entering the biogas facilities, they still contain many impurities like woody materials or plastics used to transport and collect the waste. Plastic is known to have a high energy content compared to organic waste, about 10 times higher. For wood, energy content is about 5 times higher. During deconditioning all this energy will be lost.

At the end, plastics, and wood, which have a largely higher energy content than organic waste, are not used to produce biogas, they cannot really be considered as intrants of the biogas production process. Then, we must use another approach to determine energy efficiency.

To end up with a consistent and relevant efficiency, we get rid of the deconditioning process, considered as an external process to only consider energy from *Mixed waste*. In the numerator, we still have the energy produced through electricity but in the denominator, we only consider energy available for biogas production.

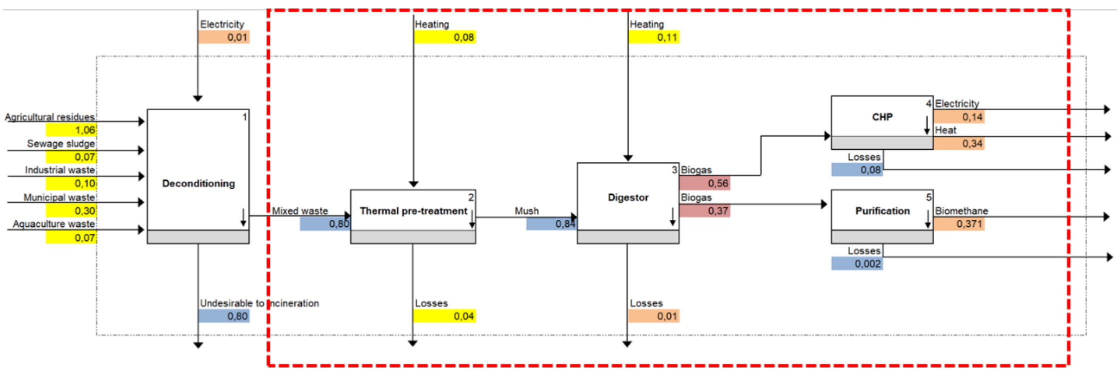

Figure 41: Part of the MFA system considered to determine efficiencies

Doing the calculations, the results are:

- France: 80.4 %
- Norway: 86 %

These efficiencies are in line with common biogas production system efficiencies.

Norway still has a better efficiency than France. This can be explained by the fact that Norway does not give so much importance to digestate yet. They focus on energy production and try to improve as much as possible every process to recover maximum energy. In France, biogas plants are mainly farming plants and farmers first want to produce as much digestate as possible and then, if possible, recover some energy. Because producers are mainly interested in digestate, France is optimizing digestate production and then focus on energy. This difference in digestate use and market in the two countries is at the root of efficiency differences.

VI.2.4. Share of energy production from biogas at national scale

The aim in this part is to have an overview of the weight of energy production from biogas in the national energy consumption.

		
Part of the electricity production from biogas in the national electricity consumption (2022)	$\frac{2.8}{459} = \mathbf{0.6\%}$	$\frac{0.14}{140} = \mathbf{0.1\%}$
Part of the biomethane production in the national gas consumption (2022)	$\frac{4.3}{430} = \mathbf{1\%}$	$\frac{0.37}{40} = \mathbf{0.9\%}$

Table 70: Share of energy production from biogas in the national energy consumption (TWh)

In 2022, global:

- French electricity consumption was 459 TWh while only 2.8 TWh have been produced thanks to biogas.
- Norwegian electricity consumption was 140 TWh while only 0.14 TWh have been produced thanks to biogas.
- French natural gas consumption was 430 TWh while only 4.3 TWh of biomethane have been produced.
- Norwegian natural gas consumption was 40 TWh while only 0.37 TWh of biomethane have been produced.

At first sight, all shares of energy produced from biogas compared to national consumption are under 1%. It means that nowadays, biogas only meet under 1% of national energy consumption. The question is: Is it really a relevant technology to invest? Indeed, it seems unlikely that one day biogas could meet the entire energy requirement, or even 10%.

Nowadays, biogas production is one of the only *Waste to Energy* technology. With the population increasing and our current lifestyle, more and more waste would be generated in the future. Rather than sending organic waste to landfill where they would decompose and emit greenhouse gases, or to incineration where assets would be lost, biogas utilizes this waste to recover energy and nutrients.

All in all, biogas production should not be seen as a solution to the energy issue but rather to the waste issue. Indeed, biogas will never replace fossil fuel or other renewable energy, but it would take part in an efficient and virtuous waste management system, combining circular economy, energy production and nutrient management.

VI.3. Nutrient Layer

The aim of the nutrient layer is to determine how the digestate, produced alongside biogas, can be interesting in terms of soil enrichment and fertilization.

In this layer, I calculated the nitrogen, phosphorus, and potassium content of all the flows from the intrants to the final digestate products.

After presenting the system, the aim is to present the most important source for each nutrient, where the losses are and above all the quantity of nutrient back in the soil.

VI.3.1. Nitrogen

Here are the French and Norwegian MFA systems for the Nitrogen nutrient layer.

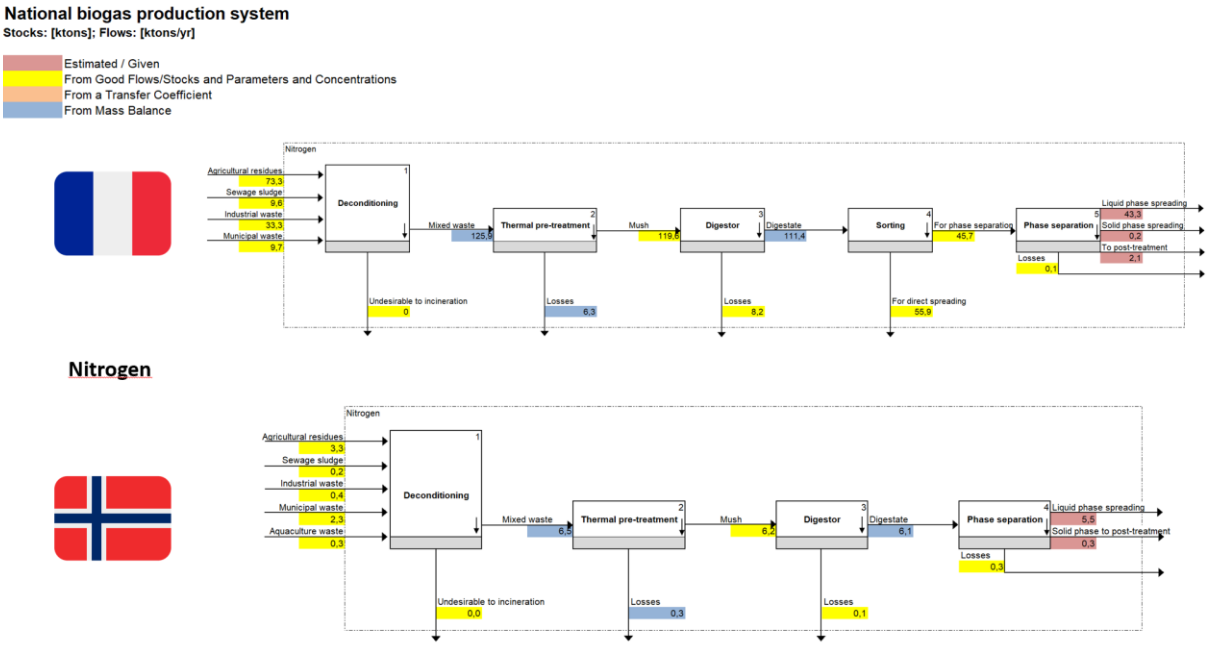

Figure 42: Comparison between the MFA French and Norwegian biogas production system on Nitrogen Nutrient Layer

The only difference for nitrogen (and the other nutrients) between the two MFA systems are the absence of solid phase spreading and the presence of aquaculture waste as intrants in Norway. Of course, for the nutrient layer, biogas flows and processes are not considered as they did not contain nutrients.

First, we will focus on the nitrogen content of intrants to see what the largest source is.

VI.3.1.1. Nitrogen content of intrants

This is the nitrogen content of each intrant.

