COMÉTHA: THE STORY

PHASE 1

2018-2019

Acknowledgements:[1]

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1. The titles and organisations mentioned correspond to Phase 1 of the Cométha project.

THE COMÉTHA PROJECT PHASE 1

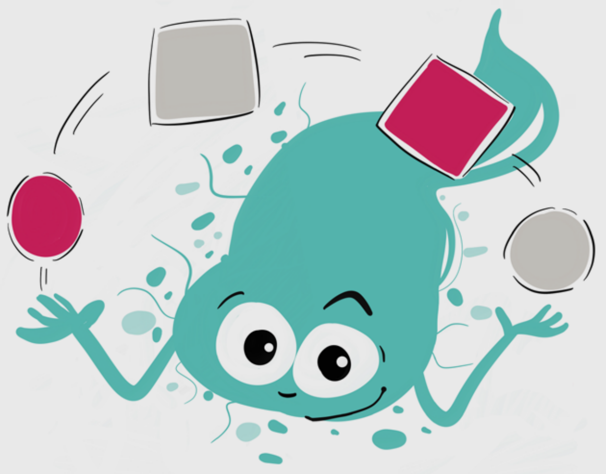
"You gave me your mud and I have turned it to gold."

The Flowers of Evil, Charles Baudelaire

Our waste is organic; our sludge and manure are precious.

The scientific and technical information in this booklet represent the extent of knowledge at the end of the first part of the adventure (the project research and development phase), completed at the end of 2019.

The results shown are from test reports and preliminary design studies submitted by the successful bidders. The potential gain described at this stage has yet to be validated (or invalidated) during the design study phase for the pilot units by the two successful bidders.



Where would we be without inquisitiveness? The beauty and nobility of science resides in the will to push back the boundaries of knowledge and investigate the secrets of matter and life without any preconceptions about the eventual outcomes.

Marie Curie

Everyone knew it was impossible, until a fool who didn't know came along and did it.

Winston Churchill

WHAT THEY SAY

The greatest challenges that the world will face in the future will be overpopulation, the scarcity of resources such as water, raw materials, oil, and so on, pandemics involving all sorts of known and new diseases, and chemical, airborne, waterborne, food-borne, and other types of pollution.

Albert Einstein

Technology innovations don't need to change the world to be significant or important.

Steve Jobs

The scientific man does not aim at an immediate result. He does not expect that his advanced ideas will be readily taken up. His work is like that of a planter – for the future. His duty is to lay the foundations for those coming after him and to show them the way. He lives, works, and hopes.

Nikola Tesla

The only route that offers any hope of a better future for all humanity is that of cooperation and partnership.

Kofi Annan

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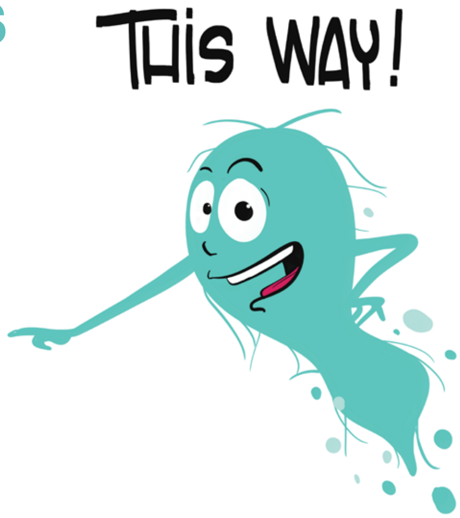


GLOSSARY

Agricultural amendment / Adding fertiliser or other material to improve soil quality in terms of structure and acidity

Anaerobic digestion / A biological process that breaks down organic matter without oxygen, producing biogas and digestate. Several anaerobic digestion pathways exist (wet, dry) and differ depending on the dryness and/or viscosity of the inputs

Batch mode / Tests performed on a closed production system operating in a discontinuous manner, in successive batches

Biochar / A solid derived from carbon-rich organic matter by thermochemical processes (pyrolysis, hydrothermal carbonisation, etc.) that can be used as fuel or an agricultural amendment

Biofuel / Fuel produced from organic matter of plant or animal origin that can be converted into thermal energy

Biogas / A gaseous product of anaerobic digestion consisting mostly of methane (CH_4), carbon dioxide (CO_2) and water vapour (H_2O); very small quantities of other gaseous compounds such as hydrogen sulphide (H_2S) are also present

Bioplastics / Plastics that are fully or partly made from materials of biological origin

Co-anaerobic digestion / A process in which anaerobic digestion takes place using inputs of varying origins

Composting / A biological anaerobic process to convert and use organic materials in the form of a standardised, stabilised, and hygienic product similar to peat, rich in humic and mineral compounds, known as compost

Digestate / A by-product of anaerobic digestion, composed mainly of organic matter that has not been converted into biogas and mineral matter (nitrogen, phosphorus)

Dryness / The percentage (by mass) of dry matter in a wet product; a product consisting of 80% water has a dryness value of 20%

Electrolysis / Chemical reaction in which substances are broken down into simple and/or composite substances under the influence of an electric current

Energy-intensive / Process or equipment that requires a large amount of energy

Gasification / High-temperature (700-1,200 °C) thermochemical conversion that takes place with little or no oxygen (anaerobic environment), converting organic matter into a synthetic gas (syngas) that can be used as a source of energy

Heating value / The quantity of thermal energy released during combustion. This value characterises an energy vector (gas, biochar, etc.)

Hydraulic residence time (HRT) / The theoretical length of time during which a particle or fluid volume being treated remains in a piece of apparatus (e.g. a mix in a reactor)

Hydrochar / A type of biochar obtained by hydrothermal carbonisation (HTC)

Hydrothermal Carbonisation (HTC) / A thermochemical process to convert organic compounds into hydrochar at high temperatures (160-260 °C) under pressure (10-50 bar) over periods of between 5 minutes and 12 hours. This process imitates the formation of brown coal (lignite) which naturally occurs over periods of between 50,000 and 50 million years

Inhibitor / Any substance or organism that slows down or hampers a process

Input / Any material introduced into a processing unit

Mesophilic / Anaerobic digestion at temperatures between 30° and 40 °C[2]

Methanation / The biological or chemical process of converting a gaseous mix consisting mainly of hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2) into methane (CH_4)

Methanogenesis / The series of metabolic pathways that produce methane in some microorganisms, known as methanogenic organisms

Methanogenic potential / BMP (Biochemical methane potential): an indicator to determine the quantity of biogas (CH_4) that can be produced by breaking down an organic substrate in the absence of oxygen

Mix / A combination of different inputs

Nutrients / Organic or mineral substances that can be directly assimilated by the soil

Organic recovery / All forms of recovery of biodegradable waste, e.g. anaerobic digestion and composting

Processing chain / In the field of waste and co-anaerobic digestion, this refers to the series of operations and procedures to treat an input (a waste treatment processing chain)

Pyro-gasification / Generic term for a set of thermochemical processes at different temperatures and pressures: pyrolysis, torrefaction, gasification, etc.

Pyrolysis / A thermochemical conversion process that takes place across a broad temperature range (350-900 °C) with little or no oxygen, allowing organic matter to be broken down into three usable by-products: syngas, biochar, and/or oil, depending on the process temperature

Reactor / A sealed tank in which anaerobic digestion takes place

Residual organic fraction (ROF) / The fraction that is mainly composed of organic matter obtained following sorting and preparation of residual household waste

Resilience / The ability of bacteria to withstand variations in a medium

2. According to René Moletta, La méthanisation chez Lavoisier Tech & Doc

Separate/selective collection / Household waste collection that is split into several differentiated flows

Spreading / A technique consisting in spreading fertiliser, amendments, or pesticides

Steam reforming / A process that, for instance, allows hydrogen to be produced from methane

Struvite / A phosphorus-rich fertilising material that can be used in agriculture

Supercritical fluid / A fluid (e.g. water) in a semi-liquid, semi-gaseous state obtained at high temperature and pressure (for water: 374 °C, 221 bar)

Sustainable Development Goals (SDGs) / Goals set by the United Nations to address the global challenges the world faces

Syngas (synthetic gas) / A gas product derived from high-temperature processes (pyrolysis, gasification), consisting mainly of nitrogen (N_2), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and hydrogen (H_2) that can be used as a source of energy

Thermochemical treatment / Changes to the structure of a product due to heat and pressure in an controlled oxygen atmosphere

Thermophilic / Anaerobic digestion taking place at temperatures between 50-65 °C[2]

TMCS / Transmembrane Chemisorption, a technology to recover ammonium sulphate

Torrefaction / Low-temperature (approx. 200-350 °C) thermochemical conversion process with little or no oxygen present that allows organic matter to be converted into biochar

Water shift reaction / A chemical reaction between water and a carbon-rich gas such as carbon monoxide or carbon dioxide with the aim of producing hydrogen

LIST OF ABBREVIATIONS

Al	Aluminium
APS	Preliminary design study
BMP	Biochemical methane potential
C	Carbon
CH_4	Methane
Cl	Chlorine
CO_2	Carbon dioxide
COD	Chemical oxygen demand
Cr	Chromium
Cu	Copper
DMA	Household and similar waste
DOC	Dissolved organic carbon
Fe	Iron
GG	Greenhouse gas
H_2S	Hydrogen sulphide
H_2SO_4	Sulphuric acid
HRT	Hydraulic residence time
HTC	Hydrothermal carbonisation
ICPE	Classified facilities subject to specific environmental protection legislation
LHV	Lower Heating Value
Mg	Magnesium
$N\text{-}NH_4$	Ammonium
$N\text{-}NO_2^-$	Nitrite
$N\text{-}NO_3^-$	Nitrate
Ni	Nickel
Nt	Total nitrogen
P_2O_5	Phosphorus pentoxide
PO_4^-	Phosphate
Pb	Lead
Pt	Total phosphorus
ROF	Residual organic fraction
SDG	Sustainable Development Goals
Si	Silicon
SRF	Solid recovered fuel
tDM	Tonne of dry matter
TOC	Total organic carbon
tRM	Tonne of raw matter
Zn	Zinc
VM	Volatile matter

INTRODUCTION

"A unique project in terms of its scale, aims, and open-mindedness"

Coralline Blind, SMET 71

This booklet is about the start of an adventure. As such it is an open door to future opportunities for cross-cutting local approaches. It is a source of inspiration for solutions and partnerships, taking stakeholders a step further in achieving the Sustainable Development Goals (SDGs), more circular use of resources, and in combating climate change.

Within the scope of Syctom, the organic fraction accounts for 30-40% of household waste. Despite the desire (and legal requirement)[3] for separate biowaste collection allowing good-quality return-to-soil, initial feedback from various localities suggests that not all of this matter will be captured by selective waste collection[4]. Considering the destiny of the residual organic fraction leads to other questions:

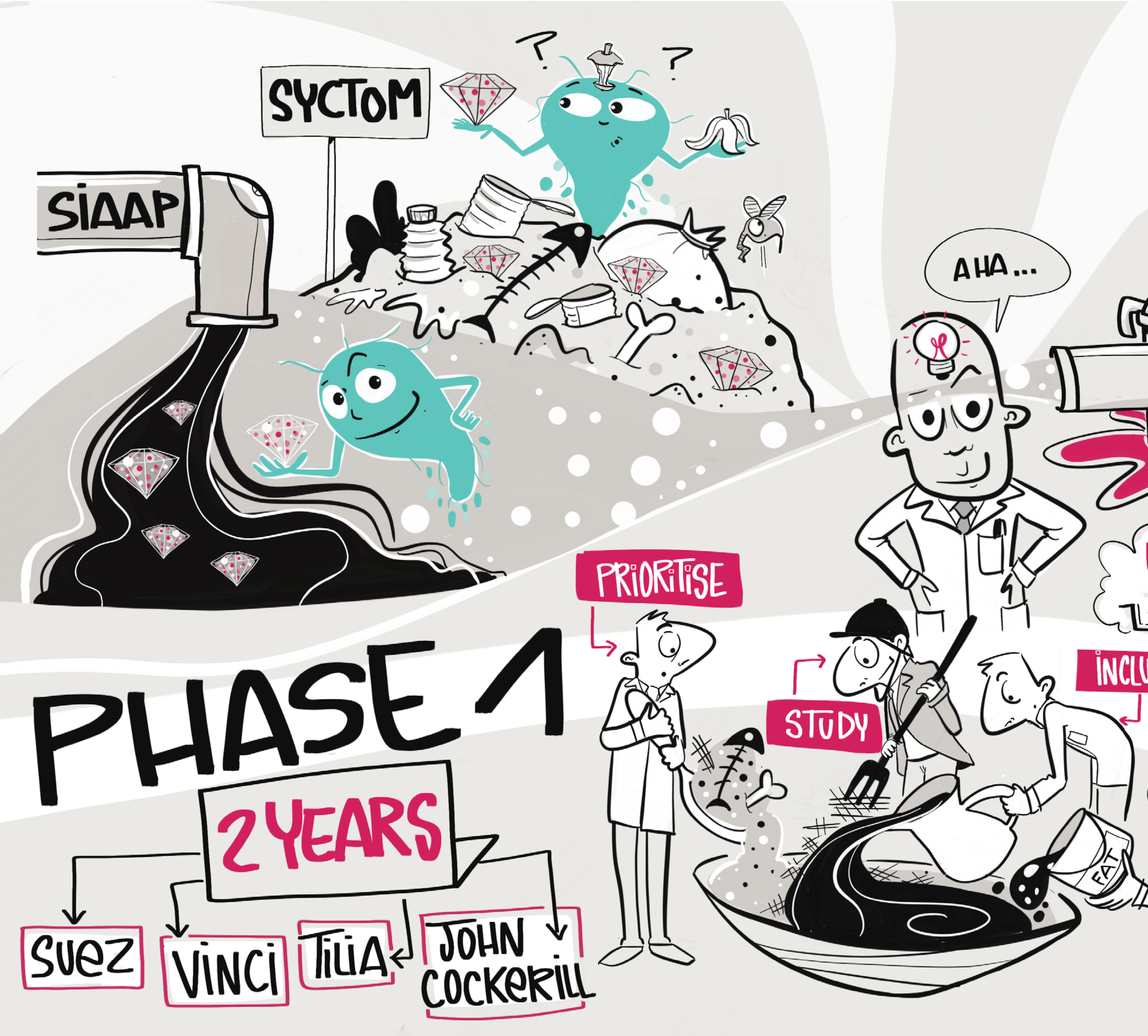
> How can more matter and energy be recovered in order to provide better resource circularity?
> Given this, how can the performance of existing incinerators be improved (inputs with less organic matter will yield a higher heating value)?

Meanwhile, SIAAP must take into consideration the uncertain destiny of urban wastewater treatment plant sludge, given that return-to-soil may not be possible in the future. New limitations could be placed on spreading and composting[5]. In addition, recovery facilities are tending to be located further and further away from the source of inputs. The current structure of the SIAAP sludge processing chain for organic recovery (47% composting, 11% spreading)[6] could therefore be compromised.

Benchmarking[7] carried out in 2016 revealed that previously, there had been little or no research into the co-anaerobic digestion of the residual organic fraction and sludge. Following this study, the Innovation Partnership was launched by Syctom and SIAAP in November 2016.

This booklet tells the story of a scientific, technological, institutional, and human adventure that is only just beginning.

