HYDRO-THERMAL GASIFI-CATION

WHITE PAPER

HYDROTHERMAL GASIFICATION
RECYCLING ORGANIC WASTE

HYDROTHERMAL GASIFICATION

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Acknowledgements

We would like to express our warmest and most sincere thanks to the members of the French Hydrothermal Gasification Working Group who helped to revise this document. Their contributions were invaluable in making this white paper an authoritative text on hydrothermal gasification!

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HYDROTHERMAL GASIFICATION
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French National Hydrothermal Gasification Working Group

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Foreword

This white paper has been produced by the French National Hydrothermal Gasification Working Group with the aim of setting out:

- the main characteristics and benefits of this innovative new process for treating and recycling organic waste,
- an overview of the technological advances made in hydrothermal gasification as it industrialises,
- suitable waste streams for this technology and its potential to produce gas that can be injected into the grid,
- the associated environmental and economic issues.

Ultimately, this document intends to provide the necessary knowledge base for the French government, institutions, project owners, regional and local authorities, design and consultancy firms and all other stakeholders affected by issues linked to energy, waste, decarbonisation and sustainable development. The aim is to successfully construct a framework to support the emergence of this new sector in France, in line with the framework in place for other renewable and low-carbon gas production sectors.

The context of the White Paper

In response to the climate emergency and the pressing need to implement ecological and energy transition across its regions, France must now strengthen its **energy sovereignty while also protecting the environment, developing its economy and limiting climate change as far as possible.** Therefore, the country must take into account **all of its options for generating renewable energy** to develop a balanced, sustainable energy mix while limiting the investments required from economic stakeholders. The role of renewable and low-carbon gases in this mix remains uncertain; however, this energy source can be **quick to implement, efficient and economical**, meaning that it can meet regions needs as part of their transition efforts, in terms both of **energy, environment and agrifood policies and of better waste recovery.**

Such an approach requires access to relevant solutions that can be quickly deployed. Recent technical and scientific advances mean that in the short term, regions and industry players can access new tools to help them to **tackle national challenges effectively.** Therefore, **hydrothermal gasification (also called SuperCritical Water Gasification (SCWG)) emerges as one of the most effective technologies for recycling many types of organic waste and producing renewable and low-carbon gas while also eliminating micropollutants, recycling minerals used in agriculture, recovering metals and protecting water resources.** Initial studies also indicate that hydrothermal gasification has very high potential due to its **many expected positive externalities and the ease with which it can be integrated into the circular economy**. In addition, because it can decontaminate and manage outbound flows, the technology **allows to assure an extremely high standard of health and environmental protection.**

Laying the foundations to help structure and support the sector development in France, this first white paper has been written to share the basic knowledge needed to gain full understanding of hydrothermal gasification as a whole with public administration, regional and local authorities, industry players, farmers and all other stakeholders in the fields of energy, waste and water management.

Introduction to the Working Group

The Hydrothermal Gasification Working Group, author of this paper, was established in March 2021. Its members, nearly 50 public and private stakeholders as of late 2022, constitute the French hydrothermal gasification sector, covering the technology entire value chain. Its aim is to develop and structure this innovative sector and to help its industrial location in the French energy landscape. With this goal in mind, two leading French industrial stakeholders, Leroux & Lotz Technologies and VINCI Environnement, took action in late 2021 to support hydrothermal gasification technology and its industrialisation, first in France, then abroad.

Aims of the White Paper

The central aims of this white paper are:

- to incorporate hydrothermal gasification into the French Climate-Energy Strategy (SNBC; PPE), helping public authorities to establish a regulatory base conducive to the industrial development of hydrothermal gasification in France;
- to assist public authorities as they implement an economic environment (including support mechanisms) that encourages the emergence of the sector and the development of the first industrial projects by 2026;
- to highlight a technology for treating and especially for valorising organic waste that contains or is mixed with water as:
  - → renewable and low-carbon gas that can be injected into the grid;
  - → multiple co-products (minerals, metals, nitrogen and water) which are recovered and thus preserved as resources that can be reused locally;
- to underline the role of hydrothermal gasification in the energy and ecological transition while strengthening local energy self-sufficiency and resource preservation;
- to highlight the positive externalities of the technology, particularly those relating to the environment (decontamination, decarbonisation, etc.) that have the potential to generate substantial macro- and microeconomic effects;
- to educate and inform managers of urban, agricultural and industrial waste, project owners and scientists about hydrothermal gasification so it is always considered as a possible choice for improving their waste recovery.

What is hydrothermal gasification?

Video introduction of the hydrothermal gasification

www.youtube.com

search 'hydrothermal gasification' (for the English version) or 'gazéification hydrothermale' (for the French version)

Executive summary

This document is the result of **a collective project launched by the French National Hydrothermal Gasification Working Group, whose aim is to establish an industrial hydrothermal gasification sector by 2025 in France**. It puts forward **strategic directions for this sector concerning economic, technical and environmental aspects** by bringing together a stakeholder group of local authorities, industrial players and agricultural producers, including: organic waste and wastewater management and treatment companies, industrial production sectors (agrifood industry, manufacturing, energy production, fertiliser industry, etc.) and the agricultural sector.

The Working Group was officially established in March 2021 during the Bio360 conference in Nantes, giving this technical solution **significant influence** in the domain of renewable and low-carbon gas production, waste treatment and waste recovery. Rising from its initial 27 members to 50 at the end of 2022, the stakeholders that make up the Working Group support the emergence and industrialisation of hydrothermal gasification in France. Today, **the Working Group covers most of the value chain**, including technology developers, producers of renewable and low-carbon gases, waste treatment and recovery companies, users, equipment manufacturers, professional associations, industrial stakeholders, engineering consultancies, gas grid operators, research laboratories and local authorities.

The list of members is as follows (updated in September 2023): AFRY, Agence de l'Eau Loire-Bretagne, AMORCE, Arol Energy, Artelia Industrie, Banzo, Bioeconomy For Change (B4C), BiogazVallée, Cabinet Merlin, CARENE (Saint-Nazaire Urban Community), Chambre d'Agriculture Pays de la Loire, CEA Liten, Cerema Ouest, Clever Values, Cristal Union, DG Skid, Engie Lab, France Gaz, Gazfio, GRDF, GreenConsult, GreenMac, GRTgaz, IMT Mines Albi, INERIS, Inovertis, Khimod, Leroux & Lotz Technologies, Naldeo, Naskeo, Nevezus, N01zet, Prodeval, Regaz, Renault, S3D, Saur, SER, SETEC Environnement, SIEL (Territoire d'Energie Loire), Sofresid, Suez, Tenerrdis, Terega, Tereos, Top Industrie, TOTAL Energies, TreaTech, Veolia, VINCI Environnement, Voltigital and Yélé Consulting.