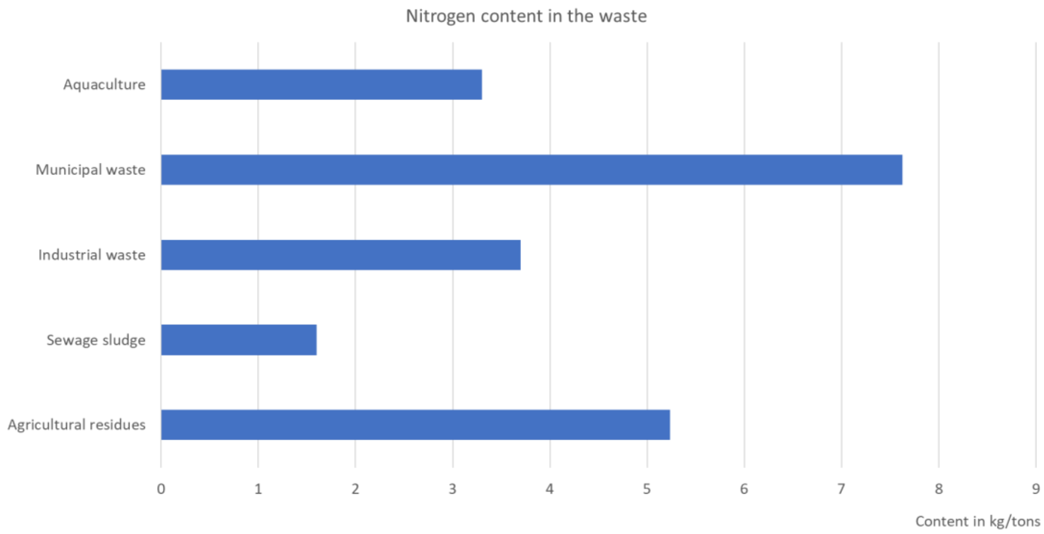

Figure 43: Nitrogen content of each intrant

The intrant with the highest nitrogen content is municipal waste. Food waste from households, restaurants or canteens present the highest nitrogen content compared to other components of municipal waste.

It is followed by agricultural residues where animal manure has the highest nitrogen content, depending on type of feedstocks and how it is managed.

Then comes industrial waste, led by food processing waste, presenting relatively high nitrogen content, aquaculture waste and sewage sludge.

VI.3.1.2. Importance of nitrogen

Nitrogen is an essential nutrient for soils as it plays a crucial role in fertilization and overall ecosystem health.

First, nitrogen is one of the most important components of proteins, enzymes and amino acids that are essential for plant growth and development. Nitrogen also takes part of plant tissues like leaves, stems, and roots.

Nitrogen is also a key component of chlorophyll which is in charge of photosynthesis. Chlorophyll captures sunlight energy, allowing conversion of carbon dioxide and water into carbohydrates and oxygen in the plant. Nitrogen ensures efficient chlorophyll production, optimizing photosynthesis, ensuring higher crop yields.

Nitrogen is also involved in more complex metabolic processes in the plant like synthesis of DNA or ATP, essential components of cell division. In addition, without nitrogen, absorption of phosphorus and potassium would be harder for the plant.

Finally, nitrogen is associated with microbial activity. Indeed, certain types of bacteria can convert nitrogen into a molecule that plant can use, that is called nitrogen fixation. Nitrogen influences the quantity and population of bacteria, influencing soil health.

For all these reasons, a good balance of nitrogen into the soil guarantees soil health, prosperity, and good yields.

VI.3.1.3. Danger of nitrogen

If nitrogen is an essential nutrient for soil health, an excessive quantity of nitrogen presents some dangers.

First is eutrophication. When nitrogen runoff leaks to rivers, lakes, or coastal areas, it causes an excessive concentration of nutrients, causing excessive algae development which depletes oxygen level in water, killing fish and other living bodies.

When spread on fields, nitrogen can take the form of nitrate (NO_3^-) and contaminate groundwater, a primary source of drinking water. When levels of nitrate are too high in drinking water, it can cause health issues, particularly for children and pregnant women. In the human body, nitrate can be converted into nitrite (NO_2^-). Nitrite can interfere with the oxygen-carrying capacity of blood and cause a disease called methemoglobinemia.

If nitrogen is spread on fields but do not penetrate the soil, it can contribute to air pollution in the form of nitrogen oxides, also known as NO_X, and ammonia (NH_3). NO_X takes part to smog formation and acid rains. Ammonia can react with other pollutants to form particulate matter and contribute to air pollution.

Like eutrophication, high nitrogen levels can have a negative impact on biodiversity. It can favorize certain plant species in place of native ones. This substitution can also jeopardize animal species that depend on specific plant for living and feeding.

That is why responsible nitrogen management in agriculture is essential. Using bio-fertilizer, like digestate, in place of chemical ones, is a promising step-forward but proper management is still the key.

VI.3.1.3. Results of the MFA study

According to the results of the MFA study, it appears that the largest source of nitrogen for both countries are agricultural residues. It supplies:

- 58% of the nitrogen for France
- 51% of the nitrogen for Norway

More than the half of nitrogen inputs are made by agricultural residues for both countries. Again, agricultural residues are primordial for biogas production system of both countries.

Compared to inputs, losses represent respectively 12% and 11% for France and Norway. In France, these losses are higher in the digestor than in thermal pre-treatment. In both cases, they are due to a remaining quantity of materials at the bottom of the tanks. As it is impossible to completely empty the tank after every passage, these quantities are lost. There are also some losses after phase separation, but they are quite low.

For Norway, there are more losses in thermal pre-treatment than in the digestor. Unlike France, losses from phase separation are as high as losses from thermal pre-treatment. It can be explained by the fact that solid phase is not used for spreading, it is sent directly to post-treatment, so it needs to be close from hundred percent dry. When liquid and solid phase are separated, some solid materials still contain liquid matter and need to be eliminated. Only hundred percent solid phase are sent to composting.

Looking at the quantity of nitrogen back in soil, so the total quantity of nitrogen spread through liquid and solid phase but also with solid phase going to post-treatment, quantities are:

- 101.5 ktons (1.5 kg/cap) for France

- 5.8 ktons (1.1 kg/cap) for Norway

Again, the fact that France presents a higher volume per capita is explained by the fact that France efficiently uses digestate with farmers paying for using bio-fertilizer, while Norway is struggling with promoting digestate value.

If we consider that the average quantity of nitrogen per hectare is equal to 170 kg, nitrogen quantities back in soil after biogas production can cover the needs of:

- 600 000 hectares in France, which represents 2% of French fields.
- 34 000 hectares in Norway, which represents 3.3% of Norwegian fields.

Just like energy production, these percentages seem very low but digestate sector is still quite immature in both countries. Gaining in efficiencies and reducing losses could increase this ratio. In addition, the aim is not to fully replace chemical fertilizers but to propose a credible substitute to these harmful substances for farmers, in order to protect biodiversity while allowing producers to maintain high field yields.

VI.3.2. Phosphorus

Here are the French and Norwegian MFA systems for the Phosphorus nutrient layer.

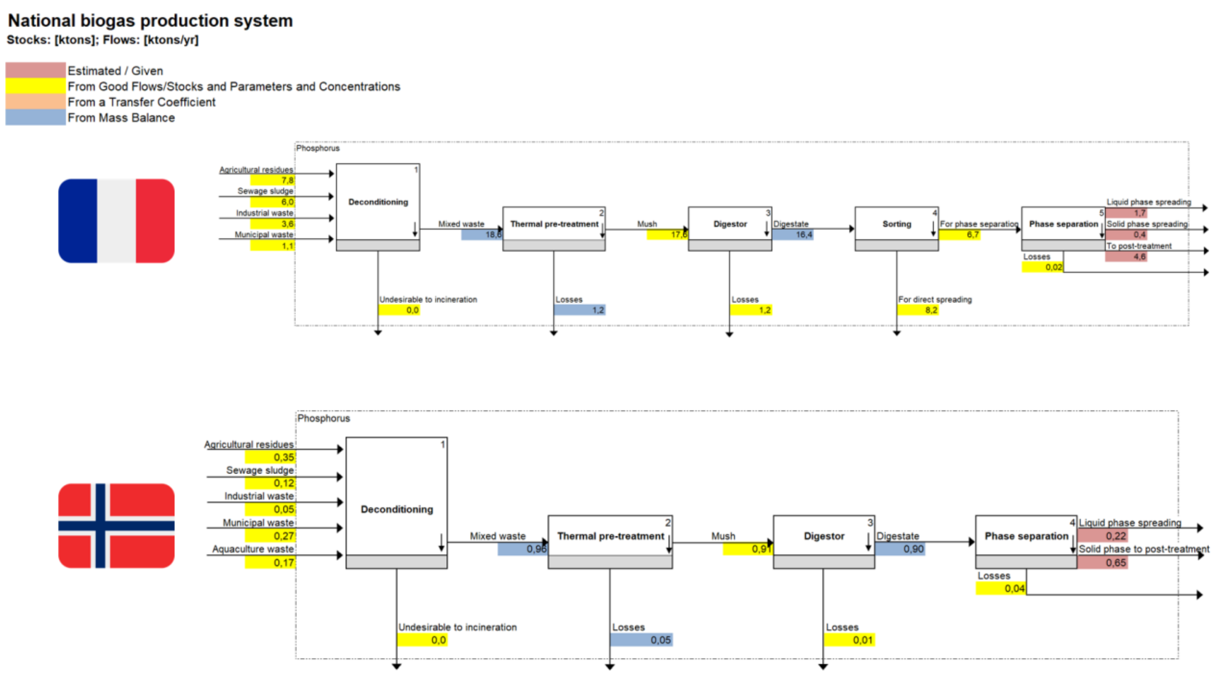

Figure 44: Comparison between the MFA French and Norwegian biogas production system on Phosphorus Nutrient Layer

Again, the only difference for phosphorus between the two MFA systems are the absence of solid phase spreading and the presence of aquaculture waste as intrants in Norway. Of course, for the nutrient layer, biogas flows and processes are not considered as they did not contain nutrients.