3. [REF A]
4. In Lorient, 37kg/inhabitant of biowaste was collected in 2017; the figure in the Colmar Urban District was 36kg/year/inhabitant; in the Sictom Val de Saône territory in 2017 it was 32kg/inhabitant/year [REF B]. The best ratio identified to date is 69kg/inhabitant/year, achieved in a door-to-door collection by the Thann-Cernay public-private board [REF C]. On average, organic waste totals 83kg/year/inhabitant – [REF D]
5. [REF F]
6. 2019 figures.
7. [REF G]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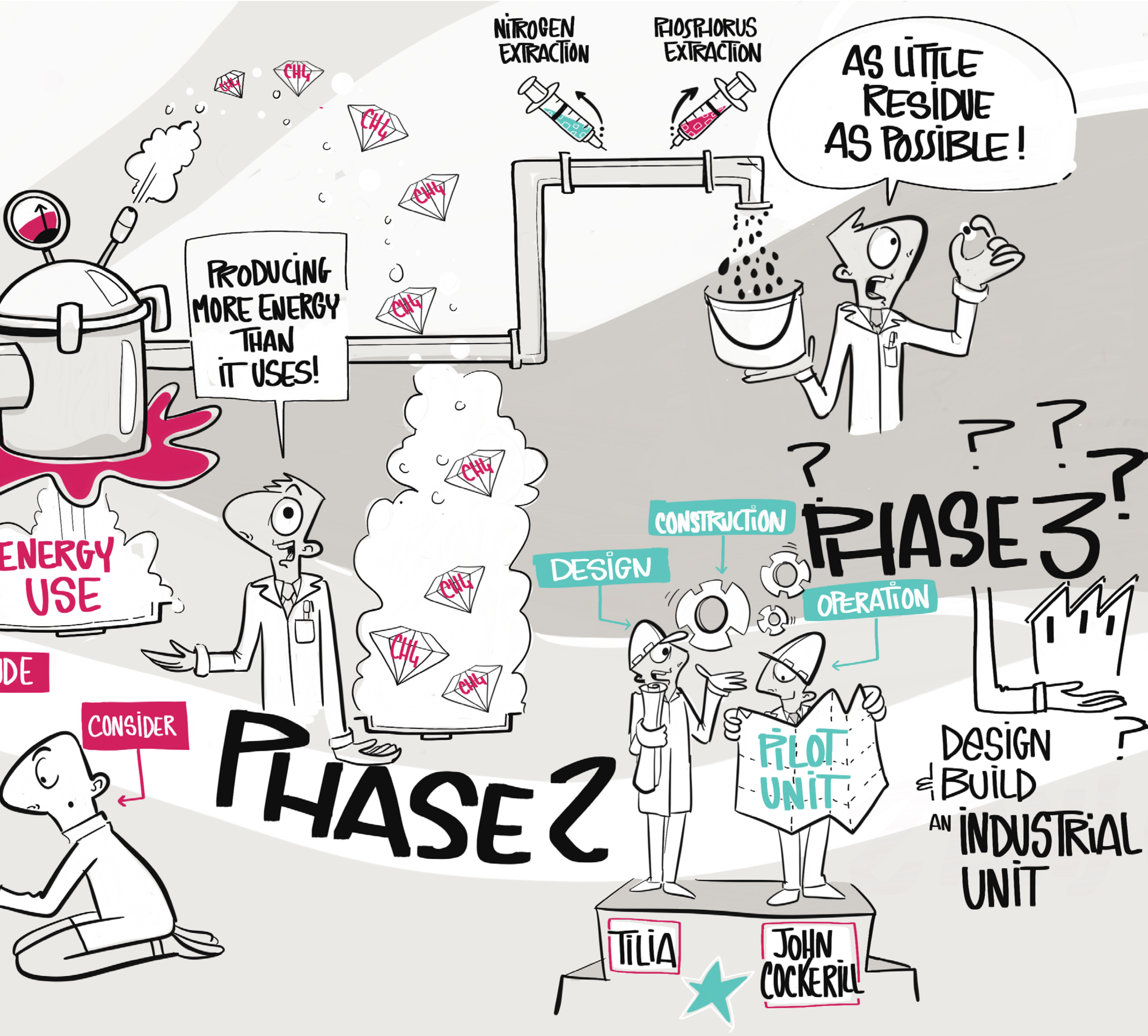

NITROGEN EXTRACTION
PHOSPHORUS EXTRACTION
AS LITTLE RESIDUE AS POSSIBLE!
CH_4
PRODUCING MORE ENERGY THAN IT USES!
ENERGY USE
CONSIDER
PHASE 2
CONSTRUCTION
DESIGN
OPERATION
PHASE 3
PILOT UNIT
DESIGN & BUILD AN INDUSTRIAL UNIT
TILIA
JOHN COCKERILL

THE HIDDEN RESOURCES IN WASTE

The argument that it is appropriate to consider recovery of the residual organic fraction (ROF) of household waste is not universally accepted by stakeholders in the sector today. **Is there enough organic matter to be recovered in this fraction despite the development of specific selective waste collection?**

One consideration is that the rules applying to food waste sorting do not apply to all organic waste; furthermore, not everybody takes part fully in this specific waste collection. Existing selective waste collection allows 40-80% of organic matter contained in household waste to be redirected to specific recovery processing chains[8] .

Embarking on the Cométha project was simply a case of deciding that not all eggs should be placed in just one basket.
Despite the awareness-raising initiatives put in place to minimise waste, encourage re-use and the installation of effective selective waste collection, some of the organic fraction nevertheless looks set to end up in the grey bin in the medium term. Wastewater treatment plants will continue to produce sludge and fatty residues. It therefore appears to make sense to identify, define, and compare ways of recovering this waste.

The aim of the Cométha project is to develop knowledge and experience:
- about possible ways of extracting the nitrogen and phosphorus in sludge, ROF, manure, and fat;
- about the potential for material and energy recovery from what is left after effective selective food waste collection has been put in place;
- about the relevance of working with input mixes with effective materials and energy recovery in mind.

76,000
tonnes per year of residual organic fraction are for the project

8. See Introduction

1. The extraction of what is recoverable and valuable from our sludge and waste

"The European Union has classified phosphorous as a critical resource.
France has no fossil phosphorus and imports all of it to add it to its crops in order to grow food."

Fabien Esculier, LEESU

France is currently 95% dependent on imports for its mineral fertilisers. The production of nitrogen-rich fertilisers is a large source of greenhouse gas emissions: it uses large quantities of natural gas. Moreover, the natural phosphates used come from non-renewable resources, of which there is a limited supply[9].

The recovery of nutrients such as phosphorus or nitrogen from sludge, waste, and manure will help make territories more resilient and thus help contribute to SDG 2 ('End hunger, achieve food security and improved nutrition, and promote sustainable agriculture') **and combat climate change.**

For equal proportions of ROF and sludge (dry matter), the relative quantities of nitrogen in ROF and sludge are 15% and 85% respectively; the figures for phosphorous are 10% and 90% respectively.[10]

During the project, the teams are looking at ammoniacal nitrogen ($N\text{-}NH_4$), total nitrogen (Nt), nitrates ($N\text{-}NO_3^-$), nitrites ($N\text{-}NO_2^-$), and phosphorus, and how they can be converted to produce the following outcomes:

- ammonium sulphate solution: used as fertiliser;
- struvite: used as slow-release agricultural fertiliser;
- concentrated ammonia solution: used in many industrial processes and sometimes in incinerator furnaces to treat gaseous nitrogen oxides.

DID YOU KNOW?

In Roman times, the nutrients contained in urine were used in agriculture.

In the early twentieth century, over half of the nitrogen from urine and fecal matter from the Paris city district was recycled and used in agriculture[11].

9. [REF H]
10. [REF P]
11. [REF I] and [REF J]

2. The limits of extraction and recovery

"Regenerative, low-energy, selective urban services"

Denis Penouel, Syctom (formerly of SIAAP)

The Cométha project is seeking to expand our knowledge of the range of forthcoming technology solutions.

The challenges involved in this project are extremely interesting from both a scientific and a technical point of view. At a time when energy is a valuable resource, **it is vital for a project like this to form part of a policy that seeks to encourage low energy use. Indeed, one of the stated aims of Syctom and SIAAP is to achieve a positive energy balance overall.** The challenge – and it is a massive one – is thus to come up with a series of solutions that use less energy than they produce.

Optimising technologies, increasing the number of technology building blocks and adding input pre-treatment processes that improve their methanogenic potential are all by definition energy-intensive.

We cannot afford to engage in the extraction and recovery of matter and energy irrespective of costs, be they economic (investment and operating costs), social (integration in dense urban environments taking into account individuals' safety and social acceptability), or environmental (the environmental impact in general and 'energy sobriety' in particular).

All the stakeholders involved have thus taken care to ensure that the energy balance of the proposed process sequencing is better than positive, and that the environmental impacts are kept to a minimum, or offset if they cannot be avoided.

In this respect, tests have demonstrated the following:

- processing a mix of different inputs can achieve better energy and environmental balances than distinct processing chains;
- the energy equilibrium of the entire processing chain is possible when energy is recovered from anaerobic digestate through thermochemical processing. This is because the residual content of the digestate is carbon-rich.

TAKEAWAYS

The implementation of thermochemical digestate processing offers potential for modernising infrastructure and adapting industries in such a way as to make them sustainable, thereby contributing to achieving Sustainable Development Goal 9 ("Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation").

3. The strength of complementary approaches

"Taking up the environmental challenges our planet is facing by playing an active role in the energy transition which France has resolved to undertake"

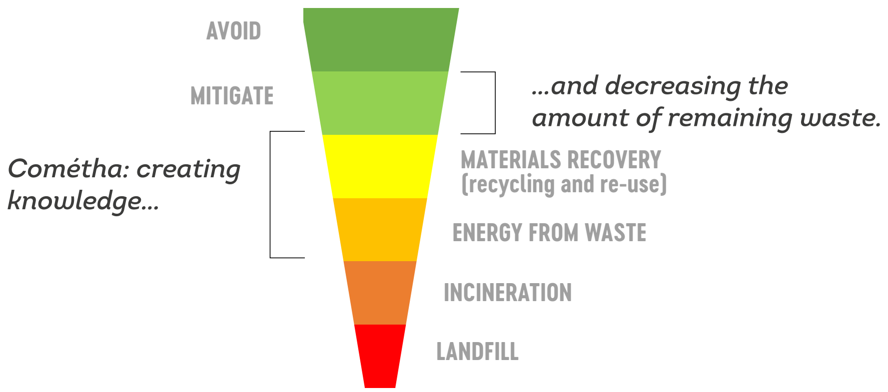
Jacques Olivier, SIAAP

The complementary nature of the approaches taken allow improved overall performance in terms of circularity and recovery, as well as a more agile stance – vital to adjust to the dramatic changes that will undoubtedly occur in a wide range of fields: return-to-soil, the scarcity of certain resources, and the importance of energy self-sufficiency.

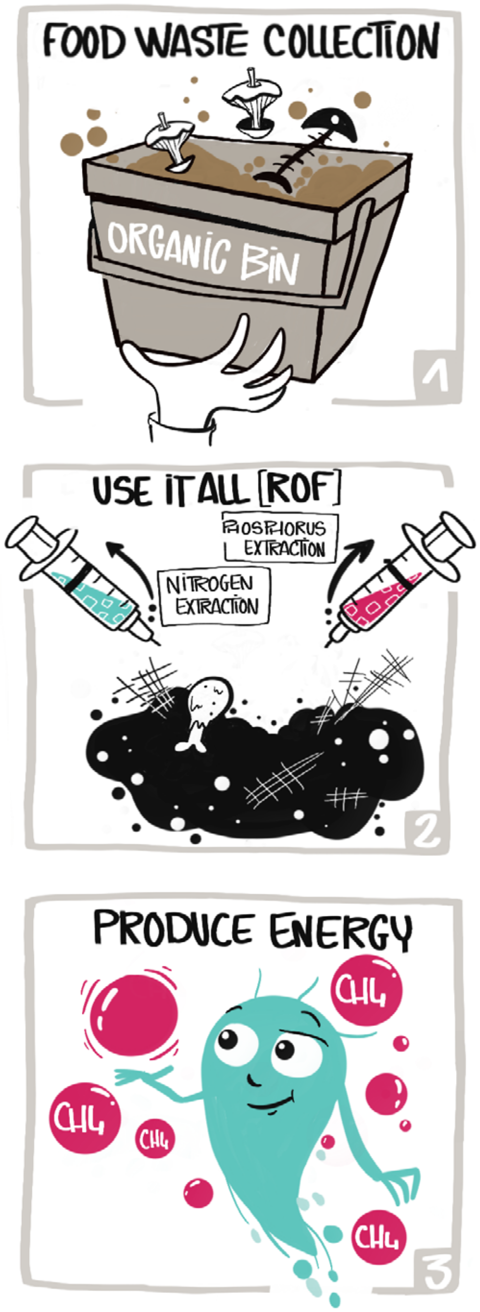
The French Environment Code *(Code de l'environnement)*[12] establishes a treatment hierarchy.
To address the forthcoming challenges, it makes sense to have a range of available solutions. To optimise recovery in all forms, these should be combined and ranked rather than be made to compete against each other.

This is what the Cométha project is all about. It starts downstream from the selective food waste sorting set out in policy and legislation, seeking to promote organic recovery and return-to-soil. The benefits include:

- recovering nutrients that are still present in the residual organic fraction of household waste so as to use matter to exhaustion;
- ultimately, energy recovery that produces more renewable energy than the processing chain in question uses.



The complementary nature of the approaches delivers better performance and more agility in order to adjust to future circumstances.



12. [REF K]

PREPARING THE FUTURE

"For several years now, we haven't been able to make progress. Innovation is clearly needed; we had to get something done, push the envelope!"

Jean-Marie Chaumel, ADEME Île-de-France

By bringing together all this knowledge and experience, the Cométha project is playing an active role in moving France along the path towards achieving Sustainable Development Goals (see pages 22-23).

To further strengthen the virtuous circle of the circular economy, the authorities will have to coordinate and adjust legislation accordingly. This project helps meet the requirements of France's Energy Transition Act[13], and at the same time identifies present-day legislative hindrances or indeed barriers. Areas where these may occur include:

- authorisations to process mixes;
- categories of facilities subject to specific environmental protection legislation ('ICPE' facilities) that are suitable for potential new technologies;
- no longer classifying extracted nutrients and other treatment by-products as waste, thus allowing for organic recovery;
- the dispatch of next-generation renewable gases in natural gas networks.

There is a need for agility, rapid change, and new frameworks where appropriate.

13. [REF A]

1. The difficult issue of 'return-to-soil'

"Nutrient recovery is in the public interest."