The main goal of the Working Group is to support **the establishment of a French hydrothermal gasification sector by 2025** while working with international stakeholders to grow it up to a European level. More generally, the Working Group aims to **contribute to the goals of the energy transition, the ecological transition and the circular economy.**

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HYDROTHERMAL GASIFICATION: OVERVIEW AND CONTEXT

1.1 A waste treatment and recovery technology that produces renewable and low-carbon gas

1.1.1 General principle

Hydrothermal gasification is a thermo-chemical conversion process that takes place under high-pressure (210-350 bar) and high-temperature (360-700 °C) conditions, and is particularly suitable for organic waste (liquid, humid and dry) that contains or can be easily mixed with water. Water is the essential reagent that is necessary to create the specific operating conditions that the technology requires. These conditions allow the production of gas (containing methane and dihydrogen in particular) but also eliminate pathogens and pollutants (viruses, bacteria, pathogenic organisms, medicinal residues, etc.) while preserving water resources and recoverable mineral components (metals, phosphorus, nitrogen, etc.) contained in the feedstock and limiting final waste (such as certain heavy metals) to an absolute minimum or even preventing it entirely.

Among the organic waste of interest, hydrothermal gasification is primarily focused on water-based waste from biogenic sources (some of which can be mixed or polluted with waste of fossil origin[a]) but also on liquid hydrocarbon or even dry organic waste, such as:

- **A range of agricultural waste and effluent,** including livestock manure;
- **A range of waste and effluent from the agrifood industries**;
- **Sludge from urban and industrial wastewater treatment plants;**
- **Dredging and cleaning sludge;**
- **A range of organic urban waste and effluent** from household waste (organic fraction), tertiary activities (restaurants, etc.) and biowaste;
- **Digestate** from anaerobic digestion plants where spreading limits apply.

However, it is also compatible with a range of waste of fossil origin (such as soiled plastics, solvents, oils, waste from the chemicals and petrochemicals industries, etc.), some of which can be solid and dry. This waste often arises from industrial activity and is not recycled or recyclable in its current form. As such, it is sent to incineration facilities (with or without energy recovery) or to landfill with all of the associated air, soil and water pollution risks.

[a] Example: (micro-)plastic packaging or other fossil- or hydrocarbon-based chemical waste

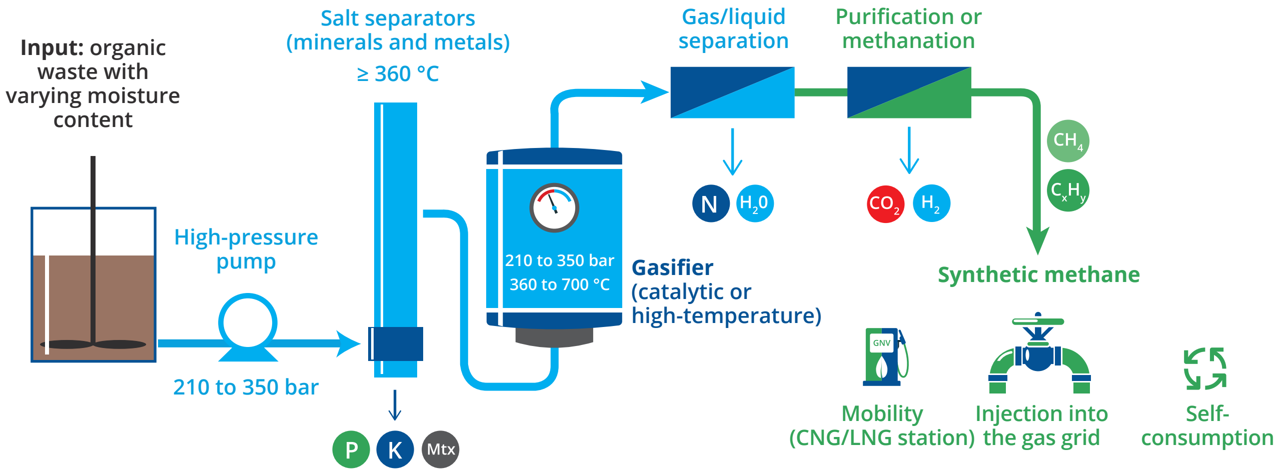

Figure 1: Simplified process diagram for hydrothermal gasification (Source: GRTgaz/Cerema).

1.1.2 Hydrothermal gasification: optimum waste processing and recovery

In keeping with the waste treatment and recovery hierarchy, hydrothermal gasification targets wet or dry organic waste that is non-recyclable, non-recoverable and/or polluted and is currently incinerated or sent to a waste disposal facility.

Hydrothermal gasification thermochemically converts almost all of the carbon contained within the feedstock by forming co-products used for energy recovery purposes (biomethane and dihydrogen), while also recycling and recovering materials (water, nitrogen, minerals and metals) from the initial waste.

The following diagram illustrates hydrothermal gasification positioning within the processing sector for primarily wet organic waste:

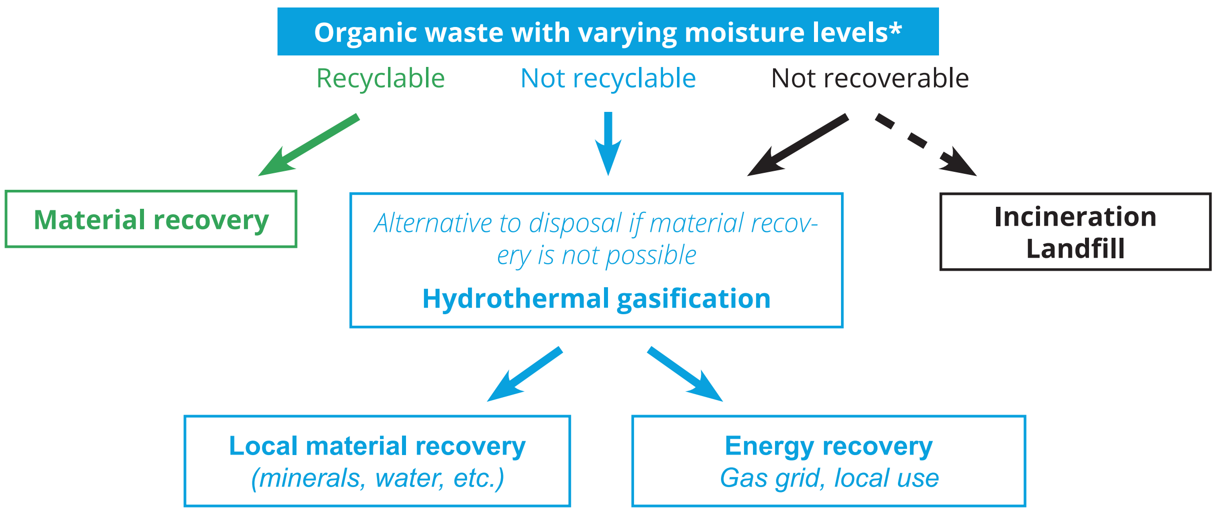

Figure 2: Positioning of hydrothermal gasification for treatment of organic waste with varying moisture levels (Source: Cerema/GRTgaz). (* Waste containing water or dry matter waste to which water can be added.)