First, we will focus on the phosphorus content of intrants to see what the largest source is.

VI.3.2.1. Phosphorus content of intrants

This is the phosphorus content of each intrant.

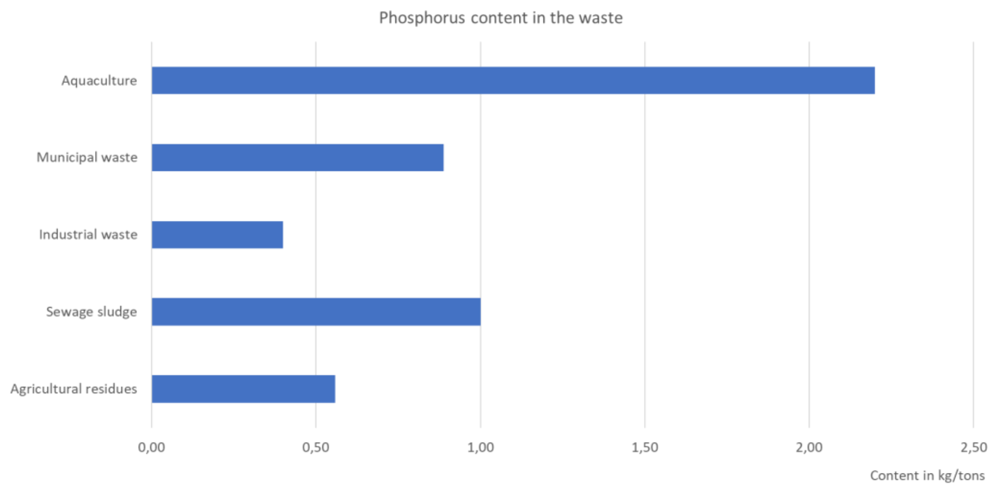

Figure 45: Phosphorus content of each intrant

The intrant with the highest phosphorus content is by far aquaculture waste. Aquaculture feedstock is considered as one of the major phosphorus contributors for human consumption. That is even one of the many reasons why aquaculture is developing. Phosphorus content in aquaculture waste is driven by the feed composition. In most of cases, commercial aquaculture feed provides necessary nutrients, like phosphorus, for optimal growth and health of the feedstocks.

Sewage sludge is the second largest phosphorus contributor, followed by municipal waste. Agricultural residues and industrial waste present lower phosphorus content.

VI.3.2.2. Importance of phosphorus

Phosphorus is essential to all life forms. It is a critical nutrient for plants and animals as there is no substitute.

Phosphorus is the key component of ATP which is the energy carrier in cells. ATP provides energy to the plants, allowing photosynthesis, respiration, and nutrient use. Enough phosphorus ensures efficient energy transfer and storage for plant growth and health.

Phosphorus is also crucial for root development, allowing cell division and elongation. Phosphorus stimulates the production of new cells and tissues, leading to robust and healthy root systems.

Phosphorus also plays a role in the development and activation of reproductive organs, promoting pollination, seed set and fruit development. Without phosphorus, no flowering, seed production or crop quality.

Finally, phosphorus enhances stress tolerance, strengthening cells walls to increase disease resistance. It also influences water relations in plants, balancing water uptake and transpiration rates. That is why phosphorus is crucial during critical periods of drought and water stress.

VI.3.2.3. Danger of phosphorus

The main issue with phosphorus is shortage issue.

Phosphorus is a finite and non-renewable resource. As phosphorus underpins all food systems, the increase of population and incomes lead to a risk of depletion in the future. Already, in some areas, the increasing price of phosphorus limited the access for farmers to this nutrient, essential for plant growth.

In addition, if all farmers need phosphorus, yet just 5 countries, including Morocco, China, USA and Russia, control around 85% of the word's remaining phosphate rock reserves.

In addition, if phosphorus is an essential nutrient for soil health, an excessive quantity presents some dangers.

Like nitrogen, first is eutrophication. As it is used as a fertilizer, runoffs are unavoidable. It stimulates algae growth in marine environments, depleting dissolved oxygen, creating hypoxic zones. These hypoxic zones are called "Dead zone". In Gulf of Mexico, there is a record high of 22 000 square kilometer dead zone, it represents 5% of Norway.

Excessive phosphorus content can also lead to nutrient balance alteration, leading to nutrient deficiencies and toxicities.

Just like nitrogen, excessive phosphorus could jeopardize biodiversity, favorizing certain plants in place of native ones, putting animal also in danger.

Finally, it could lead to soil degradation as phosphorus accumulation may result in phosphorus being locked up in unavailable forms, reducing nutrient availability and negatively impacting soil fertility.

To minimize risks, it is recommended that farmers conduct soil test to determine phosphorus requirements. Again, fertilizer management is the key be it with chemical fertilizer or digestate.

VI.3.2.4. Results of the MFA study

According to the results of the MFA study, it appears that the most important source of phosphorus for both countries are agricultural residues, even if it presents a low phosphorus content. It supplies:

- 42% of the phosphorus for France
- 36% of the phosphorus for Norway

Compared to inputs, losses represent respectively 13% and 10% for France and Norway. Phosphorus losses are quite similar to nitrogen ones.

In France, these losses are equal in the digestor and in thermal pre-treatment. In both cases, they are due to lost quantities of materials at the bottom of the tanks.
For Norway, again there are more losses in thermal pre-treatment than in the digestor. Unlike France but like nitrogen, losses from phase separation are as high as losses from thermal pre-treatment.

Looking at the quantity of phosphorus back in soil:

- 14.9 ktons (0.2 kg/cap) for France
- 0.87 ktons (0.2 kg/cap) for Norway

These quantities are largely lower compared to nitrogen. Biogas production systems in both countries are producing far more nitrogen than phosphorus. It is linked to the fact that phosphorus becomes a rare and researched resource, explaining why prices are increasing.

Unlike nitrogen, France and Norway are producing the same amount of phosphorus per capita. It is due to high phosphorus content in aquaculture waste. Once ago, Norwegian specificity presents a huge advantage.

If we consider that the average quantity of phosphorus per hectare is equal to 70 kg, phosphorus quantities back in soil after biogas production can cover the needs of:

- 200 000 hectares in France, which represents 0.8% of French fields.
- 12 400 hectares in Norway, which represents 1.2% of Norwegian fields.

As expected, these percentages are lower compared to the nitrogen layer. Besides, as there is a risk of scarcity for this resource, these percentages could become lower in the future if phosphorus contents decrease in the intrants. So, less phosphorus would be available to the soil, creating a downward spiral.

However, nowadays, digestate can be seen as a cheap opportunity for farmers with low incomes to produce and use phosphorus on their fields. It is a tool to reduce dependency on fertilizer producers even if digestate phosphorus content is not enough to meet entire soil requirements.

VI.3.3. Potassium

Here are the French and Norwegian MFA systems for the Potassium nutrient layer.

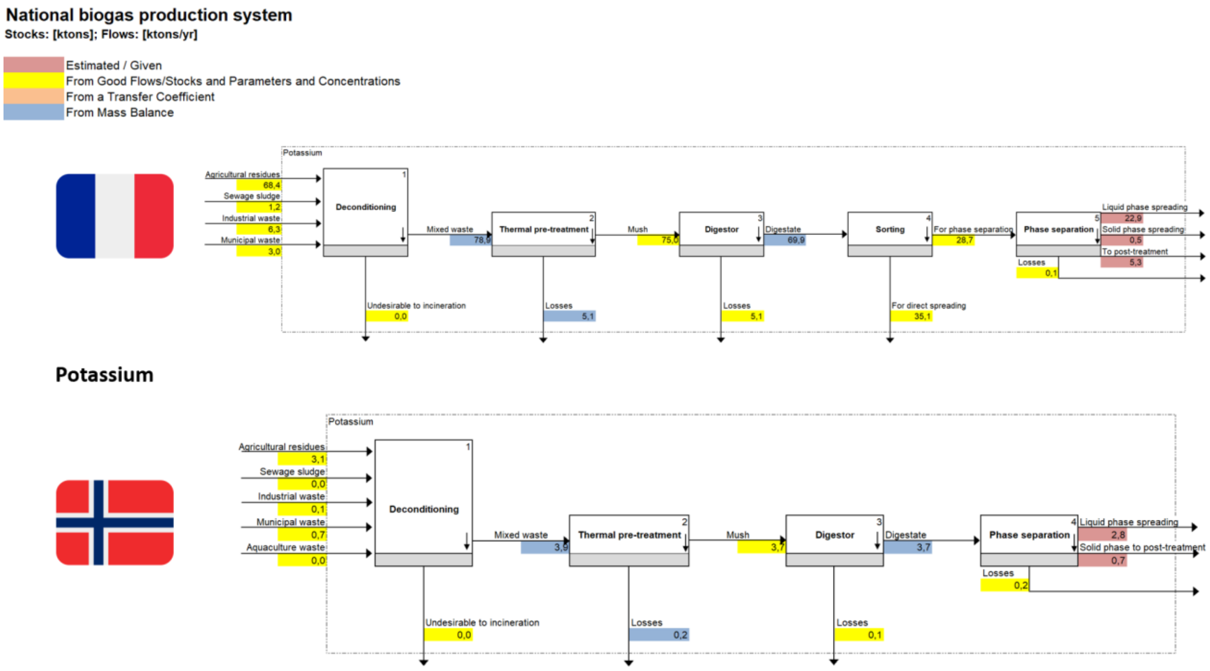

Figure 46: Comparison between the MFA French and Norwegian biogas production system on Potassium Nutrient Layer

Again, the only difference for potassium between the two MFA systems are the absence of solid phase spreading and the presence of aquaculture waste as intrants in Norway. Of course, for the nutrient layer, biogas flows and processes are not considered as they did not contain nutrients.