Fabien Esculier, LEESU

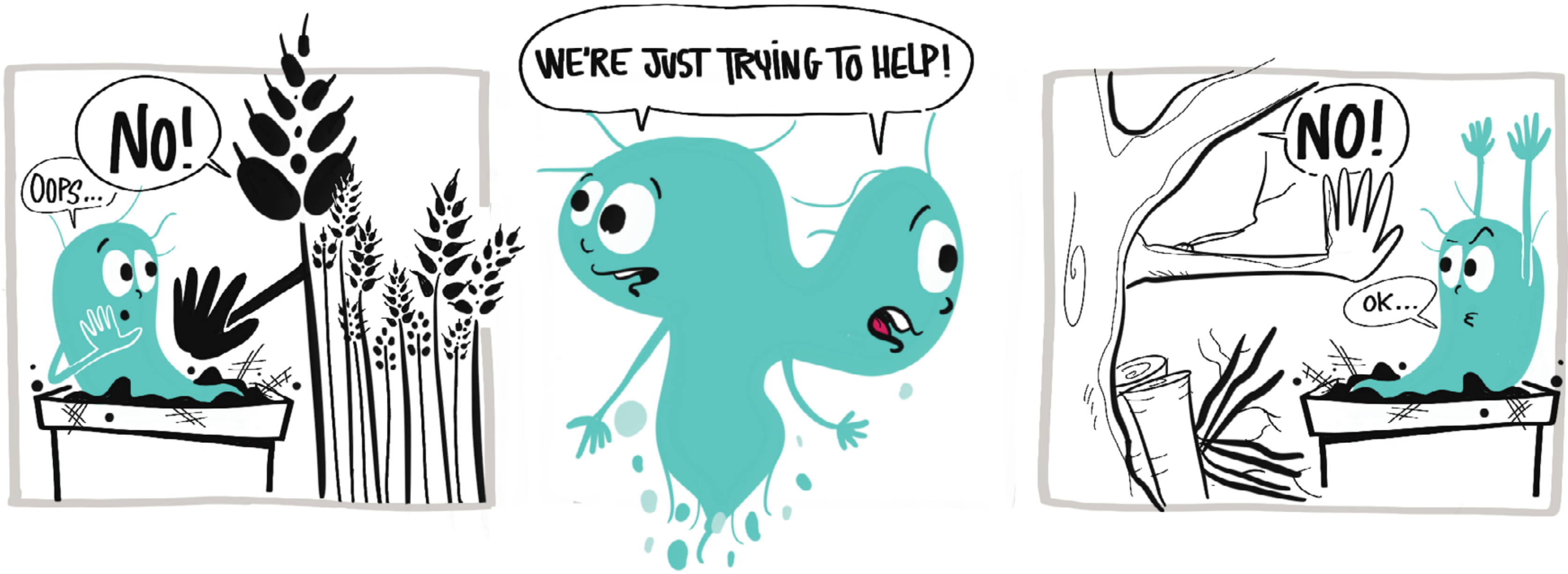
Water and waste have a role to play in the implementation of increasingly 'circular' societies. Sludge, fat from wastewater treatment, manure, and the residual organic fraction all contain many valuable resources (see chapter 1).

Projects to recover the residual organic fraction in the form of agricultural amendments are highly complex to implement for reasons of acceptability and compatibility with existing legislation in France.

The issue of sludge being returned to the soil is also at a delicate stage[14], with a possible ban on it being mixed with green waste sorted at source after 2026 and a potential decrease in the thresholds defined in France's Common Core Decree *(Décret Socle Commun)* on spreading.

RETURN-TO-SOIL STRATEGIES

The major existing barriers to return-to-soil led the project to focus on maximising energy recovery. However, the Cométha project has been put together in such a way as to ensure no doors are closed. It seeks to define the extraction capacities for nutrients (phosphorus, nitrogen) at various stages of the processing chain, on the assumption that legal and social barriers may one day be lifted.



The issue of return-to-soil: changes are vital

14. [REF E]

2. The benefits of methane

"For its '100% renewable gas by 2050' scenario, French Environmental & Energy Management Agency ADEME assumes that 30% of the gas in question will come from anaerobic digestion and 40% from thermochemical processes, notably pyro-gasification."

Anthony Mazzenga, GRTgaz

Anaerobic digestion of organic waste to produce biogas is all the more relevant in that biomethane can be stored and easily transported, particularly in dense urban areas. Natural gas transport and distribution networks are extensive, and capable of receiving and transporting additional quantities of gas.

Methane: an energy vector of the future

Biogas, a renewable clone of natural gas, consists mainly of methane, carbon dioxide, and water vapour. Once purified, the resulting biomethane can meet gas network operators' technical specifications. The regulatory environment is currently favourable to the emergence of a processing chain for biomethane (derived from anaerobic digestion or other thermochemical processes) dispatched into natural gas networks and used as a substitute in all natural gas applications. Biomethane can also be used for domestic purposes (heating, cooking, sanitary hot water) and mobile applications (such as fuel for some vehicles or to produce both heat and electricity in cogeneration).

Existing anaerobic digestion processes for the production of biogas do not break down all of the organic matter, only the part that is the most accessible to bacteria. The resulting methane production is therefore limited and generates large quantities of residue (digestate) that must be treated: this still has quite a high residual organic matter content.

Digestate is therefore suitable for thermochemical rather than biological post-treatments. The former maximise the production of gas, a large part of which can be recovered.

In a recently updated study[15], ADEME, GRDF, and GRT Gaz remind readers of the significant potential of synthetic gas production: after treatment, this can increase the quantities of methane of non-conventional origin dispatched into public natural gas transport and distribution networks. Recent crises illustrate how important it is for France to seek gas independence and make the case for speeding up investment to this end.

Towards a 100% renewable 'made in France' gas mix[16]

15. [REF L]
16. [REF M]

All renewable gas producers now have the right of access to gas distribution infrastructures[17]. Although the concept of "renewable gas" has not yet been explicitly defined in law, it seems likely that it will include all forms of syngas produced from waste and biomass.

For this right of access to be actually implemented for all projects aimed at dispatching syngas produced by thermochemical processes into the network, procedures for access to gas infrastructure (currently defined for biomethane) need to be extended to cover all natural gas qualified as "renewable". Doing so will require the compatibility of syngas produced in this way with gas network specifications to be tested and confirmed.

The emergence of a renewable methane production industry using new thermochemical treatments is faced with a number of challenges at present:

> technical issues: demonstrating industrial operability, technical and economic relevance, and the compatibility of the syngas produced with the technical specifications of natural gas grid operators;
> regulatory issues: finalising the terms of access to natural gas grids for dispatch projects (detailed studies, access to the capacity register, contractual terms of dispatch, the right to dispatch, etc.).

CO_2 emissions in the Cométha project

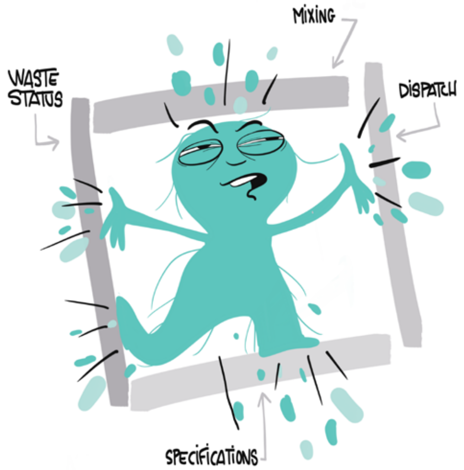
Ever since the start of the Cométha project in late 2016, various ways of mitigating the related carbon dioxide emissions have been investigated. Methanation (studied in Phase 1 by two consortiums, after which a pilot project was set up by one of the two successful bidders) is a way of maximising the conversion of carbon dioxide into methane, thus decreasing the amount of carbon dioxide produced.
Two successful bidders have also looked at recovering the carbon dioxide generated: one via the production of microalgae to consume the carbon dioxide, the other examining the possibility of industrial use after recovery.

DID YOU KNOW?

Other SIAAP and Syctom projects currently underway are testing the feasibility of using carbon dioxide to feed microalgae using carbon sinks[18] or photobioreactors in order to convert it into biofuel or bioplastic.

Although they are still in development, these carbon dioxide storage technologies are promising.

17. [REF N]
18. [REF O]



3. Aiming to change regulatory frameworks

"Let's keep anticipating"

Martial Lorenzo, former General Manager, Syctom

Phase 1 of the project has already revealed four regulatory issues:

Mixes	Categorisation	Waste status		The dispatch of new types of methane
The results of Phase 1 of the Cométha project have demonstrated the relevance of treating a mix of different inputs, rather than treatment via distinct processing chains.	New techniques relating to thermochemical processes simply cannot be placed in the same category as incineration; the thermochemical process involved is entirely different.	The by-products of thermochemical treatment are a mix of residues with a high heating value and ash.	Irrespective of the processing chain and processes involved, the nutrients extracted are qualified as waste.	Methane from co-anaerobic digestion, methanation, and pyro-gasification (i.e. from projects such as Cométha) may offer a route to a French renewable gas mix by 2050, thereby contributing to the country's gas independence.
If co-anaerobic digestion units are to be built, legislation must allow for the treatment of certain input mixes.	There need to be 'ICPE' facility classifications for torrefaction, pyrolysis, hydrothermal carbonisation and gasification.	The related residue and ash must no longer be qualified as waste if it is to be recovered instead of being buried in landfill sites.	By no longer being qualified as waste, the nutrients extracted could be repositioned as part of the circular economy. For instance, this would allow them to be returned to the soil.	Legislation allowing the dispatch of these new types of methane into the grid has yet to be developed.

Social feasibility and public perception

Water and waste and their related infrastructures are regularly faced with acceptability issues. It is likely that new technologies with which the general public are unfamiliar will give rise to environmental and/or sanitary concerns in respect of quality of life and urban integration.

The issue of perceived risks must be taken into account as early as possible in communication and consultation about projects of this type to raise awareness and win the public over on the grounds that these innovations enable more circular systems. These new treatment modes are more virtuous than those currently in place.

COMÉTHA'S CONTRIBUTION TO THE SUSTAINABLE DEVELOPMENT GOALS

The recovery of nutrients such as phosphorus and nitrogen contributes to the resilience of agricultural practices.

Maximising the conversion of organic matter into renewable gas and the reduction of the load in effluent discharged at the end of a processing chain helps mitigate water and air pollution.

Completion of pilot units will provide further knowledge and allow innovative building blocks to mature further.

Completion of the Cométha project will allow the environmental impact of existing processing chains to be significantly reduced.

The recovery of nutrien
sustainable manageme
Minimising residues and
reduce discharges into

Decreasing the load in effluent discharged at the end of a processing chain helps mitigate water pollution.

One of Cométha's primary objectives is to increase the production of renewable gas. The Cométha project is helping to promote a partnership between European stakeholders for the development of innovative technologies.

The Cométha project is helping to promote a policy focusing on innovation that stimulates the growth of companies, research laboratories, and startups. Recovering phosphorus and nitrogen helps make the use of resources more efficient.

ts contributes to more
nt of natural resources.
l by-products helps to
water and the atmosphere.

Completion of the Cométha project will help reduce damage to natural environments.

A European partnership, promoting sharing and discussion worldwide.

THE COMÉTHA PROJECT'S TECHNICAL INNOVATIONS

"Our aim, ambitious as it may be, is also to advance the cause of science."

Pierre Hirtzberger, Syctom

The approach taken here is **to give an overview of all the processing chains suggested by the successful bidders.** The idea is that a blended presentation of the projects is likely to be more instructive than reading through the details of each of the 4 preliminary projects (put forward at the end of Phase 1) in turn, and more representative of how Phase 1 actually played out. Indeed, 4 projects were undertaken in parallel during this research and development phase. This naturally led to an iterative approach for each project owner and its consultants, and to the four successful bidders being dealt with transparently, on an equal basis.

This chapter thus introduces readers to a series of questions and innovations relating to the following:
1. inputs and how they are prepared;
2. co-anaerobic digestion itself;
3. supplementary recovery from the digestate produced by anaerobic digestion;
4. thermochemical processes (including pyro-gasification);
5. methanation;
6. the recovery of nutrients (nitrogen and phosphorus).
It will also provide readers with a summary view of each of the four processing chains proposed at the preliminary design stage. Throughout chapter 3, bibliographical references are denoted by the abbreviation [REF P].

How can the work of over 100 people, 300 tests, the testing of 50 processes or combinations of processes, and the analysis of 20 tonnes of inputs be summarised in some 60 pages?

Inevitably, this is a summary, and a very brief summary at that.

Some things had to be left out.

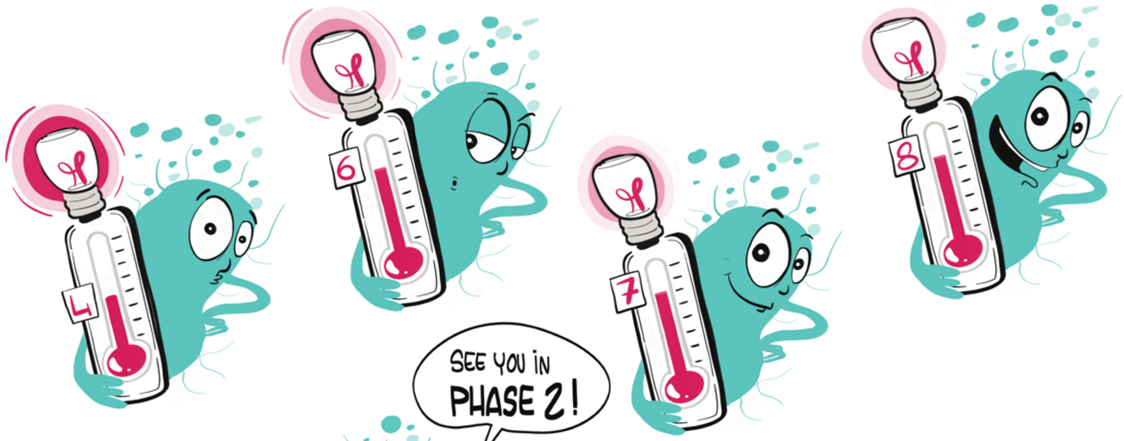
What follows is an attempt to provide insights into thermochemical conversion processes, the methanation following these processes, and information about recovering nutrients.
Not all of the technology building blocks may be included in Phase 2 of the pilot units, but that does not mean they are of no interest; presenting them in parallel provides further information and the possibility of comparing them from various perspectives.

ENVIRONMENTAL IMPACT

Doing more to seek the expression of methanogenic potential requires the addition of technologies and processes that are often energy-intensive.
The initial energy balance estimates for the pilot proposals confirm that the leading source of GG emissions from this type of processing chain is energy (85% of emissions) and more specifically, heat requirements.
It is vital to ensure that the energy balances are more than positive in order to ensure that some of the processing chain processes can operate on a self-consumption basis. Indeed, this is one of the goals SIAAP and Syctom set themselves at the launch of the project.