a) Hydrothermal gasification avoids the need for incineration

Despite having relatively high moisture levels, a large quantity of organic waste is currently **pre-dried**, a process which consumes significant amounts of energy, before being incinerated. This stage is carried out in incinerators, with or without energy recovery (MWI/WtE plant), or in high-temperature furnaces (cement plants, lime production, etc.) in France and abroad.

The overall energy balance of this processing is zero at best and generally negative, with a very high environmental cost! Some waste even ends up in landfill. For example, this can include:

- Sludge from urban WWTPs (26% incinerated according to AMORCE [1], equivalent to 286,000 tonnes of DM[a]/year),
- Industrial sludge classed as 'hazardous',
- Animal waste (all categories) from abattoirs, some of which requires prior thermal treatment (production of meat-and-bone meal), an avoidable process that can easily be substituted with hydrothermal gasification while significantly increasing overall recycling of this type of feedstock,
- The organic fraction of household waste (OFHW), obtained via mechanical-biological treatment (MBT), that is not suitable for recycling into compost or for spreading due to non-compliance,
- Special waste from a range of different industry sectors (including solvents, production residue, paint, contaminated oil, etc.), some of which is, at least in part, of fossil origin,

[a] DM = Dry Matter

- **Any other wet waste that breaches agricultural safety criteria for returning matter to the soil (high concentration of trace metal elements, microplastics[a], pathogens, etc.).**

Through the use of hydrothermal gasification, incineration (combustion) – with or without energy recovery – can be avoided. Incineration presents problems on multiple levels because:

- Wet feedstock must be dewatered and dried before it is combusted, **a process that consumes a non-negligible portion of the energy produced during combustion** [2];
- Heat recovery varies widely depending on the season and **this heat can only be stored in limited quantities, unlike renewable and low-carbon gas, which can easily be stored in gas grids throughout the year;**
- Combustion at very high temperatures (> 1000 °C) **generates extremely polluting and toxic gases that require very costly processing to minimise the environmental impact;**
- **Incineration destroys the majority of resources contained within the feedstock,** making recycling almost impossible.
- **Incineration is a very expensive method of waste treatment**, costing up to several hundred euros per tonne.

b) Hydrothermal gasification avoids the need to send waste to landfill

Hydrothermal gasification is capable of treating and recovering organic waste with varying levels of pollutants, within a certain limit and depending on the type of pollutant. Thanks to this key benefit, it is able to position itself as an eco-friendly alternative for a number of final waste types[b] that are currently buried in Waste Disposal Facilities (WDFs) for want of better solutions. Although open landfill sites are doomed to disappear, hydrothermal gasification technology could also be used to redirect some landfilled waste for final recycling.

In parallel, this redirection could have a positive impact by helping to lower the prevalence of illegal waste dumping and the impact that this has on the environment.

1.1.3 Hydrothermal gasification positioning compared to other gas-producing sectors

Hydrothermal gasification is positioned as a new method of treating and recovering a wide range of wet or water-miscible organic waste, as an **additional or alternative solution** depending on the type of waste, whether it is biogenic or fossil in origin and its composition (mixed or separated; whether pollutants, pathogens or microorganisms are present) (Table 1).

It presents an alternative to other renewable and low-carbon gas conversion technologies by treating segregated and mixed organic waste with varying levels of moisture. Hydrothermal gasification drastically reduces the proportion of final waste (by a factor exceeding 15 to 20 compared to the initial quantity) while producing a raw gas, called synthetic gas, that is rich in methane and hydrogen:

- **Catalytic hydrothermal gasification:** 60-70% CH_4 + 5-10% H_2
- **High-temperature hydrothermal gasification:** 30-40% CH_4 + 25-50% H_2 + up to 12% C_xH_y[c]

Hydrothermal gasification can also be incorporated downstream of other processes, for example:

- **anaerobic digestion plants:** when located at the digester output, a hydrothermal gasification system can recycle digestates that are difficult or impossible to recover due to spreading

[a] Hydrothermal gasification technology converts microplastics into methane-rich gas. See section on waste streams.
[b] Final waste – according to the French law of 13/07/92 – is waste that can no longer be processed under current technical and economic conditions, including by extracting the recyclable portion or minimising its polluting or hazardous nature
[c] C_xH_y = heavier hydrocarbons than methane (especially ethane, butane, propane) that can be injected into the gas grid

Table 1: Positioning of hydrothermal gasification compared to other renewable and low-carbon gas sectors (GRTgaz).

Sectors	Feedstocks recovered	Conversion process/ Details	Maturity (2022) (with gas grid injection)
Anaerobic digestion (wet or dry)	Fermentable organic waste (may be mixed subject to conditions, not polluted and hygienised where required)	Anaerobic digestion Carbon conversion: medium (40 to 70%)	TRL 9 Industrial
Thermal gasification (various processes)	Solid organic waste of biogenic or fossil origin (lignocellulosic material, SRF, tyres, etc.) varying degrees of pollution	High-temperature thermochemical conversion (850 to 1500 °C); Carbon conversion: high (> 80%)	TRL 6-9 Depending on the process Industrial demonstrators: Gaya project (France), GoBiGas (Sweden)
Power-to-Methane	Water + Renewable (or low-carbon) electricity	Water electrolysis + methanation ($H_2 + CO_2 \rightarrow CH_4$)	TRL 6-9 Industrial demonstrators: Jupiter 1000 (France) and several PtG projects in Europe.
Hydrothermal gasification	Organic waste of biogenic or fossil origin containing – or miscible with – water	Thermochemical conversion (210 to 350 bar + 360 to 700 °C) Carbon conversion: Between 85 and 99%	TRL 5-9* Several pilots, a demonstrator and an industrial facility in Europe (see Chapter 5). * *The world first industrial facility, by SCW Systems, will be finally commissioned in 2023.*

limits (for zones with a nitrogen surplus) or bans on spreading or composting, for example if pollutant thresholds, such as for metals or microplastics, are exceeded (cf. changing regulations). It can also avoid the need for the hygienisation of certain waste that is typically processed prior to anaerobic digestion due to the potential presence of pathogens.