First, we will focus on the potassium content of intrants to see what the largest source is.

VI.3.3.1. Potassium content of intrants

This is the potassium content of each intrant.

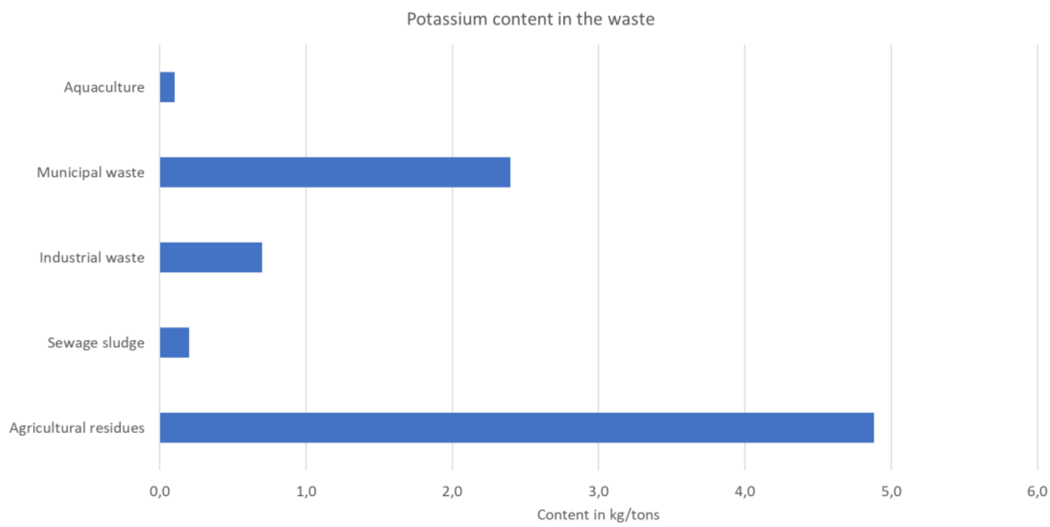

Figure 47: Potassium content of each intrant

For potassium, there is no competition, agricultural residues are by far the largest contributor to potassium inputs. It is the same nutrient content compared to nitrogen, about 5 kg/tons.

Potassium is an essential nutrient for plants. During their growth, it is taken up from soil and distributed to different organs of the plants. When they are harvested, crop residues are left on fields, containing significant share of potassium, originally in the soil.

Municipal waste followed with a relative high potassium content compared to the other intrants.

VI.3.3.2. Importance of potassium

Like nitrogen and phosphorus, plants required potassium for several physiological processes including photosynthesis, water regulation, and protein synthesis. More specifically, potassium helps regulate osmotic potential within plant cells. In other words, it helps the movement of water and nutrient inside the plant.

Potassium also plays a role in activation of enzymes, responsible for biochemical reactions like energy production, hormone synthesis and stress response mechanisms. Potassium ensures enzymes functioning and efficiencies.

The nutrient is also useful to make the plants more resistant to pests, enhancing its overall structural integrity.

Finally, potassium takes part in soil structure and stability improvement. It plays a role in the formation of humus, which helps gathering soil particles together, reducing erosion risks.

VI.3.3.2. Danger of potassium

Like nitrogen and phosphorus, excessive potassium content in soils can have negative impacts.

As strange as it seems, too much potassium can lead to reduced nutrient availability. Indeed, it can cause antagonistic interactions with other nutrients, making them less available to plants. In other words, even if nutrients are present in the soil, plants would not use it, creating nutrient deficiencies and reducing crop yields.

When harvested, excessive potassium content can be dangerous for livestock. Indeed, high proportion of potassium can disrupt the potassium-to-magnesium ration in the diet, increasing the risk of hypomagnesemia, a life-threatening condition for livestock.

Another negative impact is the risk of soil salinity. Inappropriate potassium content can affect soil osmotic potential, reducing water uptake and creating drought issues.

VI.3.3.3. Results of the MFA study

According to the results of the MFA study, the largest source of potassium for both countries are agricultural residues. It supplies:

- 87% of the potassium for France
- 79% of the potassium for Norway

Compared to inputs, losses represent 13% % for both countries. Phosphorus losses are quite like the two other nutrient ones.

In both countries, these losses are equally distributed alongside the production chain.

Looking at the quantity of potassium back in soil:

- 63.8 ktons (1.0 kg/cap) for France
- 3.5 ktons (0.6 kg/cap) for Norway

These quantities are largely higher compared to phosphorus but lower compared to nitrogen.

As aquaculture waste have a relatively low potassium content, Norway is producing a lower quantity of potassium per capita. France puts the stress on digestate for many years now and even if the system is still immature yet, production of nutrients is higher compared to Norway.

If we consider that the average quantity of phosphorus per hectare is equal to 310 kg, potassium quantities back in soil after biogas production can cover the needs of:

- 200 000 hectares in France, which represents 0.8% of French fields.
- 11 300 hectares in Norway, which represents 1.1% of Norwegian fields.

If production of potassium is higher compared to phosphorus for both countries, the higher quantity required per hectare balances the higher production. At the end, percentages are comparable to phosphorus.

If quantities of nutrients produced through digestate are interesting, they are far away from quantities required to cover entire field requirements. Chemical fertilizers still have a bright future.

However, digestate can still be interesting for small or medium size farms, where incomes are not high, to reduce the volume of expensive fertilizers while keeping high crop yields.

VII. Conclusion

After MFA study and discussions about the results, general questions of the Thesis can be answered.

Regarding intrants, the two countries rely on similar organic waste, agricultural residues, sewage sludge, municipal and industrial waste. However, Norway also uses aquaculture waste, a specific and major sector of its economy.

Regarding volume, agricultural residues is by far the most important input for both countries. Comparing volume per capita, France is using more intrants compared to Norway, especially for agricultural waste as France mainly relies on farming facilities.

One of the major differences between France and Norway relates to the use of municipal waste and more specifically household waste, or biowaste. If Norway is source sorting organic waste from household almost all around the country, France is still sending it to incineration. To abide by the EU regulation in 2024, France will have to adapt, which could be an important step forward regarding biogas production.

Agricultural residues are also by far the largest energy contributor, covering around 70% of the energy inputs for both countries. It is the same for nutrient, agricultural residues present the largest nitrogen, phosphorus, and potassium contents.

Thus, agricultural residues hold a key position in the biogas chain.

These intrants undergo several treatments before entering the digestor. First is the deconditioning process where all plastics and undesirable materials are taken off and sent to incineration. This is where major losses are located, be it on a volume basis or in an energy basis, but this step is mandatory and similar in both countries to ensure efficient biogas production.

Then, intrants undergo thermal pre-treatment to abide by safety and sanitary regulations. In the analysis, it has made clear that the regulations are softer in France compared to Norway, especially for sewage sludge anaerobic digestion. Norway uses strict regulations to ensure that no pathogen could contaminate biogas or digestate, which reduce Norwegian production capacity.

In France, biogas is mainly used to produce heat, valorized directly on site to heat buildings but also the biogas production system. Heat is closely followed by biomethane production and injection into the natural gas grid, well-developed in France.

In Norway, the main use of biogas is biomethane and bioLNG production to substitute fossil fuels in the transportation sector.

Compared to global fossil fuel consumption, biogas production can seem very low, around 1%, but if it will not solve immediately the energy issue, it is one of the only Waste-to-Energy technologies. If biogas production is of course aiming to tackle the issue of fossil fuel dependency, it is also deeply linked to waste management and waste hierarchy.

Regarding energy efficiencies, Norway presents a higher ratio compared to France. As Norway is not gambling on digestate, they put all efforts on energy production, taking the maximum of all process and reducing losses at its best.

Indeed, the most considerable difference between the two countries is digestate production and utilization. While in France, biogas production has increased because farmers wanted to use digestate to replace chemical fertilizers, in Norway biogas producers need to pay farmers to export digestate.

As agricultural field is developed in France, requirements in nutrient are huge for farmers who do not want to rely on foreign fertilizer producers anymore. That is why they are developing biogas production, to have a local and organic soil amender, ensuring interesting crop yields while reducing their carbon footprint.

In Norway, as the regulations on digestate spreading are stricter and discouraging, producers do not get rid of digestate and need to pay farmers to recover it. Per capita, digestate production is far more important in France compared to Norway.

Regarding nutrient requirements, digestate is still only covering a small part of the total field surface in the two countries, around 1% to 2%. But it is important to notice that digestate production is still immature. Financial and technological investments need to be done to increase its efficiency to tackle the issue of chemical fertilizing, destroying biodiversity and jeopardizing soil health.