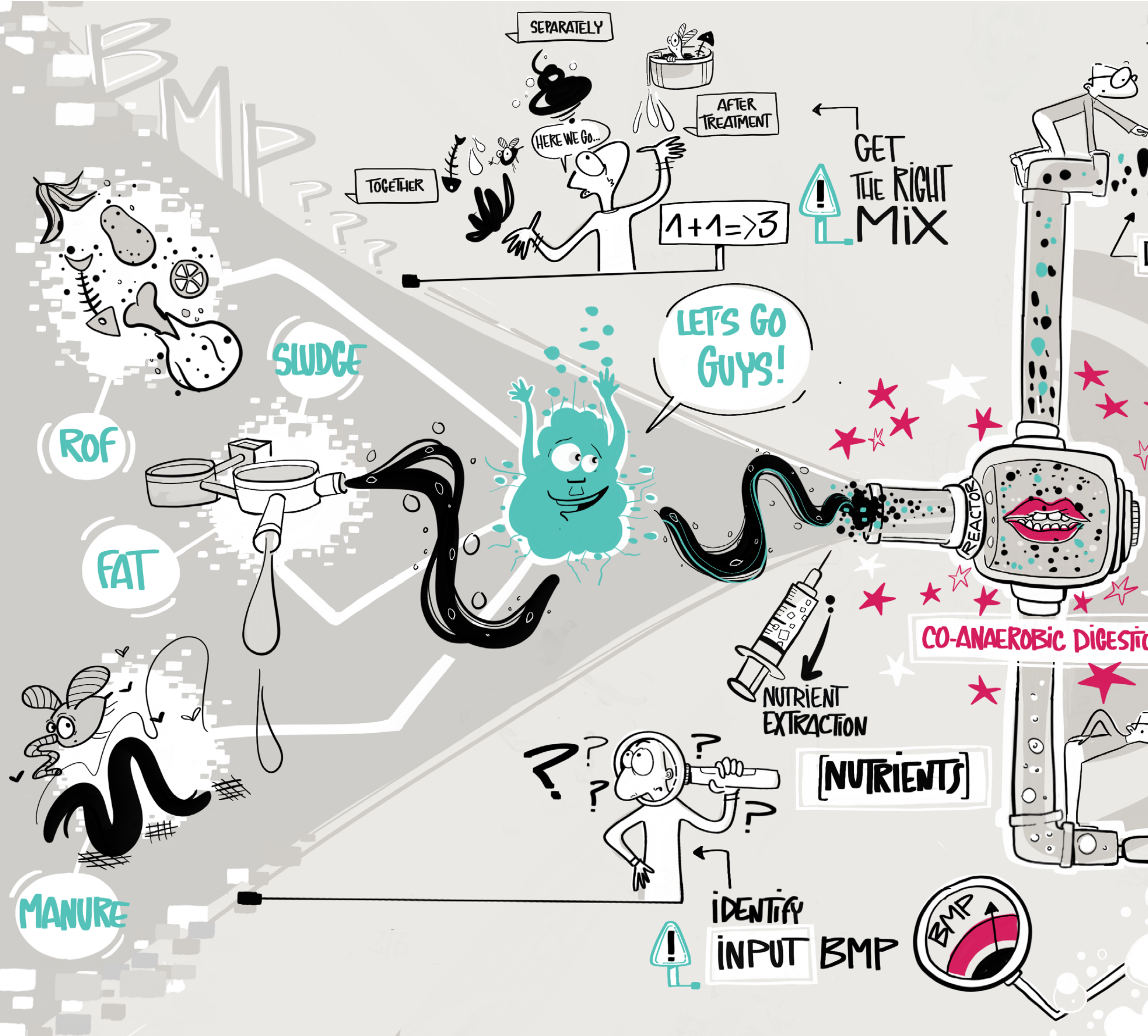
INNOVATION

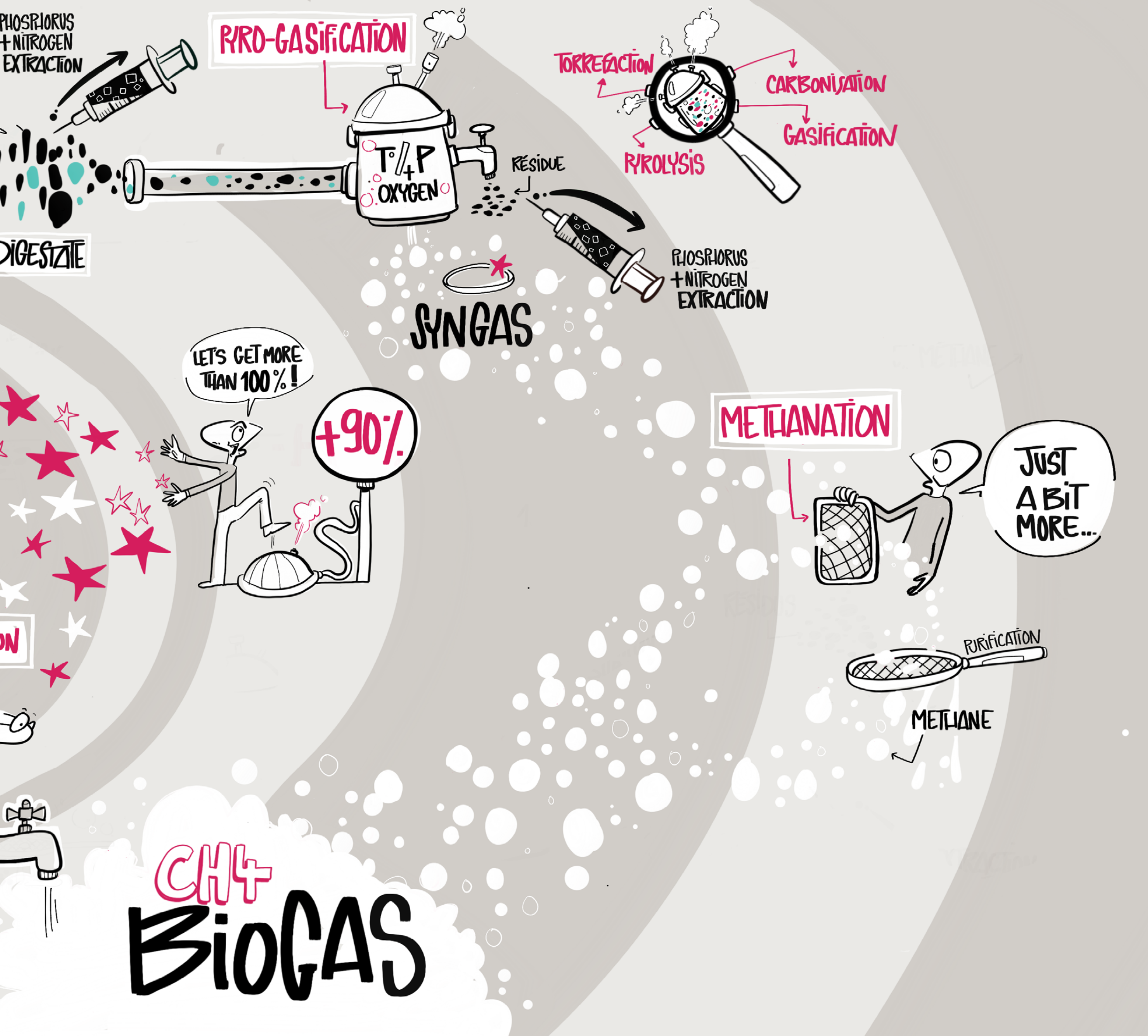
All of the proposals made by the teams were ranked on a 9-point scale in terms of their technological maturity. Level 1 corresponds to the lowest level of technological maturity. Level 4 corresponds to laboratory validation, while level 9 corresponds to a system that has been tried and tested, with successful implementations.



TOWARDS PHASE 2

While all of the processes considered in Phase 1 have potential, only some of them will be studied going forward. More detailed results will be available for these once the pilot unit phase has been completed. This logo will make it easier to identify them in the rest of this document.

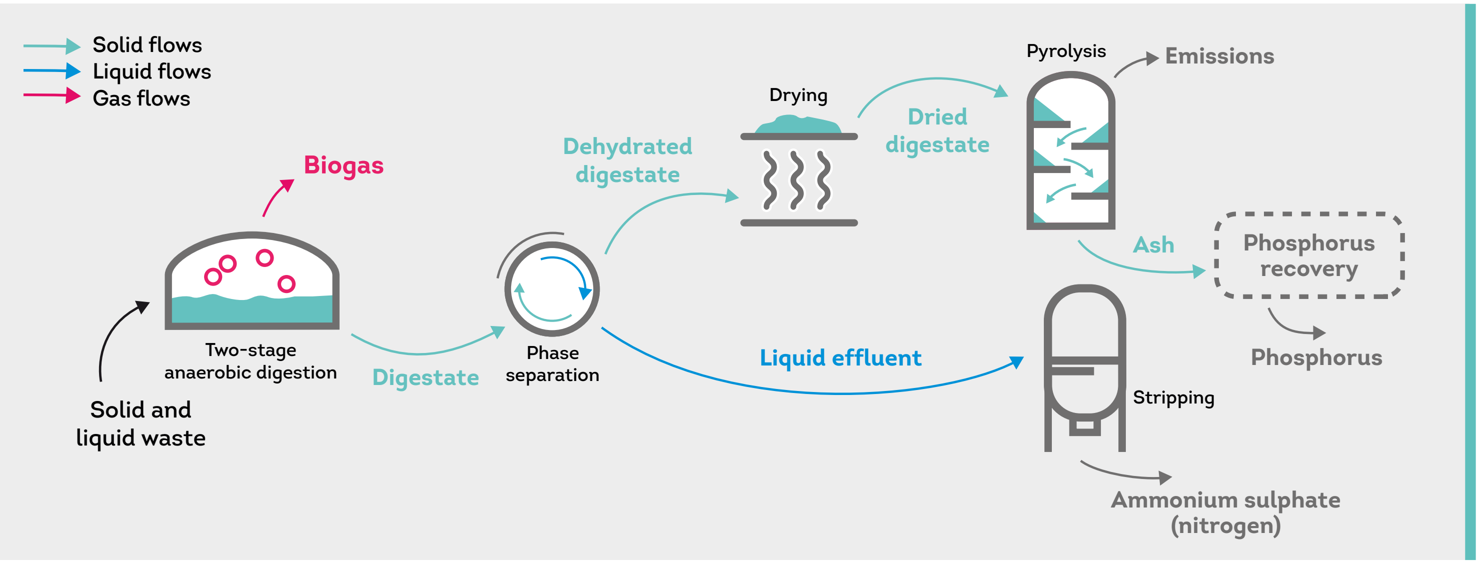

BMP
SEPARATELY
AFTER TREATMENT
HERE WE GO...
TOGETHER
1+1=>3
GET THE RIGHT MIX
ROF
SLUDGE
FAT
MANURE
LET'S GO GUYS!
REACTOR
CO-ANAEROBIC DIGESTIO
NUTRIENT EXTRACTION
[NUTRIENTS]
IDENTIFY INPUT BMP
BMP


PHOSPHORUS
+NITROGEN
EXTRACTION
PYRO-GASIFICATION
T°+P
OXYGEN
RÉSIDUE
TORREFACTION
CARBONISATION
GASIFICATION
PYROLYSIS
DIGESTATE
PHOSPHORUS
+NITROGEN
EXTRACTION
SYNGAS
LET'S GET MORE THAN 100%!
+90%
METHANATION
JUST A BIT MORE...
PURIFICATION
METHANE
CH4
BIOGAS

Complete processing chains proposed at the end of Phase 1

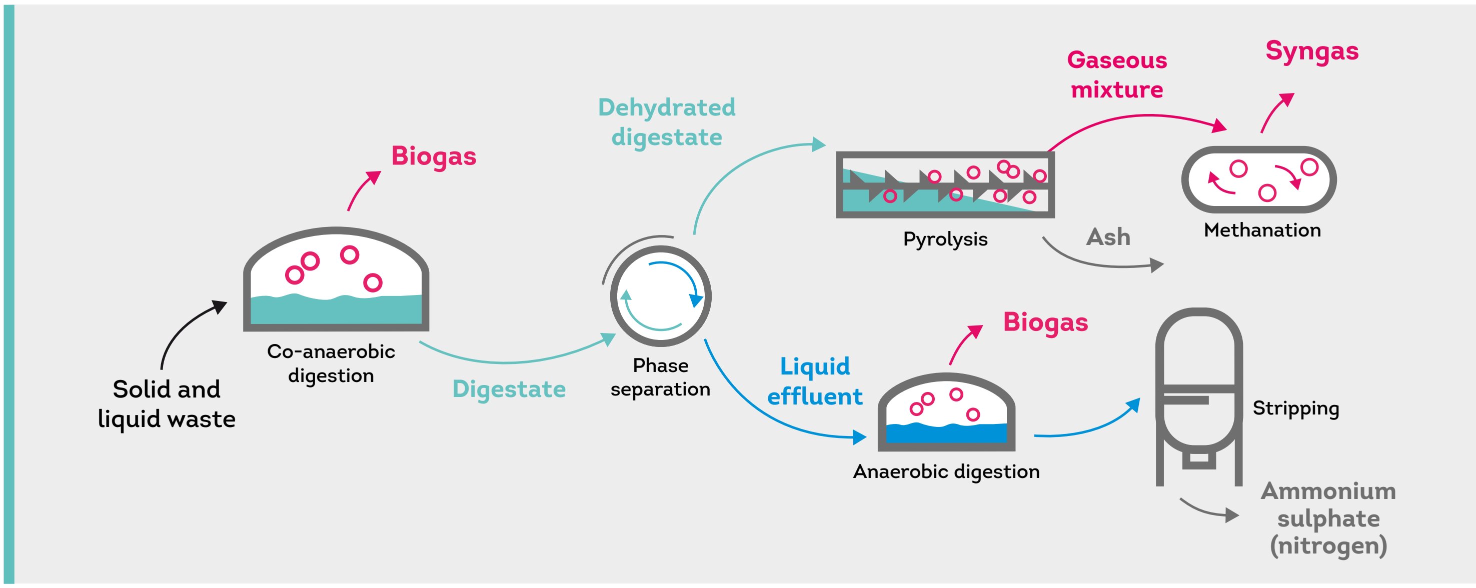
"Four different processing chains that all meet the initial criteria"

Fabrice Béline, INRAE



Two-stage co-anaerobic digestion
Pyrolysis
Stripping

Co-anaerobic digestion
Pyrolysis and methanation
Second anaerobic digestion
Stripping