- **via power-to-gas plants generating hydrogen:** the synthetic gas produced via hydrothermal gasification still contains some carbon dioxide. By combining this gas with hydrogen from electrolysis, the methane output of a hydrothermal gasification facility can be significantly increased, by up to 100%!

1.1.4 A technology rooted in the circular economy

Hydrothermal gasification creates a number of synergies, benefits and positive externalities at the regional level, a growing number of which could be monetised. In particular, it:

- Increases regions' energy self-sufficiency and resilience **via production of renewable and low-carbon gas that can easily be stored in gas grids;**
- Provides **fertilisers** (potassium, nitrogen and phosphorus) after the necessary separation and processing via specific methods (some of which still require development). These fertilisers can be **recovered and used in measured applications** to replace conventional industrial fertilisers whose production and use consumes fossil fuels and can be a source of agricultural soil pollution;
- Provides **industrial-quality residual water** from the hydrothermal gasification process. Depending on the type of feedstock treated, this water contains **varying degrees of nitrogen** (ammonium (NH_4^+)) that can:
  - > **Be used to meet agricultural or urban irrigation needs without further modification;**
  - > **Or be brought up to drinking water standards** after removing the nitrogen and meeting any final filtering process requirements;

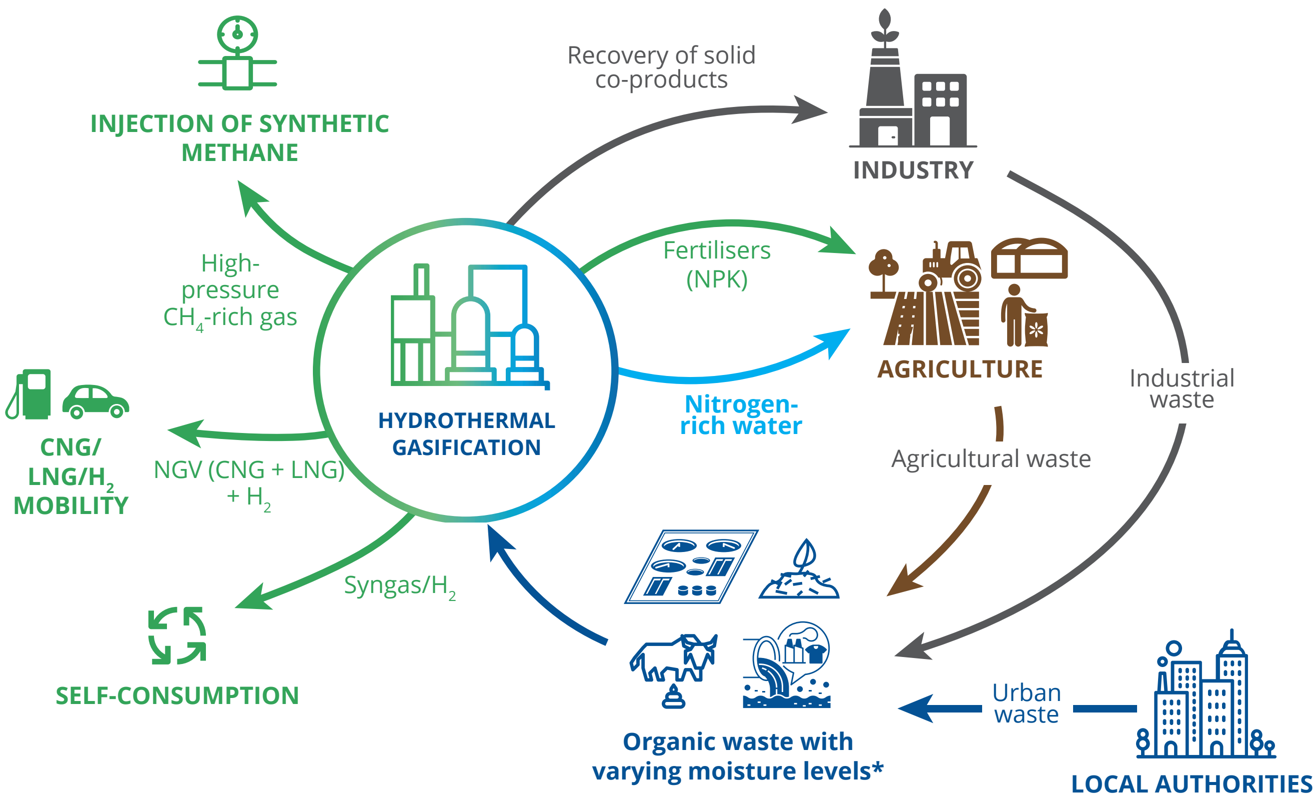

Figure 3: Potential for recycling water treatment sludge via hydrothermal gasification (Source: GRTgaz/Cerema).

- **Decontaminates** feedstocks by eliminating all complex organic compounds (medicinal residues and other micropollutants) and pathogenic microorganisms, which are unable to withstand the high-pressure, high-temperature conditions;
- Produces residual CO_2 with a minimum purity of at least 98%, which can be used as a feedstock for multiple purposes, including producing biostimulants via **microalgae production** or transforming the CO_2 into solid carbon to meet an extremely diverse range of needs and, after final purification, supply a variety of industrial processes, including agrifood processes, that use CO_2;
- Collects, separates and recovers any metals present in the processed waste that may have significant economic value in terms of either the quantities recovered (iron, aluminium, copper, etc.) or their rarity. This final point requires the existence of an economically viable separation and recovery technology. If no such technology exists, the residue could be used in the cement industry.

These externalities will be detailed alongside many others in Chapter 5 of this white paper.

This makes hydrothermal gasification a key tool for regions as they establish a circular economy. The figure above (Figure 3) presents an example of the potential for recycling when using a hydrothermal gasification facility to process sludge from water treatment plants.

In this example:

- **The synthetic methane** generated is recovered via injection as biomethane, renewable or low-carbon gas into the gas transmission grid or used locally as a source of decarbonised (bio) CNG or (bio)LNG for mobility purposes,
- **The residual water** is reused for irrigating local fields or watering in local parks,
- **The metals** (rare earth metals, heavy metals, etc.) are recycled in industry to replace non-sustainable resources.
- **The phosphorus, potassium and nitrogen** are recycled and transformed in new agricultural fertiliser products to be used to grow crops for human and animal consumption.

1.2 Context and the environmental and energy challenges

At the crossroads between waste treatment, **waste recovery and energy production**, hydrothermal gasification is fully in line with public policies on the circular economy, the bioeconomy, the energy transition and decarbonising the regions of France.