However, biogas production is one of the best waste management options for nutrient recovery, alongside composting. Compared to incineration, still dominant in both countries, where all nutrients are lost and only energy is recovered, anaerobic digestion is recovering an important share of nutrients from the waste which will be back on soil thanks to digestate.

All in all, to improve its overall biogas production system, France could draw from Norway on its biowaste management, from source sorting to final valorization. France could also take example on Norwegian energy efficiency, slightly higher, to minimize losses while maximizing energy production, to increase benefits for producers.

At the opposite, Norway has a lot to learn regarding digestate management and valorization. If Norway want an increase its biogas production, it would be relevant to take France as example in how they promote digestate by lightening safety regulations and administrative constraints. This would also be useful to diversify intrants, for example with sewage sludge, as nowadays biogas producers do not want to face heavy requirements for thermal pre-treatment.

If biogas production is increasing in both countries, a lot of efforts are still to be done to decarbonize the energy sector. Technological and scientific research are uninterrupted to increase energy efficiencies and nutrient recovery and limit greenhouse gas emissions. Ambitious projects come into existence like the *Magic Factory* in Tönsberg, Norway, developing cutting-edge anaerobic digestion conditions and resource recovery.

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Appendix 1 – List of parameters for French MFA systems with sources

Parameters

Parameter name	Symbol	Value	Unit	Source / Notes
Agricultural residues	AR	14000	ktons	2021 Methanisation report ADEME
Sewage-sludge	SS	6010	ktons	2021 Methanisation report ADEME
Industrial waste	IW	9000	ktons	2021 Methanisation report ADEME
Municipal waste	MW	1270	ktons	2021 Methanisation report ADEME
Deconditioning rate	DR	5%	%	2021 Methanisation report ADEME
Losses during hygienisation/pasteurisation	LDHP	5%	%	2021 Methanisation report ADEME
Biomethane production from biogas	BP	4,3	TWh	www.chambre-agriculture.fr
Electricity production from biogas	EP	2,8	TWh	2021 Methanisation report ADEME
Heat production from biogas	HP	4,5	TWh	2021 Methanisation report ADEME
CHP Heat efficiency	HE	60%	%	Solid Waste Technology & management book, 2011, Christensen T.H.
CHP Power efficiency	PE	25%	%	Solid Waste Technology & management book, 2011, Christensen T.H.
CHP overall efficiency	OE	79%	%	Solid Waste Technology & management book, 2011, Christensen T.H.
Energy efficiciency of the purification step	EEP	99,5%	%	Solid Waste Technology & management book, 2011, Christensen T.H.
Density of biogas	DB	1,15	kg/m3	www.biogaz-energie-renouvelable.info
PCS of biogas	PCS	7,00	kWh/m3	www.biogaz-energie-renouvelable.info
Mass of oxygen per mass of biogas	MO	1,19	kgO2/kgbiogas	
Mass of carbon dioxyde per mass of biogas	MC	1,63	kgCO2/kgbiogas	$C_{30}H_{50}O_{25} + 30O_2 = 30CO_2 + 25H_2O$
Mass of water per mass of biogas	MW	0,56	kgH2O/kgbiogas	
H2S content in biogas	HSC	0,50%	%	2015, Methanisation technical sheet, ADEME
Efficiency of H2S cleaning	EHSC	95,00%	%	2015, Methanisation technical sheet, ADEME
H2O content in biogas (volume)	HOC	6,00%	%	www.biogaz-energie-renouvelable.info
Density of H2O (gas)	DHO	0,59	kg/m3	www.biogaz-energie-renouvelable.info
CO2 content in biogas (volume)	COC	26,00%	%	www.biogaz-energie-renouvelable.info
Density of CO2	DCO	1,87	kg/m3	www.biogaz-energie-renouvelable.info
Percentage of mush becoming digestate	PM	85,00%	%	www.methafrance.fr
Percentage of digestate for direct spreading	PDS	55,00%	%	www.methafrance.fr
Percentage of digestate for phase separation	PPS	45,00%	%	www.methafrance.fr
Percentage of liquid phase after phase separation	PLP	17,6%	%	www.methafrance.fr
Percentage of solid phase after phase separation	PSP	6,6%	%	www.methafrance.fr
Percentage sent to post treatment after phase separation	PPT	75,56%	%	www.methafrance.fr
Percentage of primary energy produced required for digestor heating	PPE	11,50%	%	2015, Methanisation technical sheet, ADEME
Energy content of agricultural residues	ECA	1,69	kWh/kg	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Energy content of sewage sludge	ECS	0,54	kWh/kg	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Energy content of industrial waste (mainly food-processing)	ECI	0,82	kWh/kg	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Energy content of municipal waste	ECM	0,99	kWh/kg	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Percentage of electricity produced required for deconditioning	PED	5,00%	%	2015, Methanisation technical sheet, ADEME
Energy consumption of the thermal pre-treatment process	ECT	66,58	kWh/tons	2021, *Guide de mise en œuvre de l'hygienisation en méthanisation* , Adeline Haumont, Martin Debat, Nicolas Julien, Jeanne Lencauchez
Energy losses through the digestor walls (from energy input)	ELD	10,00%	%	2015, Methanisation technical sheet, ADEME
Nitrogen content in agricultural residues	NAR	5,23E-03	ktonsN/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Nitrogen content in sewage sludge	NSS	1,60E-03	ktonsN/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Nitrogen content in industrial waste	NIW	3,70E-03	ktonsN/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Nitrogen content in municipal waste	NMW	7,62E-03	ktonsN/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Phosphorus content in agricultural residues	PAR	5,59E-04	ktonsP/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Phosphorus content in sewage sludge	PSS	1,00E-03	ktonsP/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Phosphorus content in industrial waste	PIW	4,00E-04	ktonsP/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Phosphorus content in municipal waste	PMW	8,88E-04	ktonsP/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Potassium content in agricultural residues	KAR	4,88E-03	ktonsK/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Potassium content in sewage sludge	KSS	2,00E-04	ktonsK/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Potassium content in industrial waste	KIW	7,00E-04	ktonsK/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Potassium content in municipal waste	KMW	2,40E-03	ktonsK/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Nutrient content in undesirable to incineration	NUI	0	ktons/ktons	Hypothesis
%N from digestate for phase separation to liquid phase	NLP	95%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%N from digestate for phase separation to solid phase	NSPS	0,4%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%N from digestate for phase separation to post-treament	NSPP	5%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%P from digestate for phase separation to liquid phase	PLP	25%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%P from digestate for phase separation to solid phase	PSPS	6%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%P from digestate for phase separation to post-treament	PSPP	69%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%K from digestate for phase separation to liquid phase	KLP	80%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%K from digestate for phase separation to solid phase	KSPS	1,6%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%K from digestate for phase separation to post-treatment	KSPP	18,4%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web