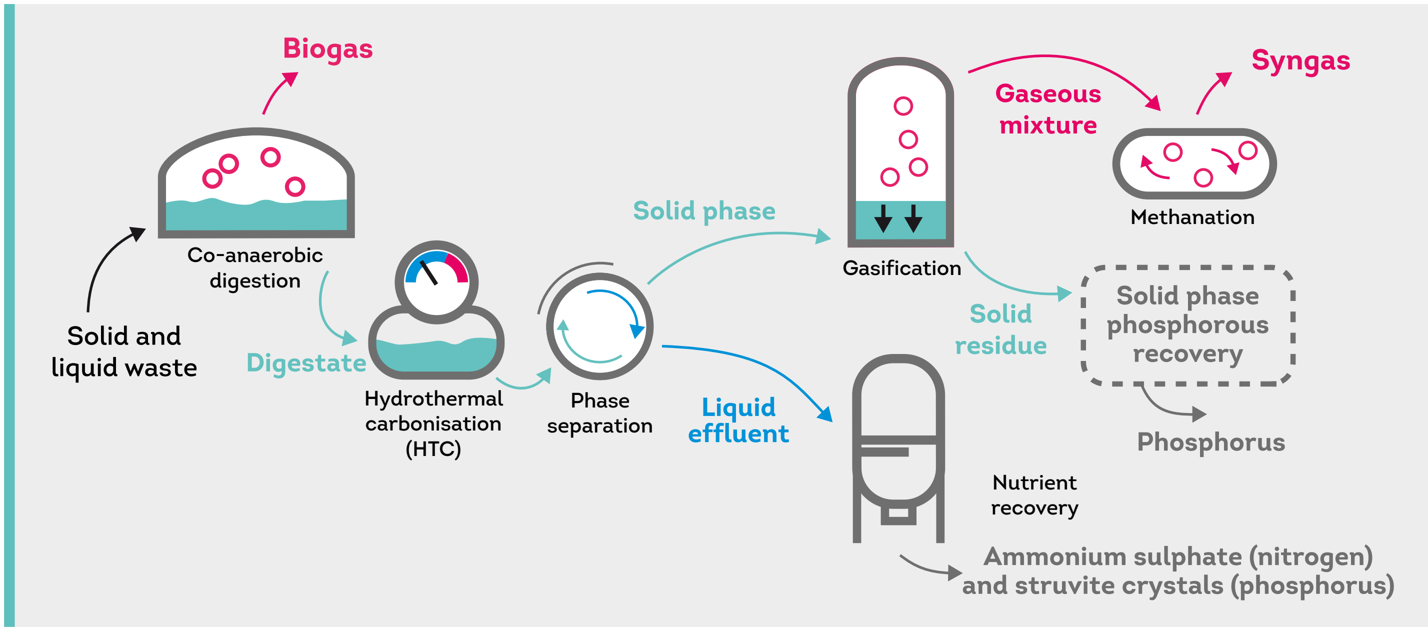


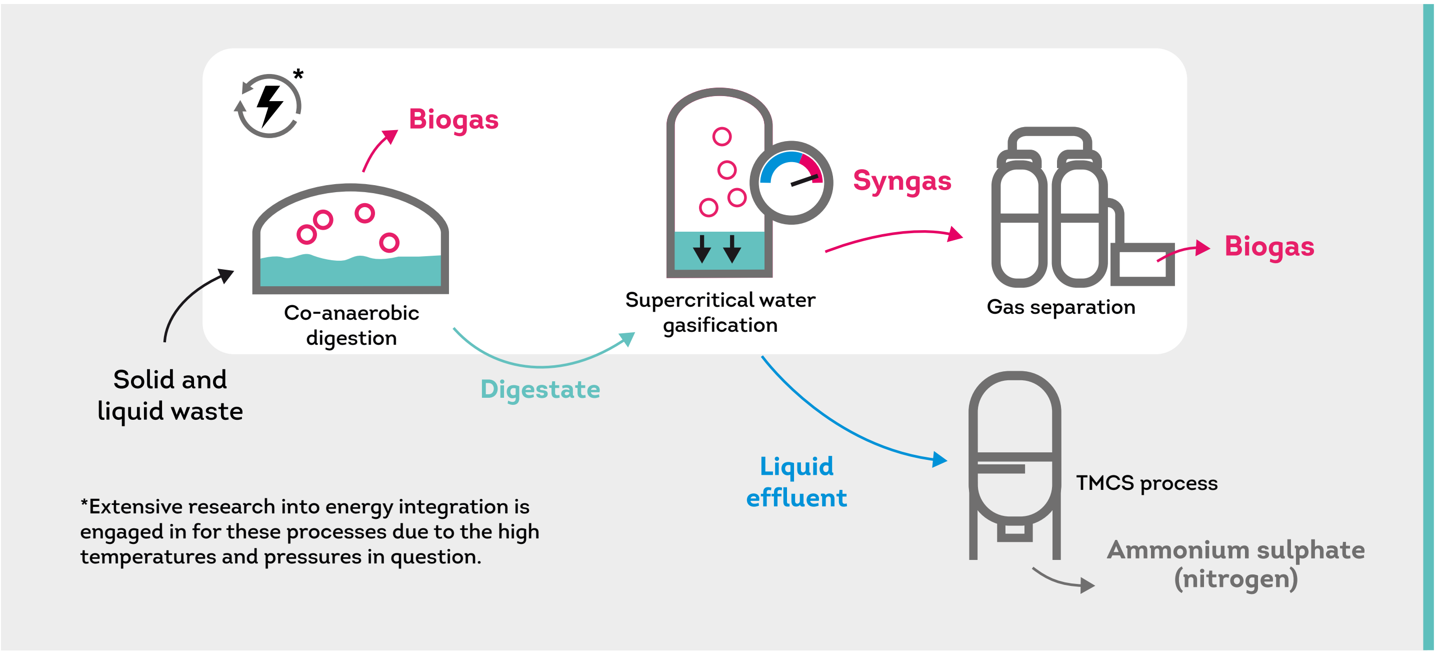
Co-anaerobic digestion

Hydrothermal carbonisation (HTC)

Gasification and methanation

Nutrient recovery





Co-anaerobic digestion

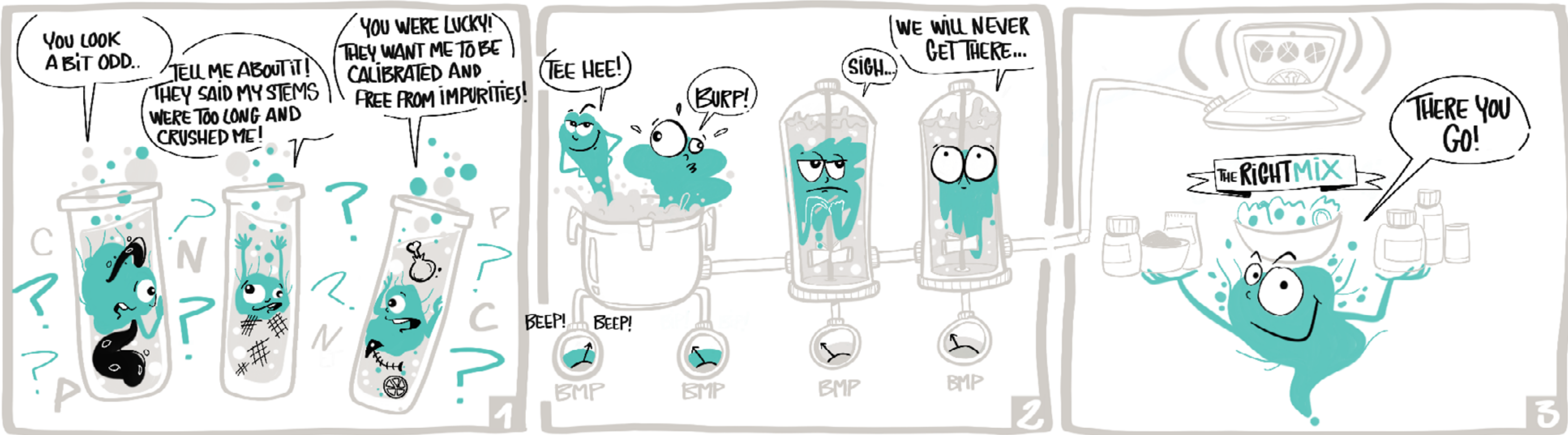
Supercritical water gasification

TMCS process

Shared management of different types of waste and by-products allowed the relevance of the various processes to be enhanced in both technical and energy terms. The overall takeaway in this respect is that it is necessary to consider a given territory as a whole.

1. Inputs and their preparation

The term 'input' here refers to what goes into a processing unit. In the Cométha project, the inputs abound in the resources (see Chapter 1.1) that the project is seeking to recover: carbon, phosphorus, nitrogen, and so on.



Goal: identifying the appropriate input/preparation/process mix

There are three stages in the study of inputs:

- firstly, for inputs to be recovered, their physical and chemical characteristics and their organic matter content must be clearly identified[19]. The related concentrations of carbon and macronutrients are thus analysed to assess the potential for recovery of nutrients such as nitrogen and phosphorus;
- next, the maximum amount of methane that can be produced by the anaerobic digestion of each input (its Biochemical Methane Potential, BMP)[20] is the subject of extensive testing;
- lastly, extrapolation of all these tests makes it possible to choose the most appropriate input mix in view of the pre-treatment and processes envisaged by the various teams.

The following inputs were analysed in the qualification stage: 6 tonnes raw material (tRM) of ROF, 11tRM of sludge[21], 3tRM of horse manure, and several hundred kilograms of fat.

19. Co-anaerobic digestion performance is directly linked with the organic dry matter content of inputs.
20.BMP is evaluated by measuring the speed at which biogas is produced (fermentation kinetics) and the methane (CH_4)
and carbon dioxide (CO_2) content of the gases produced by the reaction. BMP is expressed in litres or m^3 of CH_4 per kg of matter.
21. Various types of sludge were tested: biological, mixed, digested, and undigested sludge.

The tests also addressed the following questions:

Are there factors in the input that could limit its use in anaerobic digestion?
No parameter with the potential to inhibit the reaction in the digester (metals, ammonia, phenol, etc.) has been identified, although nitrogen levels must be monitored to avoid any sudden increase. The carbon/nitrogen ratio measured in the ROF is within the ideal range for the growth of micro-organisms.
Particular attention must be paid going forward to the presence of sulphur, which may result in an undesirably high concentration of hydrogen sulphide (H_2S) in biogas.

Why mix inputs? Is it worth doing so? What role does each input play?
Inputs are affected by a number of parameters: these include their origin, the season, and events such as heavy rain, water ingress into networks, and so on. Major variations in the composition of inputs may have an impact on the performance of the proposed treatment systems, and the fact is that the properties of ROF and sludge vary widely.

- The use of a mix of inputs naturally tends to smooth out intrinsic variations in any one input. It also makes it possible to achieve the best organic load for BMP expression, depending on the type of reactor under consideration.
- The ammoniacal nitrogen (ammonium) content of ROF and sludge samples was found to be significantly different. Preferably, the proportions of the input mix should be adjusted in order to control the ammonium content and thus avoid any inhibition.
- Non-prepared ROF and manure were found to have widely differing degradation rates. At first sight, this would not appear to encourage co-anaerobic digestion of these two inputs. Preparation is one of the avenues being explored as a way of handling these inputs and their different kinetics.

22. Input uniformity plays a role in reactor performance
23. A frequency of approximately 21kHz
24. The shorter the digestion time, the smaller the size of the reactor and of the related footprint

Mechanical crushing: more organic matter is broken down

Mechanical crushing destroys the structure of the material, making it more accessible going forward. By increasing the active surface available for microorganisms, it maximises the rate at which organic matter is broken down during co-anaerobic digestion.

Crushing also helps to homogenise[22] the input mix.
The crushing technique has been used by most of the teams only for manure. One of the teams has also used it for ROF.

RESULTS

The gain in BMP resulting from crushing has been estimated to be 8%. This figure needs confirmation in the pilot phase.

Pre-treatment using ultrasound: some tried...

The use of an ultrasound process[23] on a liquid substrate allows micro-bubbles of gas to form; these expand, vibrate, and implode during the compression and expansion phases. Due to these mechanical and chemical effects, applying the process to biological sludge or a mix of sludge and ROF allows the flocs to be broken up and large organic particles to be de-structured. This means that it could be expected that applying ultrasound to a mix of sludge and ROF would allow improved solubilisation of organic matter and more methane to be produced, faster, resulting in better BMP for the input mix. However, **the tests revealed that there was no significant effect on the speed at which methane was produced, nor on the amounts in question.**

Pressurised thermal processes for inputs: a good idea

Conducting research into pre-treatment using thermal processes has validated their effects in terms of bringing down digestion time[24] whilst at the same time increasing biogas performance and decreasing the volume of digestate.
Inputs must remain capable of being pumped, and are heated to around 160 °C. The combination of temperature, duration, and the decrease of the resulting overpressure allows cell structures to be broken down and makes the components more accessible during the anaerobic digestion phase.
These thermal hydrolysis processes have been tested for different pressures (4-10 bar) and periods (30-45 minutes).

RESULTS

BMP gains from:

> hydrolysis of ROF or manure for 45 minutes at 165 °C and 5-6 bar have been estimated at 8% by one team. The reactor residence time has also been observed to be shorter.
> hydrolysis of undigested biological sludge for 45 minutes at 165 °C and 5-6 bar have been estimated at 43%
> hydrolysis of digested sludge for 30 minutes at 165 °C and 10 bar have been estimated at +5 to +20%, depending on its origin. The reactor residence time has also been observed to be shorter.

Thermal hydrolysis of undigested sludge also leads to a significant increase in dissolved nutrients.
In addition, this accelerates the production kinetics, with the result that the reactor can be smaller. Increasing hydrolysis temperature appears to have a beneficial effect on these two parameters (kinetics and BMP). These results require confirmation in the pilot phase.

2. Co-anaerobic digestion processes

The successful bidders drew on tried and tested anaerobic digestion technologies for single and mixed inputs. The originality and the interest of the project reside in the fact that for any specific mix, **tried and tested technologies are deployed with the aim of achieving the highest possible carbon conversion rate and the best yield of methane (CH_4).**

Horizontal recirculating plug flow reactor	**Plug flow reactor with 2 compartments**	**Horizontal plug flow reactor**	**Two-stage liquid digestion unit**
ROF: 56% RM Undigested sludge: 30% RM Manure: 14% RM Fat: 0.0% RM	ROF: 48% RM Dehydrated, hydrolysed digested sludge: 49% RM Manure: 3% RM Fat: approx. 0.3% RM	ROF: 39% RM Undigested biological sludge: 51% RM Manure: 10% RM Fat: 0.3% RM	ROF: 33% RM Undigested biological sludge: 65% RM Manure: 2% RM Fat: 0.2% RM
Dry process Dryness < 35% DM	Dry process Dryness = 25% DM	Dry process Dryness = 25% DM	Liquid process Dryness = 10% DM
Thermophilic process (53-55 °C)	Two reactors: hydrolysis reactor + two-stage anaerobic digestion reactor (52 °C)	Thermal hydrolysis Methanogenesis at the mesophilic stage (37 °C)	Thermophilic stage (55 °C) Mesophilic stage (37 °C)
Plug flow (with recirculation) HRT: 21-30 days	Dual-compartment plug flow reactor HRT: 3 days, then 13 days, then 10 days	Plug flow reactor HRT: 21-24 days	Continuous or semi-continuous supply HRT: 2 days, then 12-15 days
Batch mode result: 94% of theoretical BMP	Batch mode result: 100% of theoretical BMP	Batch mode result: 94% of theoretical BMP	Batch mode result: 110% of theoretical BMP
Digestate recirculation at head of biogas plant			Use of recirculation

Selection of reactors by the 4 teams, following the completion of a large number of tests[25]

25. The results shown concern only the digestion stage. The subsequent stages, which allow CH_4 to be produced, are not taken into account here.

The following factors may affect co-anaerobic digestion:

- input characteristics (dryness, organic matter content, BMP, nitrogen content, etc.). These depend on the mix and the pre-treatments used (see chapter 3.1);
- the anaerobic digestion residence time. The longer this time, the larger the size of the installations in question. The best possible technical and economic solution needs to be found: as much conversion to organic carbon as possible using as little energy for the reactor as possible, leveraging the smallest possible amount of investment that can achieve these levels of conversion.

While it is only natural to seek innovation by optimising the input mix, pre-treatments, and processes involved, there have also been more creative adaptations of tried and tested technologies.

INFLUENCE OF THE INPUT MIX ON RESIDENCE TIME

The characteristics of the input mix and the residence time may be linked. For instance, some teams noted that as a result of their choices, the absence of manure in the mix brought down the residence time required to break down organic matter.

Agitation and recirculation: different options chosen by different teams

Agitation in the reactor is a crucial parameter to maximise the production of biogas. The two horizontal plug flow reactors and the two wet process digestion stages in the two-stage unit are agitated mechanically. The recirculation setup for the first horizontal reactor is combined with mechanical agitation: the recirculated matter, loaded with bacteria and partially decomposed, is mixed with the initial matter. In the two-compartment plug flow reactor, this agitation is produced by the biogas given off. The gas bubbles injected into certain parts of the reactor allow the matter to move from one area to the other.
The two digestion processes without recirculation distinguish an initial digestion stage (biological hydrolysis), assigning it a specific volume. This sectorised treatment is promising, and its impact on anaerobic digestion will be monitored during the design, construction, and operational phases of the pilot units.

3. Going further, recovering everything of value in digestate on completion of anaerobic digestion

"Few projects today approach organic matter from the standpoint of full recovery of both energy and nutrients."

Fabien Esculier, LEESU

When inputs are injected into a methaniser, much more than biogas is produced...

During anaerobic bacterial digestion, 70-90% of the biodegradable organic matter (lipids, proteins, carbohydrates, cellulose, and hemicellulose) introduced into the reactor is broken down and partly converted into methane and carbon dioxide. Some of the nitrogen is also mineralised, as is the organic phosphorus.

Biodegradable organic matter is therefore only partially converted in reactors. Although it is possible to optimise the expression of the methanogenic potential, some non-mineralised organic matter remains in the digestate.

Some teams have opted to separate the digestate into two phases (liquid and solid), with one of these phases undergoing thermochemical processes, while others apply this type of process to the digestate as is. **All of the teams are seeking to make progress in energy recovery by working on the digestate and by aiming to recover nutrients such as nitrogen and phosphorus.**

Did you know that still more biogas that can be extracted from the liquid phase of digestate?

The liquid phase of digestate remains rich in organic matter, whether after dehydration, drying, thermal processes, or hydrothermal carbonisation combined with digestate dehydration. It is a substrate of interest for other biogas production plants.

As a result, during the research and development phase (Phase 1) two of the four teams tested phase separation and suggested positioning a second stage of anaerobic digestion at this stage in their processing chain or following nutrient recovery, in order to produce additional methane from the liquid phase.

RESULTS

Tests and calculations performed by one of the teams suggest that use of this anaerobic digestion module for the liquid phase results in a 4% increase in methanogenic potential.