1.2.1 Combating climate change and developing the circular economy

In 2021, the European Commission reaffirmed its commitment to carbon neutrality with the publication of the 'Fit for 55' climate package, which **sets a target of reducing net greenhouse gas emissions by 55% compared to 1990 levels by 2030** and aims to make Europe **the first climate-neutral continent by 2050** [3].

To meet the terms of the Paris Agreement and comply with European policies, France also has its own ambitious legislative framework: the Energy-Climate law (2019), the Climate and Resilience law (2021) and the Energy Transition Law for Green Growth (LTECV, 2015), whose aim is **to reduce GHG emissions by 40% by 2030 and divide them by four by 2050**.

Alongside this, the AGEC (Anti-Waste for a Circular Economy) law of February 2020 is presented as a priority for France to enable sustainable green growth and strengthens the legislation mentioned above. Decarbonising France's regions requires action across all value chains: reducing gross final energy consumption (through energy sobriety and efficiency), increasing the share of renewable energy, protecting resources and improving waste recovery.

Hydrothermal gasification, with its many benefits, offers a non-negligible long-term contribution to these laws and their goals. In addition to its ability to generate renewable and low-carbon energy, hydrothermal gasification also provides an effective solution for treating and decontaminating organic waste for which recycling is currently poor, insufficient or non-existent. It appears to be a better alternative to incineration and landfill, and promotes local recycling of the co-products it generates (water, nitrogen, minerals, metals and renewable low-carbon gas). This means that hydrothermal gasification can make a positive contribution to efforts to combat climate change, lower GHG emissions and reduce resource wastage while actively contributing to the energy transition and helping to make France more self-sufficient in energy.

1.2.2 Production of renewable and low-carbon gas

In terms of energy, natural gas represents around 15.5% (≈ 415 TWh, corrected of climate variations) of annual primary consumption in France in 2021, while renewable energy including renewable and low-carbon gases (4.3 TWh_{HCV} injected in 2021) accounts for just 13% of this consumption [4]. The future of the gas market, which has been increasingly affected by the desire to reduce dependence on fossil fuels and thus minimise their climate impact, depends on its ability to become 100% renewable and low-carbon by 2050 and act as a major driver in making regional decarbonisation possible.

As part of the creation of the new **Energy and Climate Planning Law (LPEC) scheduled for 2023** and more specifically the National Low-Carbon Strategy (SNBC) and the Multi-Year Energy Programme (PPE), the gas industry – GRTgaz, GRDF, FGR and the ATEE Club Biogas, Club Thermal Gasification and Club Power-to-Gas – issued a memo estimating that renewable methane production could realistically reach **320 TWh_{HCV} by 2050**, most notably through anaerobic digestion and emergent technologies such as thermal gasification, methanation[a] and hydrothermal gasification [5]. **The hydrothermal**

[a] Methanation: another name used by the French gas sector to refer to Power-to-Gas.

gasification sector alone would provide at least 50 TWh per year of biogas production (equivalent to around 15% of estimated total renewable methane production in 2050).

1.3 The state of development of HTG technology in Europe

In Europe, the first technological developments in this field were carried out by the Karlsruhe Institute of Technology (KIT) in Germany with a pilot project (called VERENA) launched in 2004, making it the first pre-industrial facility of its type anywhere in the world. It took some 10 years before similarly sized projects were developed in Japan and the United States, along with further European projects in the Netherlands, Switzerland (Paul Scherrer Institute – PSI), Spain and France (Commissariat à l'Énergie Atomique - CEA) from 2014. At the scientific level, the KIT and the PSI, closely followed by the CEA, established the scientific and technological foundations for hydrothermal gasification in Europe, becoming the leading players in the technology scientific development at a global level. Since 2015, a number of private pilot facilities have gradually been developed across Europe, with the increasing pace demonstrating the sector interest in this waste treatment and recovery technology. Of particular note is the involvement of SCW Systems and also TreaTech, each of which is the leader in their field (SCW Systems in high-temperature Hydrothermal Gasification and TreaTech in catalytic hydrothermal gasification) in Europe and even worldwide.

As the French context presents a number of unique features in terms of waste management and energy production within Europe, **the new hydrothermal gasification sector must be consistent with the current French ecosystem**, whose focuses are changing and tending towards convergence (through updates to European directives) with those already in place among our European counterparts. As a result, new regulatory constraints, such as those governing acceptable pollutant levels when spreading sludge from WWTPs and digestate from anaerobic digesters, will ultimately open up potential waste streams for hydrothermal gasification, which, in the future, will be the sole solution capable of treating and recovering this waste.

On the question of returning carbon to the soil, which is the intended outcome of certain technologies such as anaerobic digestion, hydrothermal gasification should be regarded as an alternative in situations where limits apply to digestate spreading. The same is true for the question of alternative approaches to recovering organic biowaste material. As such, the emergence of hydrothermal gasification in Switzerland and the Netherlands, in different contexts, at the very least deserves to be taken into account to benefit from the lessons learned, a crucial element in developing a sustainable French and European sector.

The German model

Germany was a pioneer of hydrothermal gasification in Europe, with the KIT setting up its pilot facility VERENA in 2004. This pre-industrial scientific pilot facility, capable of processing up to 100 kg/hour of feedstock and operating at a maximum temperature of 700 °C with high gas yields (> 90%), was developed to treat a wide range of waste, including residue from beer production, WWTP sludge, industrial waste, etc. The success of this initial project inspired other scientific and industrial developers in Europe to focus on hydrothermal gasification and resulted in fruitful scientific partnerships, including with leading Dutch and Swiss stakeholders (for example, a partnership with the PSI that resulted in a successful test of the first industrial-scale salt separator – see the next paragraph).

The Swiss model

In Switzerland, hydrothermal gasification was identified from the very beginning in the early 2000s as a promising technology that warranted the support of the Federal Office of Energy, which was seeking an alternative solution to incinerating WWTP sludge. **Since 2006, a ban on spreading sludge or sludge digestate originating from WWTPs has been in place, forcing waste managers to dry and incinerate all of this residue. In addition to this requirement, from 2026, it will be mandatory to recover phosphorus from sludge and sludge digestate.** Currently, incineration (and more specifically, mono-incineration) is, for the moment, the only means of treating sludge and sludge digestate and shall be able ultimately to recover phosphorus from the sludge ash. **Thanks to its ability to precipitate mineral salts** (phosphorus in particular) **upstream of the reactor** (see Chapter 4), **hydrothermal gasification becomes a credible alternative, including economically** (see Chapter 6). In comparison, sludge incineration is a very energy-inefficient process: for feedstocks that are mainly composed of water[a], its net energy yield is zero.