Appendix 2 – List of parameters for Norwegian MFA systems with sources

Parameters

Parameter name	Symbol	Value	Unit	Source / Notes
Agricultural residues	AR	630	ktons	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Sewage-sludge	SS	123	ktons	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Industrial waste	IW	117	ktons	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Municipal waste	MW	300	ktons	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Aquaculture waste	AW	78	ktons	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Deconditioning rate	DR	5%	%	2021 Methanisation report ADEME
Losses during hygienisation/pasteurisation	LDHP	5%	%	2021 Methanisation report ADEME
Total biogas production in Norway	BP	0,9	TWh	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Share of biogas to biofuel Norway	EP	40%		2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Share of biogas to CHP Norway	HP	60%		2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
CHP Heat efficiency	HE	60%	%	Solid Waste Technology & management book, 2011, Christensen T.H.
CHP Power efficiency	PE	25%	%	Solid Waste Technology & management book
Energy efficiciency of the purification step	EEP	99,5%	%	Solid Waste Technology & management book, 2011, Christensen T.H.
Density of biogas	DB	1,15	kg/m3	www.biogaz-energie-renouvelable.info
PCS of biogas	PCS	7,00	kWh/m3	www.biogaz-energie-renouvelable.info
Mass of oxygen per mass of biogas	MO	1,19	kgO2/kgbiogas	$C_{30}H_{50}O_{25} + 30O_2 = 30CO_2 + 25H_2O$
Mass of carbon dioxyde per mass of biogas	MC	1,63	kgCO2/kgbiogas	
Mass of water per mass of biogas	MW	0,56	kgH2O/kgbiogas	
H2S content in biogas	HSC	0,50%	%	2015, Methanisation technical sheet, ADEME
Efficiency of H2S cleaning	EHSC	95,00%	%	2015, Methanisation technical sheet, ADEME
H2O content in biogas (volume)	HOC	6,00%	%	www.biogaz-energie-renouvelable.info
Density of H2O (gas)	DHO	0,59	kg/m3	www.biogaz-energie-renouvelable.info
CO2 content in biogas (volume)	COC	26,00%	%	www.biogaz-energie-renouvelable.info
Density of CO2	DCO	1,87	kg/m3	www.biogaz-energie-renouvelable.info
Percentage of mush becoming digestate	PM	85,00%	%	www.methafrance.fr
Percentage of digestate for direct spreading	PDS	55,00%	%	www.methafrance.fr
Percentage of digestate for phase separation	PPS	45,00%	%	www.methafrance.fr
Percentage of liquid phase after phase separation	PLP	10,0%	%	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Percentage of solid phase sent to post treatment after phase separation	PPT	85,0%	%	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Percentage of primary energy produced required for digestor heating	PPE	11,50%	%	2015, Methanisation technical sheet, ADEME
Energy content of agricultural residues	ECA	1,69E-03	TWh/ktons	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Energy content of sewage sludge	ECS	5,40E-04	TWh/ktons	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Energy content of industrial waste (mainly food-processing)	ECI	8,21E-04	TWh/ktons	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Energy content of municipal waste	ECM	9,92E-04	TWh/ktons	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Energy content of aquaculture waste	ECAW	9,28E-04	TWh/ktons	2019, Carbon Limits report, *Ressursgrunnlaget for produksjon av biogass i Norge i 2030*
Percentage of electricity produced required for deconditioning	PED	5,00%	%	2015, Methanisation technical sheet, ADEME
Energy consumption of the thermal pre-treatment process	ECT	66,58	kWh/tons	2021, *Guide de mise en œuvre de l'hygienisation en méthanisation* , Adeline Haumont, Martin Debat, Nicolas Julien, Jeanne Lencauchez
Energy losses through the digestor walls (from energy input)	ELD	10,00%	%	2015, Methanisation technical sheet, ADEME
Nitrogen content in agricultural residues	NAR	5,23E-03	ktonsN/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Nitrogen content in sewage sludge	NSS	1,60E-03	ktonsN/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Nitrogen content in industrial waste	NIW	3,70E-03	ktonsN/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Nitrogen content in municipal waste	NMW	7,62E-03	ktonsN/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Nitrogen content in aquaculture waste	NAW	3,30E-03	ktonsN/ktons	Ndeye Aida Ndiaye, Halima Maiguizo-Diagne, Hamet Diaw Diadhiou, Waly Ndianco Ndiaye, Fulgence Diedhiou, et al.. Methanogenic and fertilizing potential of aquaculture waste. Reviews in Aquaculture, 2020, 12 (3), pp.1435-1444. 10.1111/raq.12390 . hal-02619771
Phosphorus content in agricultural residues	PAR	5,59E-04	ktonsP/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Phosphorus content in sewage sludge	PSS	1,00E-03	ktonsP/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Phosphorus content in industrial waste	PIW	4,00E-04	ktonsP/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Phosphorus content in municipal waste	PMW	8,88E-04	ktonsP/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Phosphorus content in aquaculture waste	PAW	2,20E-03	ktonsP/ktons	Ndeye Aida Ndiaye, Halima Maiguizo-Diagne, Hamet Diaw Diadhiou, Waly Ndianco Ndiaye, Fulgence Diedhiou, et al.. Methanogenic and fertilizing potential of aquaculture waste. Reviews in Aquaculture, 2020, 12 (3), pp.1435-1444. 10.1111/raq.12390 . hal-02619771
Potassium content in agricultural residues	KAR	4,88E-03	ktonsK/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Potassium content in sewage sludge	KSS	2,00E-04	ktonsK/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Potassium content in industrial waste	KIW	7,00E-04	ktonsK/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Potassium content in municipal waste	KMW	2,40E-03	ktonsK/ktons	2023, The current Nordic biogas and biofertilizer potential, Axel Lindfors & Roozbeh Feiz
Potassium content in aquaculture waste	KAW	1,00E-04	ktonsK/ktons	Ndeye Aida Ndiaye, Halima Maiguizo-Diagne, Hamet Diaw Diadhiou, Waly Ndianco Ndiaye, Fulgence Diedhiou, et al.. Methanogenic and fertilizing potential of aquaculture waste. Reviews in Aquaculture, 2020, 12 (3), pp.1435-1444. 10.1111/raq.12390 . hal-02619771
Nutrient content in undesirable to incineration	NUI	0	ktons/ktons	Hypothesis
%N from digestate for phase separation to liquid phase	NLP	95%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%N from digestate for phase separation to solid phase	NSPP	5%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%P from digestate for phase separation to liquid phase	PLP	25%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%P from digestate for phase separation to solid phase	PSPS	75%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%K from digestate for phase separation to liquid phase	KLP	80%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web
%K from digestate for phase separation to solid phase	KSPS	20,0%	%	www2.agroparistech.fr/IMG/pdf/utilisation_des_digestats_en_agriculture_-_web