4. Thermochemical conversion processes to go further in the treatment of digestate or its solid phase

A range of thermochemical processes such as pyrolysis, gasification, and hydrothermal carbonisation should be seen as promising technologies. **One advantage is that these processes take up relatively little space – an especially important asset in dense urban areas. Moreover, the technologies in question allow a large number of synergies to be created between the different flows to be found at the heart of urban metabolism: those relating to the water cycle, waste and matter flows, and energy flows.**

Pyro-gasification consists in heating an organic product (or waste) at high temperature with little or no oxygen. Hydrothermal carbonisation is a similar process, with water present.

Thermal treatment of organic matter allows it to be recovered in the form of two distinct fractions:

> solid residue consisting of a mix of biochar, a residue with a high heating value and ash, mineral residue with a low heating value;
> a synthetic gas known as syngas consisting of methane, hydrogen, and carbon monoxide. Its composition varies depending on the processes and parameters used.

The quantities of energy available in each tested fraction depend on the nature of the organic matter, as well as on treatment parameters such as temperature, pressure, the concentration of oxygen in the atmosphere, and the residence time.

ISSUES IN THERMOCHEMICAL CONVERSION PROCESSES

> Demonstrating their industrial operability
> Confirming the technical/economic relevance of the processing chain
> Lifting regulatory barriers
> Where applicable, evaluating the compatibility of the syngas produced with the technical specifications for dispatch into the grid

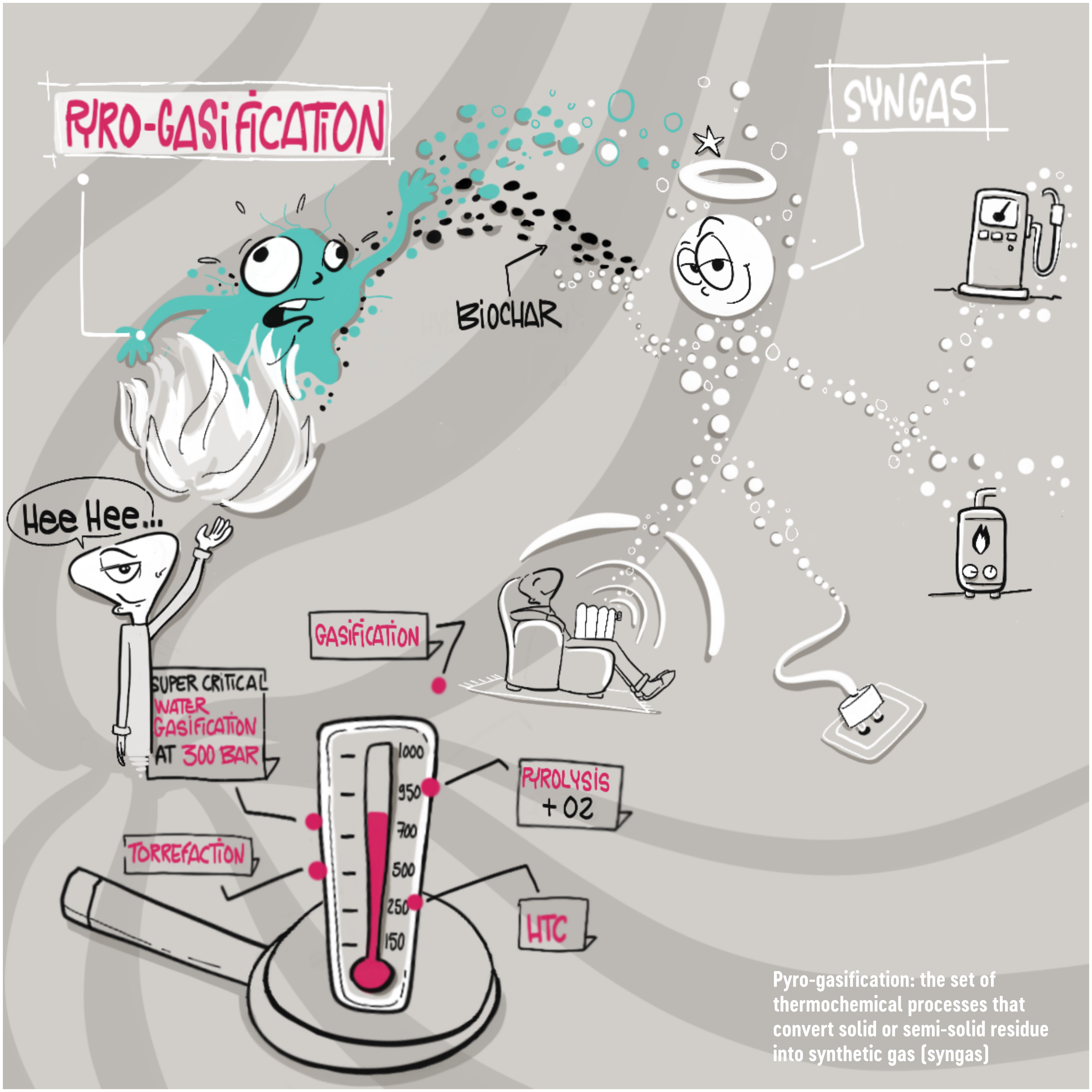
"Gasification of waste is a technology for the future, instantly creating a new layer in the hierarchy of waste treatment modes. In addition to energy from waste, it allows for materials recovery: methane and hydrogen are gases that can be used as the raw materials for industrial processes."

Pierre Hirtzberger, Syctom[26]

The teams have examined various thermochemical processes, evaluating the performance of each:

> pyrolysis, in which the product is heated to temperatures of 400-950 °C with little or no oxygen, producing a gaseous phase (syngas), a liquid phase (oil), and a solid phase (a mix of biochar and ash);
> hydrothermal carbonisation (HTC), in which digestate with a high water content is heated to 160-200 °C at pressure to convert it into a solid energy vector known as hydrochar, obtain a gas containing methane, and solubilise part of the organic matter in order to make it bioavailable for anaerobic digestion and thus increase the production of biogas;
> gasification, in which the product is heated to over 1000 °C, in the absence of an oxidant (e.g. oxygen) to convert the non-gaseous phases into syngas and obtain biochar;
> torrefaction, in which the product is heated to around 300 °C with little or no oxygen, producing gas and a solid biochar-ash mix;
> supercritical water gasification, allowing digestate to be recovered after co-anaerobic digestion in hydrothermal conditions, i.e. at high pressure (300 bar) and temperature (500-700 °C) to obtain syngas and biochar.

26. [REF Q]



Pyro-gasification: the set of thermochemical processes that convert solid or semi-solid residue into synthetic gas (syngas)

Pyrolysis of the solid phase of digestate from co-anaerobic digestion

TECHNOLOGICAL INNOVATION

The Biogreen® process allows digestate that has been previously dried to achieve a moisture content of some 10% to be converted into a syngas that is rich in methane, oil, biochar, and ash. Pyrolysis takes place at a temperature of 800 °C for 20 minutes. This process requires little oxygen, thus avoiding the gas being depleted by dilution.

The syngas produced in this way has a methane content of some 10%. The other majority components are carbon monoxide (CO) (approx. 30%), dihydrogen (H_2) (approx. 35%) and carbon dioxide (CO_2) (10-15%).

The resulting syngas is purified before moving on to the biological methanation stage (see chapter 3.5).

The oil derived from the pyrolysis process may be used as a fuel or in renewable chemicals industries.

The solid residue, a mix of biochar and ash, may be used as a fuel in an energy-from-waste facility. If the heating value of the solid residue is deemed to be too low due to too high a proportion of ash, it is not recovered as a fuel. Biochar may also be recovered for agronomy (for water retention or as a soil amendment) as part of a spreading plan. The biochar used in soil thus becomes a carbon sink.

ENERGY OPTIMISATION

Although it has significant internal energy requirements, energy optimisation of the full processing chain of which this process forms part enables a positive energy balance to be achieved.

Hydrothermal carbonisation of digestate to convert it into hydrochar, which is then gasified

TECHNOLOGICAL INNOVATION

Hydrothermal carbonisation is a thermochemical process to convert organic substances at high temperatures in the presence of water, which in theory allows the digestate to be converted into a solid energy vector (hydrochar). This technology, well-known for processing waste water treatment plant sludge, deserves to be investigated for processing digestate from a plug flow reactor processing a mix of inputs.

Operation in a hot-water environment allows wet biomass and sludge to be processed without prior drying. The use of the HTC process is less energy-intensive than conventional drying.

15 laboratory tests explored temperature variations of 180-220 °C, residence times of 30-90 minutes, and initial pH values of 3-7.

Hydrochar with a dry matter content of over 60-70% is produced without thermal drying. It can be transported and recovered for energy via combustion or pyrolysis/gasification, as will be seen later. In particular, it consists of 60% carbon dry matter and 7% hydrogen dry matter.

The gas produced by the HTC process is not very suitable for energy use, since only slight traces of methane and hydrogen (3% and 1% by volume respectively) are present in the gaseous phase. The dominant component is carbon dioxide (96% by volume).

The liquid phase at the end of the process is the most nutrient-rich fraction, in dissolved form, and is worth testing for nutrient recovery installations (see chapter 3.7).

The purpose of gasification following hydrothermal carbonisation is to produce a gaseous product (syngas) containing carbon monoxide and hydrogen from a solid phase through a reaction with a 'partner' of the gaseous reaction, known as a gasification agent.

The composition of the gas depends mainly on the composition of the original fuel, temperature (above 900 °C) and pressure. It also depends on the gasification process: fixed-bed gasification, double fluidised bed gasification, entrained-flow gasification, etc.

ENERGY OPTIMISATION

The thermal and electric energy requirements of the gasification process are relatively low.

Moreover, it has been estimated that on an industrial scale, gasification in the planned processing chain would be responsible for 16% of heat production within the processing chain as a whole. The remaining 84% would be produced by a hydrochar boiler after hydrothermal carbonisation (HTC).

The thermal balance of this hydrothermal carbonisation / gasification and hydrochar boiler process sequencing is significantly positive.

Thermochemical processing of digestate: comparing the torrefaction and pyrolysis processes

TECHNOLOGICAL INNOVATION

The team that initially chose torrefaction as the reference solution at the start of the project implemented thermal digestate processing via a multiple hearth reactor (NESA) in the laboratory. This apparatus allows a wide range of processing conditions to be tested, in terms of both temperature and the presence or absence of oxygen, enabling the properties of the resulting products to be modulated and the optimum energy balance to be identified.

The structure of this reactor allows various pyro-gasification processes such as torrefaction and pyrolysis to be used, in the form of a series of stages. Torrefaction is used to dry and preheat the digestate. The stages of pyrolysis, gas combustion, and solid combustion have been fully separated. Combustion takes place at the end of the process, to avoid there being any unburned matter. An oxidant is then added.

The benefits of torrefaction and pyrolysis have been demonstrated:

- the presence of manure in the mix increases the gross calorific value with pyrolysis;
- after 2 hours at high temperature, the solid residue is almost completely mineralised. This suggests that it would be possible to obtain virtually complete mineralisation of the digestate at high temperatures, with a residence time of some 2 hours in an industrial process;
- the ash from the pyrolysis consists mostly of calcium, silicon, and alumina oxide. The phosphorus pentoxide content (P_2O_5) is also significant (some 10%). One or more types of recovery from pyrolysis residue can therefore be carried out: phosphorous firstly, followed by ash (construction industry).

The advantage of the torrefaction process is that it provides a solid product with an attractive heating value that can in theory be used in a boiler. In actual fact, to date this product is still categorised as waste, preventing it from being recovered to produce energy in boilers. Digestate from co-anaerobic digestion has a high ash content. This makes it less attractive than conventional wood biomass, a competing substance. **These two drawbacks have resulted in torrefaction being abandoned at this stage in favour of pyrolysis.**

The selected form of pyrolysis is a high-temperature thermal treatment that allows the maximum amount of chemical energy to be transferred from the solid phase to the gaseous phase. In the process studied, the gas obtained passes through a combustion stage to cover the heat requirements of the installation. The amount of solid residue is reduced to a minimum (i.e. the mineral residue: ash).

SELF-CONSUMPTION OF HEAT

On an industrial scale, pyrolysis could contribute 80% of the heat produced by the processing chain as a whole.

RECOVERING ASH?

Ash is currently classified as waste. The idea here is to extract phosphorus from it, but this could not be directly used for agronomic purposes. Specific processes could make it possible for it to no longer be qualified as waste and thus be recovered.

Supercritical water gasification of digestate

TECHNOLOGICAL INNOVATION

As for all pure substances, the water vaporisation curve reaches a critical point (P ≥ 221 bar and T ≥ 374°C). Thereafter, the state of matter is known as a supercritical fluid (or hypercritical gas); this has highly specific properties, midway between those of a gas and a liquid.

Supercritical water gasification involves breaking down organic compounds through hydrolysis. The water present in the digestate serves as a conversion medium to produce synthetic gas. The process produces a gaseous mixture composed of carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), methane (CH_4) and other light hydrocarbons. The gases produced are completely soluble and form a single-phase mixture.

This process is applied to the digestate following co-anaerobic digestion at high pressure (300 bar) and temperature (500-700 °C).

During Phase 1, 23 tests were carried out in discontinuous (batch) mode. Key findings:

> the higher the dry matter content of the input (10%, 15% or 20% of dry matter), the more gas is produced;
> preparation of the digestate tends to decrease the volume of gas produced and the amount of methane in the gaseous mixture;
> increasing the temperature encourages the conversion of the resource to gas. A minimum working temperature of 500 °C is recommended;
> it is also important to increase the temperature gradually. This encourages methane over and above hydrogen;
> the optimum in terms of material yield and energy expenditure corresponds to dryness of 20% DM and a temperature of 600 °C.

The influence of these parameters also affects the volume of gas produced and its composition (16-36.5% methane) as well as the conversion rate of the carbon to a gas, liquid, or solid.

The 6 tests carried out continuously suggest that with the dry matter ratios of 10-13% that can be envisaged in an industrial facility and temperatures of 537-614 °C, the proportion of methane is similar to that observed in batch mode (21-23%).

There are two stages in the adopted process: pressurising the digestate heated to 150 °C to a pressure of 270-300 bar, capturing and removing most of the inorganic fraction of the co-digestate, followed by a transfer to a second reactor-exchanger at 600 °C.

Tests and calculations performed during Phase 1 suggest that the additional methanogenic potential expressed due to processing the digestate by supercritical water gasification is around 40%.

Effluent rich in mineral salts (known as brine) and clear effluent are also recovered at the end of the process. Brine contains precipitated phosphorus which is quite difficult to extract, and effluents containing nitrogen.

ENERGY INTEGRATION

With the use of a gas boiler, the hydrogen produced by the supercritical water gasification process can provide some of the heat required to achieve a temperature of 600 °C. If this is not sufficient, some of the CH_4 must be used; its combustion would provide the supplementary heat required. The aim is for the hydrogen and only part of the methane produced to be enough to maintain the process temperature. Only if this condition is met will the process result in net production of methane.

The simulations carried out showed that for a given digestate (containing at least 40% of inorganic material in dry matter) around 70-75% of internal process heat is required for the gasification system to continue to be a net producer of energy.

5. The benefits and relevance of methanation

"Methanation is a technology building-block at the crossroads of several new gas production processes. It can be added to several types of process sequencing."

Dairo Ballestas Castro, RICE

Methanation consists in creating a reaction between carbon monoxide and/or carbon dioxide and hydrogen to produce methane and water.
"Methanation" technology can only be used downstream from a process that has transformed part of the digestate into a gaseous phase: syngas. For instance, it could come after the 'pyro-gasification' technique (see chapter 3.4).

There are a range of methanation processes, including catalytic conversion and biological methanation (biocatalysis by microorganisms).