The Netherlands, the leading European player in hydrothermal gasification

The Netherlands is **undeniably the world most advanced country in the field of hydrothermal gasification technology. The company SCW Systems** launched its first industrial hydrothermal gasification plant in the Netherlands (Alkmaar 1), which has a thermal capacity of 20 MW_{th}[b] and processes feedstock at a rate of 16 t/h. Scale-up to commercial levels is planned in the 1st half of 2023. For its first two experimental industrial projects (Alkmaar 1 (20 MW) and 2A (40 MW)), the sector is receiving strong public support for the synthetic methane injected into the gas grid: €73 to €75/MWh_{HCV}, guaranteed for 12 years. Both of these projects are already part of the country 'Groen Gas 2030' roadmap in which hydrothermal gasification is a preferred method of producing renewable gas:

- its total **gas production capacity** is estimated at **11.5 TWh/year**;
- **providing up to 57% of the country renewable gas production in 2030**.

1.4 The state of development of the hydrothermal gasification sector in France

1.4.1 Hydrothermal gasification in France

In France, the development of hydrothermal gasification technology began in the early 2010s with the first scientific research works and publications from a number of academic stakeholders, including IMT Mines Albi, a specialist in hydrothermal technology, Grenoble INP and other academic institutions such as CEA-Liten, which, in 2022, had France's only hydrothermal gasification prototype (10 kg/h).

The Hydrothermal Gasification Working Group, which was officially launched in 2021, has almost 50 partners (including academic, developer and gas sector stakeholders) in 2023, and its aim is to assist the development of this technology. It works to establish a true hydrothermal gasification industry by facilitating partnerships between its members and by informing public authorities on implementing suitable support mechanisms and regulations for hydrothermal

[a] The PSI and TreaTech have a pilot hydrothermal gasification facility with a capacity of 100 kg/h (see section 4.2.2). The mineral salt separator recovers almost all of the phosphorus, which can then be converted into phosphoric acid or a fertiliser (for example struvite).

[b] MW_{th}: Megawatt thermal.

gasification technology. The growing number of demand-side stakeholders (including industry and local authorities) reflects the need for rapid development of the technology in France and its relevance as a solution for current and future issues (the strengthening of environmental and climate constraints). The Working Group aims to promote the technology to public and private stakeholders to make hydrothermal gasification a part of the energy landscape in light of its many benefits that support its inclusion at the heart of the circular economy.

Significant progress was made in early 2022 with the announcement of the first two French industry stakeholders interested in developing and promoting hydrothermal gasification technology:

- **Leroux & Lotz Technologies**: High-temperature hydrothermal gasification based on the technology first developed by the KIT (Germany),
- **VINCI Environnement**: Catalytic hydrothermal gasification technology including prior hydrothermal liquefaction, based on the technology developed and provided by the American company Genifuel, one of the global pioneers in this technology.

In France, several initiatives are under way, beginning with pilot and industrial demonstrator projects before the first industrial projects are launched from 2026. The most advanced project in 2022 is the **GHAMa demonstrator project in Montoir-de-Bretagne (Loire-Atlantique)**, the work of a group of partners seeking to build on the technology currently being developed by Leroux & Lotz Technologies to create an **initial demonstrator project capable of processing 2 t/h (2 MW_{th}) of waste, including WWTP sludge from CARENE[a], the urban community centred on Saint-Nazaire**. It is scheduled to be commissioned at the end of 2024, but this date is dependent on the public support (primarily grants) available for such a project with a relatively large budget (> 10 M€).

1.4.2 Initial practical initiatives in the sector...

Since the creation of the National Hydrothermal Gasification Working Group, work has been carried out to identify the obstacles and difficulties involved in setting up the first demonstrator projects. This process has been reinforced by prospective work to identify the necessary support requirements when the first industrial projects are launched in 2026.

In light of this, the Hydrothermal Gasification Working Group submitted **an initial stakeholder guide on hydrothermal gasification, which was published in February 2022** [6] **as part of the public consultation on the future French Strategy for Energy and the Climate (SFEC)**. The aim was to inform public authorities of Hydrothermal Gasification Working Group members' intention to focus on hydrothermal gasification as a credible tool for tackling current and future energy and environmental challenges in the near term (by 2026).

In purely technical terms, the Hydrothermal Gasification Working Group has drawn up a non-exhaustive list identifying key stakeholders in France that are capable of meeting all requirements for the equipment used in the hydrothermal gasification value chain and eliminating the remaining technological barriers in the short term.

1.4.3 ... to be supplemented with a strong framework of support from public authorities

Support measures are already in place for the anaerobic digestion sector and are currently being discussed for the thermal gasification sector. In the same way, **the hydrothermal gasification sector**

[a] CARENE: *Communauté d'Agglomération de la Région Nazairienne et de l'Estuaire* (Urban Community of the Saint-Nazaire and Estuary Region)

also needs public authorities to introduce an economic support framework through incentives and regulations as soon as possible to allow development to take place first in France, then internationally, by building on those first projects:

- **Implementing – at the operational level – experimental contracts and other long-term and incentive-based measures** (injection into the gas grid, guarantees of origin, taxation, administrative exemptions to facilitate implementation) to launch and secure the first industrial-scale projects producing biomethane or low-carbon synthetic methane using hydrothermal gasification technology,
- Creating **a specific regulatory framework for the technology** to avoid the implementation of unwarranted actions with respect to the intrinsic functioning of the technology (no combustion, no odour, no hygienisation, no atmospheric emissions, etc.), ideally by creating a specific environmental protection classification (ICPE) framework for hydrothermal gasification technology.

Finally, **the development capabilities of the French companies** that are investing in this innovative technology (both the core process and the upstream and downstream components) **would be significantly improved** if a suitable public support framework existed (for example, an expansion of Bpifrance's unsecured loans). This would be required in particular to support an increase in TRL (Technology Readiness Level) from level 5/6 to level 8/9, an essential step for any new technology prior to industrialisation. While European funding does exist, it would be worthwhile to apply this at the national level to support funding requests, in particular when increasing a technology TRL, where the funding requirements are relatively high (> 5-10 M€ per company). Creating a range of funding specific to each scope (national, regional, local) would encourage technological development and help to establish HTG itself within regions. The most advanced foreign competitors, such as SCW Systems and TreaTech, have been able to develop hydrothermal gasification much more quickly than others. One of the reasons for this is that they received the necessary financial support from both the public sector and the private sector. In Switzerland, for example, companies can save on taxes by investing the amount due in start-ups or innovative companies, with the potential to eventually make profit.