Appendix 3 – Python program for the French system

```
from uncertainty_analysis import *
#for clean coding
import warnings
import random
from typing import List, Tuple
#for further exploration
import numpy as np
import matplotlib.pyplot as plt
import time
import pandas as pd

parameters_df = pd.read_excel('Uncertainties Python France.xlsx',
sheet_name='parameters')
parameters_df

#read your excel for all parameters
parameters_df = pd.read_excel('Uncertainties Python France.xlsx',
sheet_name= 'parameters').fillna(0)
#create empty list to store the parameter objects in
parameter_list = []
#iterate over all paraneters in your dataframe
for label,parameter in parameters_df.iterrows():
    #initialize a new object for each parameter with the entries in the
excel
    p = ScalarParameter(name= parameter['Parameters'], short_name=
parameter['Symbol'], \
        unit= parameter['Units'], distribution= parameter['Distribution'],
value1= parameter['dp1'],\
         value2= parameter['dp2'], value3= parameter['dp3'], value4=
parameter['dp4'])

    #visualize distribution of each parameter
    p.plot_samples(100000)

    #store parameter in list
    parameter_list.append(p)

sample_bb = Sampler(parameter_list)
sample_bb.sample()
plot_AR_ECI = sample_bb.plot_2D('AR', 'ECI')

def biogas_production (parameters: list):
    [AR, SS, IW, MW, k_10, k_20, DB, PCS, k_341, k_342, k_343, HSC, EHSC,
HOC, DHO, COC, DCO, PM, PDS, PPS, SPLP, PSP, PPT, ECA, ECS, ECI, ECMW, PED,
ECT, ECM, PPE, ELD, BP, EP, HP, HE, PE, OE, EEP, NAR, NSS, NIW, NMW, PAR,
PSS, PIW, PMW, KAR, KSS, KIW, KMW, NLP, NSPS, NSPP, PLP, PSPS, PSPP, KLP,
KSPS, KSPP] = parameters
    A011 = AR
    A012 = SS
    A013 = IW
    A014 = MW
    A10 = (AR+SS+IW+MW)*k_10
    A12 = (AR+SS+IW+MW)*(1-k_10)
    A20 = (AR+SS+IW+MW)*(1-k_10)*k_20
    A23 = (AR+SS+IW+MW)*(1-k_10)*(1-k_20)
    A34 = (EP+HP)*DB/(OE*PCS)
    A35 = BP*DB/(EEP*PCS)
    A36 = (AR+SS+IW+MW)*(1-k_10)*(1-k_20)*PM
```

```
    A30 = (AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-
BP*DB/(EEP*PCS)
    A04 = (EP+HP)*DB*k_341/(OE*PCS)
    A401 = (EP+HP)*DB*k_343/(OE*PCS)
    A402 = (EP+HP)*DB*k_342/(OE*PCS)
    A501 = BP*DB*(1-COC*DCO+HOC*DHO+HSC*EHSC)/(EEP*PCS)
    A502 = BP*DB*COC*DCO/(EEP*PCS)
    A503 = BP*DB*HOC*DHO/(EEP*PCS)
    A504 = BP*DB*HSC*EHSC/(EEP*PCS)
    A60 = (AR+SS+IW+MW)*(1-k_10)*(1-k_20)*PM*PDS
    A67 = (AR+SS+IW+MW)*(1-k_10)*(1-k_20)*PM*PPS
    A701 = (AR+SS+IW+MW)*(1-k_10)*(1-k_20)*PM*PPS*SPLP
    A702 = (AR+SS+IW+MW)*(1-k_10)*(1-k_20)*PM*PPS*PSP
    A703 = (AR+SS+IW+MW)*(1-k_10)*(1-k_20)*PM*PPS*PPT
    A704 = (AR+SS+IW+MW)*(1-k_10)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT))
    B011 = AR*ECA
    B012 = SS*ECS
    B013 = IW*ECI
    B014 = MW*ECMW
    B015 = EP*PED
    B12 = (((EP+HP)/OE)+(BP/EEP))*(1+PPE*ELD-PPE)*(1+k_20/(1-k_20))-
(AR+SS+IW+MW)*(1-k_10)*ECT
    B10 = AR*ECA+SS*ECS+IW*ECI+MW*ECMW+EP*PED-
(((EP+HP)/OE)+(BP/EEP))*(1+PPE*ELD-PPE)*(1+k_20/(1-k_20))-(AR+SS+IW+MW)*(1-
k_10)*ECT
    B02 = (AR+SS+IW+MW)*(1-k_10)*ECT
    B23 = (((EP+HP)/OE)+(BP/EEP))*(1+PPE*ELD-PPE)
    B20 = ((((EP+HP)/OE)+(BP/EEP))*(1+PPE*ELD-PPE))/(1-k_20)*k_20
    B03 = (((EP+HP)/OE)+(BP/EEP))*PPE
    B34 = (EP+HP)/OE
    B35 = BP/EEP
    B30 = (((EP+HP)/OE)+(BP/EEP))*PPE*ELD
    B401 = EP
    B402 = HP
    B403 = (EP+HP)*((1/OE) - 1)
    B501 = BP
    B502 = BP*((1/EEP)-1)
    C011 = AR*NAR
    C012 = SS*NSS
    C013 = IW*NIW
    C014 = MW*NMW
    C12 = AR*NAR+SS*NSS+IW*NIW+MW*NMW
    C23 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW)*(1-k_20)
    C20 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW)*k_20
    C34 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW)*((1-k_20)-((AR+SS+IW+MW)*(1-
k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-
BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))
    C30 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW)/((AR+SS+IW+MW)*(1-
k_10))*((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-
BP*DB/(EEP*PCS))
    C45 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW)*((1-k_20)-((AR+SS+IW+MW)*(1-
k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-
BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PPS
    C40 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW)*((1-k_20)-((AR+SS+IW+MW)*(1-
k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-
BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PDS
    C501 = ((AR*NAR+SS*NSS+IW*NIW+MW*NMW)*((1-k_20)-((AR+SS+IW+MW)*(1-
k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-
BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PPS-
(AR*NAR+SS*NSS+IW*NIW+MW*NMW)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT)))*NLP
```

```
    C502 = ((AR*NAR+SS*NSS+IW*NIW+MW*NMW)*((1-k_20)-((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PPS-(AR*NAR+SS*NSS+IW*NIW+MW*NMW)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT)))*NSPS
    C503 = ((AR*NAR+SS*NSS+IW*NIW+MW*NMW)*((1-k_20)-((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PPS-(AR*NAR+SS*NSS+IW*NIW+MW*NMW)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT)))*NSPP
    C504 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT))
    D011 = AR*PAR
    D012 = SS*PSS
    D013 = IW*PIW
    D014 = MW*PMW
    D12 = AR*PAR+SS*PSS+IW*PIW+MW*PMW
    D23 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW)*(1-k_20)
    D20 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW)*k_20
    D34 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW)*((1-k_20)-((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))
    D30 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW)/((AR+SS+IW+MW)*(1-k_10))*((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))
    D45 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW)*((1-k_20)-((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PPS
    D40 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW)*((1-k_20)-((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PDS
    D501 = ((AR*PAR+SS*PSS+IW*PIW+MW*PMW)*((1-k_20)-((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PPS-(AR*NAR+SS*NSS+IW*NIW+MW*NMW)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT)))*PLP
    D502 = ((AR*PAR+SS*PSS+IW*PIW+MW*PMW)*((1-k_20)-((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PPS-(AR*NAR+SS*NSS+IW*NIW+MW*NMW)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT)))*PSPS
    D503 = ((AR*PAR+SS*PSS+IW*PIW+MW*PMW)*((1-k_20)-((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PPS-(AR*NAR+SS*NSS+IW*NIW+MW*NMW)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT)))*PSPP
    D504 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT))
    E011 = AR*KAR
    E012 = SS*KSS
    E013 = IW*KIW
    E014 = MW*KMW
    E12 = AR*KAR+SS*KSS+IW*KIW+MW*KMW
    E23 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW)*(1-k_20)
    E20 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW)*k_20
    E34 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW)*((1-k_20)-((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))
    E30 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW)/((AR+SS+IW+MW)*(1-k_10))*((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))
    E45 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW)*((1-k_20)-((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PPS
    E40 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW)*((1-k_20)-((AR+SS+IW+MW)*(1-k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PDS
```

```
    E501 = ((AR*KAR+SS*KSS+IW*KIW+MW*KMW)*((1-k_20)-((AR+SS+IW+MW)*(1-
k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-
BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PPS-
(AR*NAR+SS*NSS+IW*NIW+MW*NMW)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT)))*KLP
    E502 = ((AR*KAR+SS*KSS+IW*KIW+MW*KMW)*((1-k_20)-((AR+SS+IW+MW)*(1-
k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-
BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PPS-
(AR*NAR+SS*NSS+IW*NIW+MW*NMW)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT)))*KSPS
    E503 = ((AR*KAR+SS*KSS+IW*KIW+MW*KMW)*((1-k_20)-((AR+SS+IW+MW)*(1-
k_10)*(1-k_20)*(1-PM)-(EP+HP)*DB/(OE*PCS)-
BP*DB/(EEP*PCS))/((AR+SS+IW+MW)*(1-k_10)))*PPS-
(AR*NAR+SS*NSS+IW*NIW+MW*NMW)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT)))*KSPP
    E504 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW)*(1-k_20)*PM*PPS*(1-(SPLP+PSP+PPT))


    return [A011, A012, A013, A014, A10, A12, A20, A23, A34, A35, A36, A30,
A04, A401, A402, A501, A502, A503, A504, A60, A67, A701, A702, A703, A704,
B011, B012, B013, B014, B015, B12, B10, B02, B23, B20, B03, B34, B35, B30,
B401, B402, B403, B501, B502, C011, C012, C013, C014, C12, C23, C20, C34,
C30, C40, C45, C501, C502, C503, C504, D011, D012, D013, D014, D12, D23, D20,
D34, D30, D40, D45, D501, D502, D503, D504, E011, E012, E013, E014, E12, E23,
E20, E34, E30, E40, E45, E501, E502, E503, E504], ['A011', 'A012', 'A013',
'A014', 'A10', 'A12', 'A20', 'A23', 'A34', 'A35', 'A36', 'A30', 'A04', 'A401',
'A402', 'A501', 'A502', 'A503', 'A504', 'A60', 'A67', 'A701', 'A702', 'A703',
'A704', 'B011', 'B012', 'B013', 'B014', 'B015', 'B12', 'B10', 'B02', 'B23',
'B20', 'B03', 'B34', 'B35', 'B30', 'B401', 'B402', 'B403', 'B501', 'B502',
'C011', 'C012', 'C013', 'C014', 'C12', 'C23', 'C20', 'C34', 'C30', 'C40',
'C45', 'C501', 'C502', 'C503', 'C504', 'D011', 'D012', 'D013', 'D014', 'D12',
'D23', 'D20', 'D34', 'D30', 'D40', 'D45', 'D501', 'D502', 'D503', 'D504',
'E011', 'E012', 'E013', 'E014', 'E12', 'E23', 'E20', 'E34', 'E30', 'E40',
'E45', 'E501', 'E502', 'E503', 'E504']

MC_bb = MonteCarlo(biogas_production, sample_bb)
MC_bb.analyze(iterations = 10**4, visualisations=True)

# We retrieve the means and standard deviations fron the Monte Carlo
simulation
means = np.mean(MC_bb.result_lists, axis = 1)
stdev = np.std(MC_bb.result_lists, axis= 1)
names = MC_bb.result_names

# We can now export them to Excel
results = pd.DataFrame(index = names)
results.loc[:,'means'] = means
results.loc[:,'stdev'] = stdev
results.to_excel('MFA France.xlsx', sheet_name='results')
```