Chemical catalytic processes are expensive, usually require high temperature and pressure, and are sensitive to sulphur compounds (such as H_2S) present in syngas. These drawbacks can be avoided by using the biological pathway to convert syngas compounds into methane at normal temperature and pressure. However, the reaction is slower and therefore requires a larger methanation reactor.
During biological methanation, in a reactor similar to an anaerobic digestion reactor, hydrogen and carbon dioxide are converted to methane by bacteria. The composition of the gas produced is similar to that of biogas from anaerobic digestion and can be mixed with the latter to be processed (purification, odorisation) in a single purifier before being dispatched into natural gas transport and distribution networks.

Those teams that opted for this technology have envisaged its use in a mesophilic environment (35-37 °C).

Methanation: a process that increases the proportion of methane in a syngas produced by pyro-gasification.

The tests carried out by some teams have identified the following prospects:

Digestate → Hydrothermal carbonisation → Hydrochar → Gasification → Gaseous mix → Water shift → Gaseous mix → Methanation → Biogas →

This sequencing achieved a potential methane content of around 40%.
The additional methanogenic potential expressed by this sequencing chain has been estimated at 20-30%.

Supplementary processing (water shift reaction) is incorporated between gasification and methanation to mix the carbon monoxide with water vapour, converting it to hydrogen ($CO + H_2O \Rightarrow CO_2 + H_2$). This allows more hydrogen to be introduced to the methanation reactor, thus boosting methane conversion by as much as 45%.

In one of the tests conducted by the teams, the energy efficiency of this sequencing (between the hydrochar to be gasified and the methane produced by the methanation) was 22%.
In this sequencing, it is mainly the hydrogen contained in the syngas produced by gasification that is recovered.

Digestate → Thermal drying → Dried digestate → Pyrolysis → Gaseous mix → Methanation → Biogas →

This sequencing achieved a potential methane content of over 25%.
The additional methanogenic potential expressed by this sequencing chain has been estimated at 10-15%.

METHANATION AND ENERGY

The thermal and/or energy requirements for methanation are lower than for other processes, in particular with respect to pyro-gasification.

6. Recovering nutrients

Cométha is focusing mainly on phosphorus and nitrogen. For the purposes of simplification, it has been assumed that after various processes including co-anaerobic digestion, most nitrogen and phosphorus contained in the input mix will be found in the liquid and solid phases respectively.

One of the teams has studied the possibility of recovering part of the phosphorus directly from part of the input mix prior to anaerobic digestion. All the other options examined for recovering nitrogen and phosphorus intervene after co-anaerobic digestion, just before or after various supplementary processes.

Investigations into the recovery of nutrients are a fundamental part of the project, in order to minimise post-process residues; this is one of SIAAP and Syctom's stated goals, as well as that of minimising the amount of effluent discharged and treated by SIAAP installations at the end of the various processing chains.

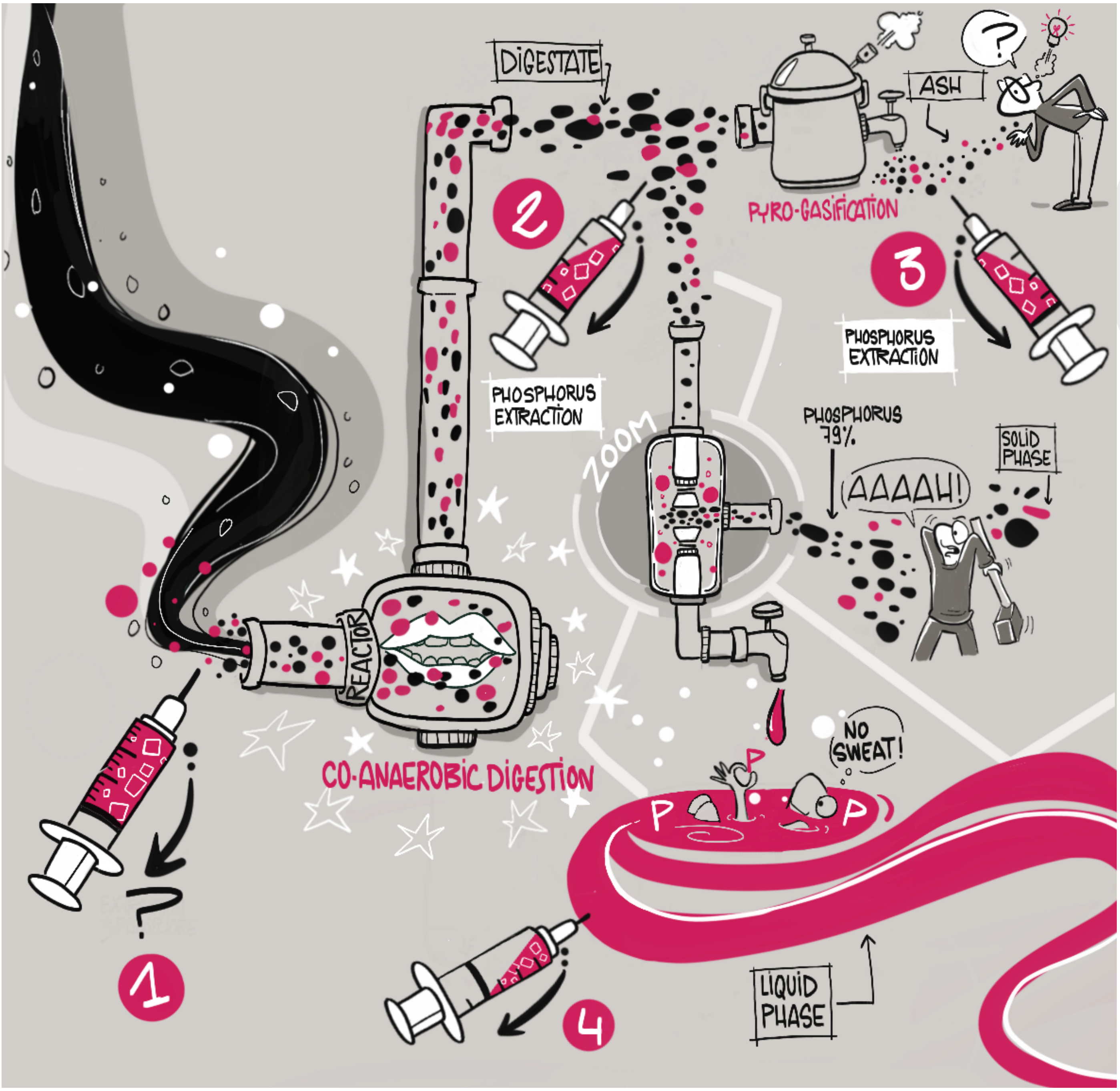
THE PARTICULAR CHALLENGES OF PHOSPHORUS RECOVERY

Fertiliser production may avoid significant greenhouse gas emissions in an optimised balance if the reagents in question have a low carbon contribution.

Citric acid, used to produce struvite, appears to play a major role in greenhouse gas emissions (the third-largest in one of the proposed processing chains). Over and above the quest for alternative solutions for the reagents used in phosphorus extraction, it may be worth investigating recovery from ash, which could also reduce the amount of waste generated.

When characterising the digestate produced by co-anaerobic digestion, **it has been estimated that following digestion, over 85% of the phosphorus in the inputs is still present in solid phase.** This illustrates the difficulty of recovering phosphorus in liquid phase and encourages research into it being recovered from the solid phase (for instance, from pyrolysis ash).

Experimental methods for the recovery of phosphorus



Why not recover phosphorus where it is easily accessed, rather than where it is most abundant?

Recovering phosphorus directly from the input mix

TECHNOLOGICAL INNOVATION

The idea here is to carry out electrochemical recovery of the phosphorus contained in sludge and ROF prior to digestion.
The ePhos® process, positioned here after a module for pressurised thermal hydrolysis of sludge and ROF, allows phosphate to be obtained via an electrochemical pathway, without the use of any other chemicals.

Using a magnesium electrode, the phosphate and ammonium precipitate into magnesium ammonium phosphate ($MgNH_4PO_4$*6 H_2O), also known as struvite.

The relatively low electricity consumption (approximately 0.78 kWh/m³) is a considerable benefit of this process, which will be compared with the BioEcoSim® process (see below) during the pilot unit phase.

If it is positioned after thermal hydrolysis, it is expected that the nutrients will be easier to access, and that there will therefore be a larger 'harvest'. Indeed, hydrolysis increases nutrient solubilisation. Tests carried out on sludge from a process incorporating physical/chemical dephosphatation have shown a sevenfold multiplication of phosphate concentrations (PO_4-P) and a threefold multiplication of ammoniacal nitrogen (NH_4-N).

RESULTS

In phase 1, the efficiency of phosphorus recovery using this process following thermal hydrolysis was estimated to be 12%. The difficulty of recovering phosphorus from wastewater treatment sludge (and thus from the mix) is due in particular to it precipitating during ferric chloride treatment at the wastewater treatment plant. In the pilot phase, the positioning of the process within the processing chain and the resulting yields will change.

Recovering phosphorus after co-anaerobic digestion

TECHNOLOGICAL INNOVATION

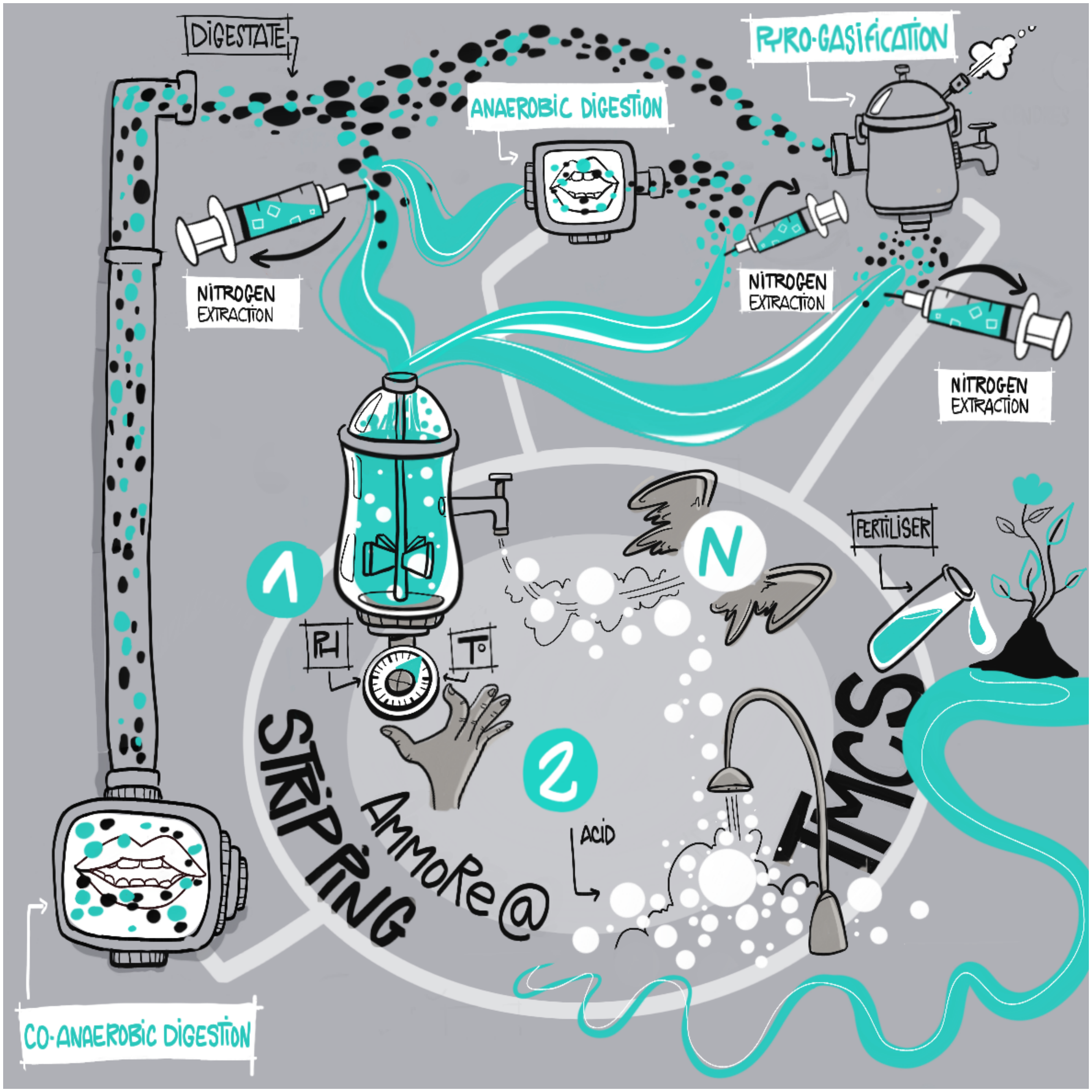
BioEcoSim® is an innovative technology that was initially developed to recover manure and anaerobic digestion digestate in an agricultural environment. The technology has been tested as part of the Cométha project to recover:

- co-anaerobic digestion digestate (liquid fraction);
- the residue from hydrothermal carbonisation (liquid fraction).

RESULTS

The efficiency of phosphorus recovery from co-anaerobic digestion digestate has been estimated to be 43%, compared to 50% from sludge produced by the HTC process.

Experimental methods for the recovery of nitrogen



While the processes envisaged by the different teams are very similar, the issue of where a process should be positioned in the processing chain was the subject of a great many tests.

The four teams considered two technical pathways for nitrogen recovery: stripping, and the AmmoRe process using TMCS /Transmembrane Chemisorption.

There are two stages to the stripping process:

> the first releases ammonia and transfers it from the liquid phase to the gaseous phase. Adjustment of effluent pH and temperature is required to create the optimum conditions for stripping;

> the second stage allows the ammonia recovered from the gaseous phase to be transferred and concentrated in a liquid phase in the form of ammonium sulphate by washing the gas with an acid solution.

An ammonium sulphate solution is produced as a result.
The AmmoRe process uses Transmembrane Chemisorption (TMCS), a technology to recover nitrogen in the form of ammonium salts.

SPECIFIC ISSUES IN NITROGEN RECOVERY

The use of sodium hydroxide to extract nitrogen results in a large amount of greenhouse gas emissions. An alternative solution to increase the pH value in processes without adding sodium hydroxide would be beneficial.

The amount of energy used in stripping processes to extract nitrogen is considerable. The AmmoRe process appears to be less energy-intensive.

Recovering nitrogen just downstream from co-anaerobic digestion

TECHNOLOGICAL INNOVATION

The team that positioned the stripping unit for the liquid phase downstream from co-anaerobic digestion tested a range of temperatures between 39 °C and 70 °C. It was observed that the higher the process temperature, the greater the yield. The optimum temperature noted was approximately 65-70 °C.

Tests also revealed that the higher the pH, the greater the yield. However, increasing the pH requires the use of more sodium hydroxide. The team therefore examined the impact of carbon dioxide stripping (CO_2) at 30 °C before nitrogen stripping in order to increase pH. The aim was to reduce the amount of sodium hydroxide used in the process by adding this extra stage. The tests performed showed that carbon dioxide stripping (CO_2) allowed the optimum pH value (identified as being 9.5 for nitrogen stripping) to be achieved whilst also making considerable savings on sodium hydroxide (up to 30%). The third parameter studied was the air/liquid ratio in the second stage of this process. Given the same pH and temperature values, the higher the ratio, the better the yield.

RESULTS

At this stage, the estimated yield for the abatement of nitrogen present in the liquid phase is approximately 90%, i.e. about half of the nitrogen present in the mix of selected inputs.

Recovering nitrogen after hydrothermal carbonisation

TECHNOLOGICAL INNOVATION

One team chose to implement the AmmoRe process and studied two potential positionings:

> downstream from co-anaerobic digestion to process the digestate;
> downstream from hydrothermal carbonisation to process the liquid phase at the end of the process.