To highlight the technology short-term potential and to achieve a sufficient number of hydrothermal gasification projects to create an initial market in France, **the members of the Hydrothermal Gasification Working Group believe that by 2030, an annual target of new injectable gas production capacity of 2 TWh_{HCV}/year is entirely realistic with suitable support mechanisms.** The hydrothermal gasification sector would then be capable of contributing to the **overall cross-sector target of producing 60 TWh of renewable and low-carbon gas annually** within the same timeframe. It will actively contribute to better local processing of a wide range of waste types for which recovery is currently poor, insufficient or non-existent. It will also contribute to decarbonising a number of business sectors, to the energy self-sufficiency of both France and its regions and ultimately to a 100% renewable and low-carbon gas mix in French and European gas grids while encouraging the adoption of a circular economy approach.

02

OVERVIEW OF HYDROTHERMAL GASIFICATION

2.1 Introduction to the technology

Hydrothermal gasification is a thermochemical conversion technology that uses organic waste to produce synthetic gas, a mix primarily composed of methane (CH_4), hydrogen (H_2) and carbon dioxide (CO_2). It is one of a broad family of hydrothermal technologies that all use water as a reaction medium and do not require the use of an oxidiser. They use different pressures and temperatures, either below or above the critical point of water (374 °C, 221 bar). Their common characteristic is that they convert the organic component of waste into a number of recyclable products. Of these technologies, hydrothermal gasification is considered the most advanced form because of the many possibilities it offers in terms of waste recovery and energy production.

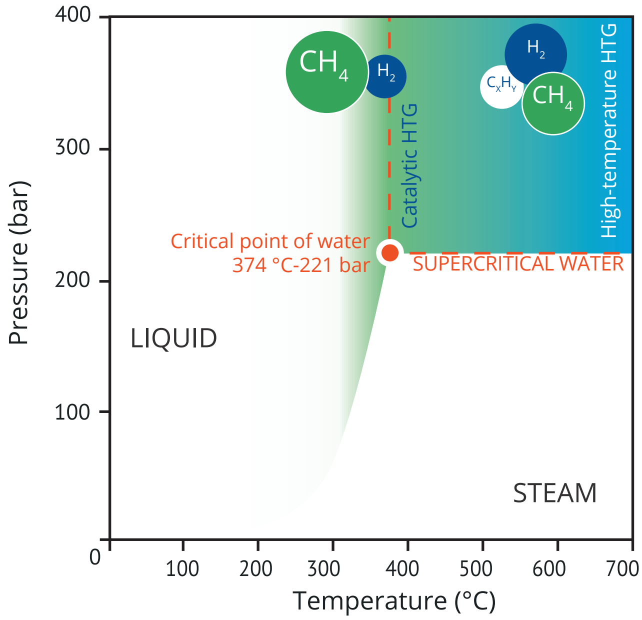

Figure 4: Water phase diagram (pressure/temperature) (Source: Cerema/GRTgaz).

The principle behind hydrothermal gasification

Hydrothermal gasification relies on the presence of water in 'supercritical' conditions of high pressure and high temperature. In this state, near to and beyond the critical point (Figure 4), water is highly reactive and, most notably, can 'crack' carbon-based molecules, precipitating out inorganic elements. In nature, such conditions can occur at great depths, such as in the Earth crust or in the sea in the hydrothermal vents found near ocean ridges.

In hydrothermal gasification, the water either comes from the feedstock itself or is added to it or directly to the gasification reactor. This is the case for organic waste or effluent that does not contain water and whose particles are no larger than a few millimetres in diameter.

The technology can also be used to treat a very wide range of organic waste and effluent, whether segregated or mixed, and whether biogenic (as in most cases) or fossil in origin.

Several parameters must be met to convert organic waste via hydrothermal gasification. Firstly, the feedstock must be pumpable (fluidity and granulometry compatible with the pump) and contain sufficient energy to allow its conversion into renewable and low-carbon gas.

Table 2: Hydrothermal technologies (GRTgaz).

Hydrothermal process	Temperature and pressure	Sub- or supercritical water	Primary product (at output)
Hydrothermal carbonisation (HTC)	180 to 250 °C 10 to 50 bar	Subcritical water	(Bio)char
Hydrothermal liquefaction (HTL)	250 to 350 °C; 40 to 220 bar	Subcritical water	(Bio)crude (≈ crude oil)
Hydrothermal gasification (HTG)	360 to 700 °C; 210 to 350 bar	Supercritical water	Synthetic gas/Synthetic methane

The main parameters are:

- **the water content:** This parameter is determined by measuring the dryness[a], expressed as the percentage of dry matter (DM). This content varies greatly, from 5% to over 85%. If the feedstock is too deficient in water, addition may be necessary.
- **the carbon content:** Measured by the proportion of organic matter (OM), this parameter is crucial in optimising the production of renewable and low-carbon gas.

Therefore, it is essential that the dry matter fraction of the waste or waste mixture contains as much Organic Matter (OM) and thus carbon as possible, a crucial resource for the conversion of waste into synthesis gas. **An OM/DM ratio of at least 40-50% is generally targeted.**

As the pressure and temperature are increased to water critical point, its physico-chemical properties change drastically. Supercritical water behaves as much like a gas as it does a liquid, combining the benefits of each of these states with high solvation and extraction properties (low viscosity, high diffusivity, excellent dissolving properties, etc.). This means that supercritical water can dissolve and reorganise a wide variety of organic and inorganic compounds. Although it is highly complex, in summary, the reaction affects:

- **inorganic or mineral compounds** (minerals such as phosphorus, potassium and metals) contained within the feedstock, which precipitate in the form of salts and concentrate at the bottom of the reactor by gravity, where they are removed from the initial fluid. The salt separator was developed for this exact purpose upstream of the gasifier. Because the gasifier is installed downstream of the separator, it receives only organic compounds and water (which may contain nitrogen), and as a result the desired chemical reactions are much easier to achieve.
- **organic compounds** from the feedstock, which, once separated from the inorganic compounds, take the forms of molecules of varying complexity: they are 'cracked' in the gasifier, or, in other words, are broken down into components with lower molecular weight (including to the elemental level) before being recombined through several chemical reactions, most notably between hydrogen and carbon to create methane.

As the residence time in the gasifier (the name for the hydrothermal gasification reactor) is fairly short, a few seconds at most, the transformation of the carbon- and hydrogen-rich fluid (which is also nitrogen-rich) into synthetic gas is not complete. Reassembling these elements results in:

- a **high-pressure synthetic gas** (at 210-350 bar), which is high in methane and, more or less, in hydrogen along with carbon dioxide and sometimes alkanes (higher hydrocarbons such as ethane, butane and propane),
- and a **liquid residue** (if the initial feedstock contained water) formed primarily of water high in ammoniacal nitrogen (NH_4^+).