Appendix 4 – Python program for the Norwegian system

```
from uncertainty_analysis import *

#for clean coding
import warnings
import random
from typing import List, Tuple

#for further exploration
import numpy as np
import matplotlib.pyplot as plt
import time
import pandas as pd

parameters_df = pd.read_excel('Uncertainties Python Norway.xlsx',
sheet_name='Parameters')
parameters_df

#read your excel for all parameters
parameters_df = pd.read_excel('Uncertainties Python Norway.xlsx',
sheet_name= 'Parameters').fillna(0)
#create empty list to store the parameter objects in
parameter_list = []
#iterate over all paraneters in your dataframe
for label,parameter in parameters_df.iterrows():
    #initialize a new object for each parameter with the entries in the
excel
    p = ScalarParameter(name= parameter['Parameters'], short_name=
parameter['Symbol'], \
        unit= parameter['Units'], distribution= parameter['Distribution'],
value1= parameter['dp1'],\
         value2= parameter['dp2'], value3= parameter['dp3'], value4=
parameter['dp4'])

    #visualize distribution of each parameter
#     p.plot_samples(100000)

    #store parameter in list
    parameter_list.append(p)

sample_bb = Sampler(parameter_list)
sample_bb.sample()
plot_AR_ECI = sample_bb.plot_2D('AR', 'KMW')

def biogas_production (parameters: list):
    [AR, SS, IW, MW, AW, k_10, k_20, DB, PCS, k_341, k_342, k_343, HSC,
EHSC, HOC, DHO, COC, DCO, PM, PDS, PPS, SPLP, PPT, ECA, ECS, ECI, ECMW,
ECAW, PED, ECT, ECM, PPE, ELD, BP, EP, HP, HE, PE, EEP, NAR, NSS, NIW, NMW,
NAW, PAR, PSS, PIW, PMW, PAW, KAR, KSS, KIW, KMW, KAW, NLP, NSPP, PLP,
PSPS, KLP, KSPS] = parameters
    A011 = AR
    A012 = SS
    A013 = IW
    A014 = MW
    A015 = AW
    A10 = (AR+SS+IW+MW+AW)*k_10
    A12 = (AR+SS+IW+MW+AW)*(1-k_10)
    A20 = (AR+SS+IW+MW+AW)*(1-k_10)*k_20
```

```
    A23 = (AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)
    A34 = BP*HP*DB/PCS
    A35 = BP*EP*DB/PCS
    A36 = (AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*PM
    A30 = (AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS
    A04 = BP*HP*DB*k_341/PCS
    A401 = BP*HP*DB*k_343/PCS
    A402 = BP*HP*DB*k_342/PCS
    A501 = BP*EP*DB*(1-COC*DCO+HOC*DHO+HSC*EHSC)/PCS
    A502 = BP*EP*DB*COC*DCO/PCS
    A503 = BP*EP*DB*HOC*DHO/PCS
    A504 = BP*EP*DB*HSC*EHSC/PCS
    A60 = (AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*PM*PDS
    A67 = (AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*PM*PPS
    A701 = (AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*PM*PPS*SPLP
    A702 = (AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*PM*PPS*PPT
    A703 = (AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*PM*PPS*(1-(SPLP+PPT))
    B011 = AR*ECA
    B012 = SS*ECS
    B013 = IW*ECI
    B014 = MW*ECMW
    B015 = AW*ECAW
    B016 = EP*PED
    B12 = BP*(HP+EP)*(1+PPE*ELD-PPE)*(1+k_20/(1-k_20))-(AR+SS+IW+MW+AW)*(1-
k_10)*ECT
    B10 = AR*ECA+SS*ECS+IW*ECI+MW*ECMW+EP*PED+AW*ECAW-
BP*(HP+EP)*(1+PPE*ELD-PPE)*(1+k_20/(1-k_20))-(AR+SS+IW+MW+AW)*(1-k_10)*ECT
    B02 = (AR+SS+IW+MW+AW)*(1-k_10)*ECT
    B23 = BP*(HP+EP)*(1+PPE*ELD-PPE)
    B20 = (BP*(HP+EP)*(1+PPE*ELD-PPE))/(1-k_20)*k_20
    B03 = BP*(HP+EP)*PPE
    B34 = BP*HP
    B35 = BP*EP
    B30 = BP*(HP+EP)*PPE*ELD
    B401 = BP*HP*PE
    B402 = BP*HP*HE
    B403 = BP*HP*(1-(PE+HE))
    B501 = BP*EP*EEP
    B502 = BP*EP*(1-EEP)
    C011 = AR*NAR
    C012 = SS*NSS
    C013 = IW*NIW
    C014 = MW*NMW
    C015 = AW*NAW
    C12 = AR*NAR+SS*NSS+IW*NIW+MW*NMW+AW*NAW
    C23 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW+AW*NAW)*(1-k_20)
    C20 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW+AW*NAW)*k_20
    C34 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW+AW*NAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))
    C30 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW+AW*NAW)/((AR+SS+IW+MW+AW)*(1-
k_10))*((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)
    C45 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW+AW*NAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))*PPS
    C40 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW+AW*NAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))*PDS
```

```
    C501 = ((AR*NAR+SS*NSS+IW*NIW+MW*NMW+AW*NAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))*PPS-
(AR*NAR+SS*NSS+IW*NIW+MW*NMW+AW*NAW)*(1-k_20)*PM*PPS*(1-(SPLP+PPT)))*NLP
    C502 = ((AR*NAR+SS*NSS+IW*NIW+MW*NMW+AW*NAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))*PPS-
(AR*NAR+SS*NSS+IW*NIW+MW*NMW+AW*NAW)*(1-k_20)*PM*PPS*(1-(SPLP+PPT)))*NSPP
    C503 = (AR*NAR+SS*NSS+IW*NIW+MW*NMW+AW*NAW)*(1-k_20)*PM*PPS*(1-
(SPLP+PPT))
    D011 = AR*PAR
    D012 = SS*PSS
    D013 = IW*PIW
    D014 = MW*PMW
    D015 = AW*PAW
    D12 = AR*PAR+SS*PSS+IW*PIW+MW*PMW+AW*PAW
    D23 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW+AW*PAW)*(1-k_20)
    D20 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW+AW*PAW)*k_20
    D34 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW+AW*PAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))
    D30 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW+AW*PAW)/((AR+SS+IW+MW+AW)*(1-
k_10))*((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)
    D45 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW+AW*PAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))*PPS
    D40 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW+AW*PAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))*PDS
    D501 = ((AR*PAR+SS*PSS+IW*PIW+MW*PMW+AW*PAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))*PPS-
(AR*PAR+SS*PSS+IW*PIW+MW*PMW+AW*PAW)*(1-k_20)*PM*PPS*(1-(SPLP+PPT)))*PLP
    D502 = ((AR*PAR+SS*PSS+IW*PIW+MW*PMW+AW*PAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))*PPS-
(AR*PAR+SS*PSS+IW*PIW+MW*PMW+AW*PAW)*(1-k_20)*PM*PPS*(1-(SPLP+PPT)))*PSPS
    D503 = (AR*PAR+SS*PSS+IW*PIW+MW*PMW+AW*PAW)*(1-k_20)*PM*PPS*(1-
(SPLP+PPT))
    E011 = AR*KAR
    E012 = SS*KSS
    E013 = IW*KIW
    E014 = MW*KMW
    E015 = AW*KAW
    E12 = AR*KAR+SS*KSS+IW*KIW+MW*KMW+AW*KAW
    E23 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW+AW*KAW)*(1-k_20)
    E20 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW+AW*KAW)*k_20
    E34 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW+AW*KAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))
    E30 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW+AW*KAW)/((AR+SS+IW+MW+AW)*(1-
k_10))*((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)
    E45 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW+AW*KAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))*PPS
    E40 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW+AW*KAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))*PDS
```

```
    E501 = ((AR*KAR+SS*KSS+IW*KIW+MW*KMW+AW*KAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))*PPS-
(AR*KAR+SS*KSS+IW*KIW+MW*KMW+AW*KAW)*(1-k_20)*PM*PPS*(1-(SPLP+PPT)))*KLP
    E502 = ((AR*KAR+SS*KSS+IW*KIW+MW*KMW+AW*KAW)*((1-k_20)-
((AR+SS+IW+MW+AW)*(1-k_10)*(1-k_20)*(1-PM)-BP*HP*DB/PCS-
BP*EP*DB/PCS)/((AR+SS+IW+MW+AW)*(1-k_10)))*PPS-
(AR*KAR+SS*KSS+IW*KIW+MW*KMW+AW*KAW)*(1-k_20)*PM*PPS*(1-(SPLP+PPT)))*KSPS
    E503 = (AR*KAR+SS*KSS+IW*KIW+MW*KMW+AW*KAW)*(1-k_20)*PM*PPS*(1-
(SPLP+PPT))


    return [A011, A012, A013, A014, A015, A10, A12, A20, A23, A34, A35, A36,
A30, A04, A401, A402, A501, A502, A503, A504, A60, A67, A701, A702, A703,
B011, B012, B013, B014, B015, B016, B12, B10, B02, B23, B20, B03, B34, B35,
B30, B401, B402, B403, B501, B502, C011, C012, C013, C014, C015, C12, C23,
C20, C34, C30, C40, C45, C501, C502, C503, D011, D012, D013, D014, D015, D12,
D23, D20, D34, D30, D40, D45, D501, D502, D503, E011, E012, E013, E014, E015,
E12, E23, E20, E34, E30, E40, E45, E501, E502, E503], ['A011', 'A012', 'A013',
'A014', 'A015', 'A10', 'A12', 'A20', 'A23', 'A34', 'A35', 'A36', 'A30', 'A04',
'A401', 'A402', 'A501', 'A502', 'A503', 'A504', 'A60', 'A67', 'A701', 'A702',
'A703', 'B011', 'B012', 'B013', 'B014', 'B015', 'B016', 'B12', 'B10', 'B02',
'B23', 'B20', 'B03', 'B34', 'B35', 'B30', 'B401', 'B402', 'B403', 'B501',
'B502', 'C011', 'C012', 'C013', 'C014', 'C015', 'C12', 'C23', 'C20', 'C34',
'C30', 'C40', 'C45', 'C501', 'C502', 'C503', 'D011', 'D012', 'D013', 'D014',
'D015', 'D12', 'D23', 'D20', 'D34', 'D30', 'D40', 'D45', 'D501', 'D502',
'D503', 'E011', 'E012', 'E013', 'E014', 'E015', 'E12', 'E23', 'E20', 'E34',
'E30', 'E40', 'E45', 'E501', 'E502', 'E503']


MC_bb = MonteCarlo(biogas_production, sample_bb)
MC_bb.analyze(iterations = 10**4, visualisations=True)


# We retrieve the means and standard deviations from the Monte Carlo
simulation
means = np.mean(MC_bb.result_lists, axis = 1)
stdev = np.std(MC_bb.result_lists, axis= 1)
names = MC_bb.result_names

# We can now export them to Excel
results = pd.DataFrame(index = names)
results.loc[:,'means'] = means
results.loc[:,'stdev'] = stdev
results.to_excel('MFA Norway.xlsx', sheet_name='results')
```

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