After filtration, the water drains into a closed tank where it is agitated; sodium hydroxide is added to maintain the pH at 10. When it leaves the tank, the fluid is heated to 50 °C and recirculated through a membrane module, where acid is used to draw off the ammonium from the liquid. As the water recirculates through a membrane along the side, its ammonium content is depleted. The acid recirculates adjacent to the conduit until it is saturated in ammonium. A pH measurement automatically triggers the end of the process; the ammonium-enriched solution is drawn off into a storage tank.

RESULTS

The efficiency of nitrogen recovery from co-anaerobic digestion sought in the pilot unit phase is 79%. Hydrothermal carbonisation allows the nitrogen recovery rate from the input mix to be optimised.

Recovering nitrogen after supercritical water gasification

TECHNOLOGICAL INNOVATION

The team that included supercritical water gasification in its processing chain studied the introduction of nitrogen recovery using a TMCS process. This process is implemented on clear effluent from gasification and takes place in two main stages:

> carbon dioxide stripping (CO_2), increasing the solution's pH and encouraging the form of ammonia (NH_3), in preference to the form of ammonium ions (NH_4^+);
> a stage to filter the ammonia by passing it through a gaseous phase, with filtration on dedicated membranes, followed by recovery of the ammonia transferred in a sulphuric acid solution to encourage the transfer and ultimately produce an ammonium sulphate solution.

RESULTS

The tests performed show that it is possible to recover some 50% of the nitrogen present in the clear effluent produced by supercritical water gasification. The recovery rate can be almost 95% if sodium hydroxide is added to achieve a pH value of 9.3. Across the entire processing chain, the recovery rate at the industrial scale is estimated to be 64% of the nitrogen from the mix of selected inputs.

Recovering nitrogen after anaerobic digestion of the digestate

TECHNOLOGICAL INNOVATION

The team in question also decided to position stripping at the very end of the processing chain. The process is applied after anaerobic digestion to the liquid phase of the digestate.

RESULTS

Tests show that in the adopted conditions (60 °C and a pH of 9.5), **this position in the processing chain allows 80% of the ammoniacal nitrogen present at this stage to be recovered,** i.e. around 30% of the nitrogen from the mix of selected inputs.

TOGETHER, TO GO FURTHER

"The relevance and benefits for users of public services combining their skills"

Jacques Olivier, SIAAP

Together,
the inputs produced by co-anaerobic digestion achieve a better energy and environmental balance than they would do in separate processing chains.

Together,
SIAAP and Syctom are devising breakthrough solutions to supplement the available palette of solutions in the future.

Together,
clients and consultants conducted 4 research projects in parallel (400 hours' worth of meetings!).

Together,
each of the successful bidders' teams leveraged all their creativity to achieve and in some cases exceed the 3 goals[27] that had been set (9 patents were registered).

Underpinning this adventure is the desire for synergy on the part of two clients, driven by the desire to pool forces, know-how, and ideas.

27. 1. Maximising the conversion of organic carbon into methane / 2. Achieving an overall energy balance that is positive / 3. Minimising post-treatment residue.

The adventure began in 2016. The two clients have a shared interest in organic mattter. Between them, they have brought together a range of consultants on technical and legal matters, specialists in consultation and communication, and industrial property experts.

All of them joined the adventure, along with four teams from the successful bidders: two French teams and two European teams. All of these teams involved engineering, operators, and research laboratories.

In technical terms, Phase 1 turned out to be a genuine learning space for peers in each of the winning teams, as well as for the clients, consultants, and the teams themselves.

Cométha brings together specialists from different sectors to focus on the same set of issues. This is very much the benefit of this multi-sector approach, allowing ideas to emerge and challenges to be taken up.

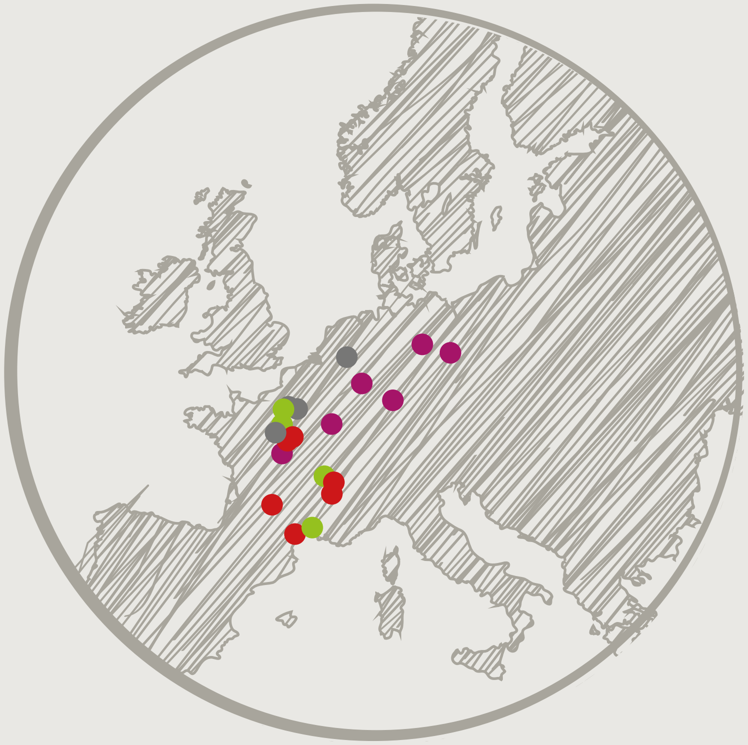
17 PARTNERSHIPS FOR THE GOALS

The ethos of the Sustainable Development Goals is structured around robust cooperation and global partnerships.
These inclusive partnerships are a prerequisite for any successful sustainable development programme. Built around principles, values, and a shared vision and objectives that put people and the planet at the centre, they are necessary at global, regional, national, and local level.

The two pilots currently under construction will allow 250-350kgDM/day to be treated. Depending on the chosen input mix, the pilots will each take in 150-250tRM/year of ROF, 200-500tRM/year of undigested sludge, 15-40tRM/year of horse manure, and some fat.

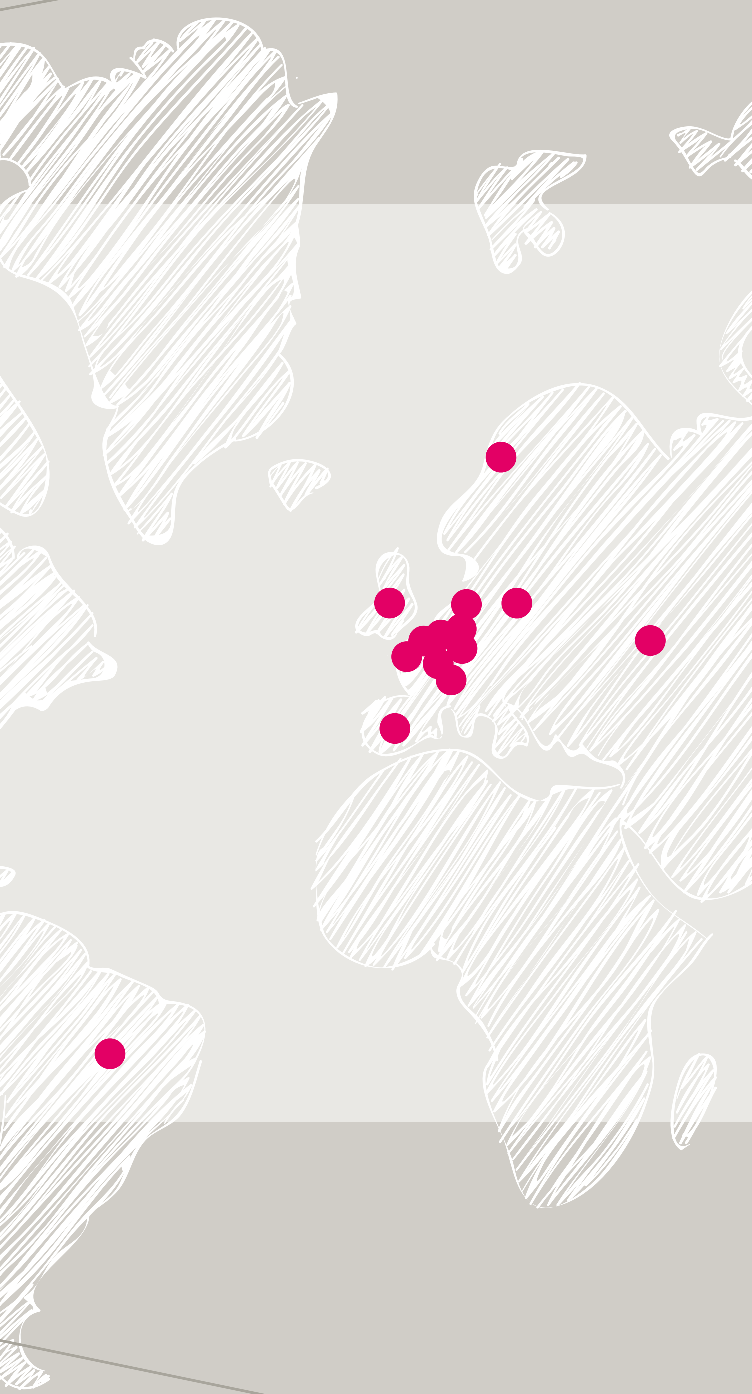
> *Megacities across the world are watching Cométha closely*

Denis Penouel, Syctom (formerly of SIAAP)



Partners:

Tilia	France and Germany
DBFZ	Leipzig, Germany
Fraunhofer IGB	Stuttgart, Germany
Gicon	Cottbus, Germany
France Biogaz	Strasbourg
Suez	Paris / Narbonne
Arkolia énergies	Mudaison
Etia	Compiègne
INSA	Lyon
Vinci Environnement	Paris
CEA Liten	Grenoble
Naldéo	Paris
INSA	Lyon, Toulouse
INRAE	Narbonne
John Cockerill	Liège, Belgium
Sources	Paris
UniLaSalle	Beauvais
UTC	Compiègne



Where we're being talked about:

2015 Paris, France / **COP21**
2017 Stockholm, Sweden / **Stockholm International Water Week**
2017 Bonn, Germany / **COP 23**
2017 Astana, Kazakhstan / **International Exhibition**
2017 Colmar, France / **ASTEE**
2018 Brasilia, Brazil / **World Water Forum**
2018 Rennes, France / **First National Pyrogasification Summit**
2018 Paris, France / **AFITE**
2018 Paris, France / **Syctom-SIAAP Technical Morning**
2018 Le Havre, France / **Amorce**
2018 Rennes, France / **JRI**
2018 Paris, France / **French Circular Economy Institute - Chinese Delegation**
2018 Lyon, France / **Pollutec**
2018 Katowice, Poland / **COP 24**
2019 Lille, France / **Expo Biogaz**
2019 Liège, Belgium / **ECSM**
2019 Colombes, France / **SIAAP 2019 Conference: Resource management: a key issue in smart cities**
2019 Leipzig, Germany / **HTC Fachforum**
2019 Rennes, France / **RISPO FNCCR**
2019 Madrid, Spain / **COP 25**
2019 London, UK / **Global water summit**
2019 Paris, France / **UNESCO Metropolitan ECO-RISE R2020 "Facing Climate Changes"**
2019 Paris, France / **Cométha Technical Day**
2020 Paris, France – online / **IDEA SPGE presentation**
2020 Paris, France – online / **European Week of Regions and Cities – Circular economy joined organic recovery**
2020 France / **Energie Plus, issue 649, 1 September 2020**
2021 Paris, France – online / **Salon Bio 360**
2021 Paris, France – online / **IDEAL CO**
2021 Paris, France / **ASTEE**
2021 Baden-Württemberg / **Ressourceneffizienz kongress**
2021 Dresden / **Energy Saxony Summit**

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Report on sub-phase 1A –**Definition of the Treatment System**, August 2018
Report on sub-phase 1B –**Experimental tests,** August 2019
Report on sub-phase 1C – (Pilot Unit preliminary design study) – **Presentation of the pilot unit,** September 2019
Response framework – **Summary of proposed innovations** , September 2019

SUEZ / Arkolia Energies / ETIA / INSA
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Report on sub-phase 1C – (Pilot Unit preliminary design study) – **Presentation of the pilot unit,** September 2019
Response form – **Summary of proposed innovations**, November 2019

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Response framework – **Summary of proposed innovations**, September 2019

Vinci Environnement / Naldeo / CEA Liten / INSA / INRAE
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Patents lodged:

- A system for high-pressure injection of an organic resource
- A process for supercritical water gasification
- A system for the high-pressure injection of a wet mix
- Thermal exchanger reactor
- An installation and process for the hydrothermal gasification of biomass
- A process for a system for the production of biogas and the processing of wastewater treatment plant sludge
- A system for processing inputs used such a system
- A system for extracting phosphorus and nitrogen nutrients contained in a liquid effluent and the extraction process used in such a system
- A two-stage system for the treatment of inputs and the treatment process used in such a system

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- AMODEO CORRADO, HATTOU STEPHANE, BUFFIERE PIERRE, BENBELKACEM HASSEN. Temperature phased anaerobic digestion (TPAD) of Organic Fraction of Municipal Solid Waste (OFMSW) and Digested Sludge (DS): effect of different hydrolysis conditions, February 2021. Available at https://hal.archives-ouvertes.fr/

SYCTOM AND SIAAP: AN OVERVIEW

"The most efficient approach is multi-sector and multi-disciplinary"

Denis Penouel, Syctom (formerly of SIAAP)

Syctom is Europe's leading operator for the treatment and recovery of household waste, serving an area with a population of almost 6 million – around 10% of the population of France.

Syctom, the French metropolitan agency for household waste, is the public body responsible for treating and managing the waste produced by the 6 million inhabitants of 82 municipalities (Paris and its immediate suburbs) – around 10% of the population of France. Some 2.3 million tonnes of waste are treated every year. In an era of raw material scarcity and energy transition, all of this waste must be seen as a resource. This is a daily challenge for Syctom as it constantly seeks innovations to optimise its facilities' performance, increase energy efficiency, improve sorting and recycling processes, and identify treatment solutions for the entire range of waste flows.

In doing so, Syctom is contributing to the emergence of the circular economy: a more virtuous, more sustainable model fit for the ecological transition and for the cities of tomorrow.

syctom
l'agence métropolitaine des déchets ménagers

**More information:
syctom-paris.fr**

SIAAP, the Greater Paris Interdepartment Sanitation Board, is the leading public-sector stakeholder for the sanitation of domestic and industrial wastewater and rainwater, serving 9 million people.

2,300,000m^3 plants, wastewater is carried to its facilities via a network of pipes with a total length of 440km. When it reaches one of SIAAP's 6 wastewater treatment plants, it is depolluted before being discharged into the Seine or Marne rivers in such a way as to ensure the water remains in good ecological condition and that biodiversity is preserved. As a stakeholder committed to the environment, SIAAP is engaged in a public-interest mission above and beyond wastewater treatment itself: recovering energy from the by-products of wastewater treatment, protecting natural environments, and anticipating climate and demographic change.

In 2016, SIAAP committed to a long-term strategic plan: 'SIAAP 2030: building the future together' in order to have the resources for better performance by optimising its processes, organisation, and industrial assets.

SIAAP
Service public de l'assainissement francilien

**More information:
siaap.fr**

cométha

syctom l'agence métropolitaine des déchets ménagers

The public authority for the sustainable management of household waste in the Paris region

SIAAP

Service public de l'assainissement francilien

INNOVATION PARTNERSHIP
CO-TREATMENT OF SIAAP'S WASTEWATER SLUDGE
AND SYCTOM'S ORGANIC FRACTION OF RESIDUAL HOUSEHOLD WASTE