Gaseous, solid and liquid co-products

The composition of the gas varies based on the characteristics of the organic waste treated, the operating conditions (temperature, pressure, flow, residence time and whether a salt separator is present) and in particular the type of hydrothermal gasification technology used. There are two types:

- **'Catalytic'**, with a catalyst integrated into the gasifier intake: the presence of a catalyst reduces or limits the reaction temperature to around 360-400 °C and promotes the production of methane, which can account for as much as 70%, and limits the hydrogen part at 5 to 10% of the synthetic gas generated [7].
- **'High-temperature'**: this type uses higher temperatures of 550 to 700 °C. These temperatures result in synthetic gas with a much higher hydrogen content (30-50%), which can even exceed the proportion of methane (30-40%) under certain conditions.

With a very high carbon conversion rate, ranging from 85% for more complex waste such as sludge to almost 100% for simpler organic waste such as glycerol, this technology can recycle almost all of the carbon contained in the feedstock.

[a] Dryness: Proportion of Dry Matter in the Total Matter (%DM/TM).

The composition of the synthetic gas, which is the reactor output product with the highest economic value, nonetheless differs depending on the type of technology and the parameters described above and:

- **in all cases, contains methane (CH_4) and hydrogen (H_2) to varying degrees, along with carbon dioxide (CO_2). This gas can be processed downstream to generate synthetic methane that can be injected into the grid,**
- **sometimes contains up to 12% hydrocarbons with a higher energy content than methane. These alkanes (C_xH_y) include especially ethane, butane and propane.**

As shown above, in addition to the production of synthetic gas, hydrothermal gasification also recovers and recycles the water and the inorganic and mineral components contained in the waste. Their proportions in the outbound flows are based on the nature of the feedstock and their value also varies. These inorganic components primarily include:

- **minerals (phosphorus, potassium, etc.) and nitrogen,** which are of interest for agronomic applications as they can be used to make new fertilisers,
- **metals** that, depending on their volume or rarity, may be of economic interest,
- **water**, which can be recycled directly or following suitable treatment (production of drinking water) and
- **any other solid components**, which can be used in cement production.

2.2 Pretreatment of feedstocks

Preparing the feedstock is the first step in hydrothermal gasification. The preparation process is heavily dependent on the type or composition of the feedstock – whether it is of a single type or mixed – and aims first to homogenise its gross composition to ensure it is fully pumpable. This step helps to simplify the process of separating out the inorganic matter contained in the feedstock and facilitates the desired thermochemical reaction. The aim is to achieve the correct viscosity by adjusting the dryness, the granulometry (maximum particle size of a few millimetres), the composition and the temperature while also maximising the energy content of the feedstock.

To do this, the granulometry of the feedstock can be limited within the system (to a few millimetres) via sieving or grinding, certain unwanted components can be separated out (inert organics, corrosive compounds, etc.) and the feedstock organic matter can be concentrated or diluted to optimise its gas conversion.

It can also be beneficial to pre-heat the target organic waste to 80-90 °C upstream of the high-pressure pump: for some feedstocks, such as WWTP sludge, which become very compact at relatively low concentrations (from 17% DM/TM), the higher temperature improving pumpability and pressurisation by modifying the viscosity. Thus, it is possible to further concentrate and energetically enrich (with a greater carbon input) the sludge (to 20% or more) without the risk of blocking the high-pressure pump. Another method to improve pumpability, which is also cheaper, is to mix organic waste types with complementary characteristics: for example, combining sludge with grease or oils simultaneously increases pumpability, dryness and the average energy content of the mixture.

2.3 Pressurising the feedstock and increasing the temperature

Having been prepared, the feedstock is then compressed using a high-pressure pump until it reaches 210-350 bar, with the pressure determined by the operating conditions specified by the developer. It is then (pre-)heated until it reaches supercritical (or near-supercritical) conditions. The heat is provided either from an external source (when starting up the facility) or from the residual heat recovered from the gasifier itself. Heat can be provided by, for example, a gas or biomass boiler or by electrical resistance, and serves to maintain the gasifier nominal temperature, which is between 360 °C and 700 °C, depending on the requirements of the type of hydrothermal gasification used (catalytic or high-temperature).

2.4 The salt separator

A significant portion of the organic waste that can be processed in a hydrothermal gasification facility contains inorganic compounds, including minerals (phosphorus, potassium, calcium, etc.) and sometimes also metals. As they are not involved in the targeted thermochemical reactions, these compounds precipitate under the conditions required for supercritical water (section 2.1), concentrating at the bottom of the gasification reactor by gravity.

To facilitate the process of separating out these salts, HTG technology developers (KIT, PSI, TreaTech, etc.) have worked on designing a separate device, the **salt separator**, which optimises mineral and metal separation upstream of the gasifier. The PSI and TreaTech have successfully demonstrated the added value of their systems, which has drawn the attention of other developers working in the field.

The inorganic solids that are collected are removed from the separator via a ‘flush’-type system that works by depressurising a semi-open circuit. However, this circuit, located at the bottom of the separator, captures a small proportion of the carbon-containing fluid. After separation, a ‘brine’ is recovered. To keep the loss of carbon-containing fluid to an absolute minimum, high-pressure recycling systems are used to reinject the carbon (trapped in the brine) downstream of the high-pressure pump, into the main process.

The remaining concentrated brine with its high mineral and metal concentration must then undergo one or more treatment processes beyond the scope of the hydrothermal gasification facility to be recycled into finished products. Because of its ability to recycle metals, hydrothermal gasification is also used in laboratories to recycle circuit boards (such as in the REMETOX project by the CNRS).

Some minerals can be recovered from the brine via a range of processes such as acid leaching. For example, phosphorus[a] can be recovered in the form of phosphoric acid to be used in fertilisers. Furthermore, several promising technologies for recovering phosphorus from sewage sludge are currently being developed or tested at the European level[b]. These technical advances could complement the hydrothermal gasification process to optimise its phosphorus recovery capabilities.

Ultimately, depending on the composition of the residue after separating out all minerals of interest, the remaining by-product could have applications in certain industries, such as the cement industry (for example, in the raw mix).

[a] France, like all other European countries, depends on fossil phosphorus imports, primarily from mines in Morocco and Russia. Intensive agriculture consumes large volumes of phosphorus, mainly through the use of artificial fertilisers. Hydrothermal gasification can be an extremely effective way of recovering almost all of this phosphorus – which is found in particular in certain feedstock types, such as sludge from WWTPs and dredging sludge – for processing (see ‘Switzerland’, section 1.3)

[b] www.phosphorusplatform.eu

2.5 The two main hydrothermal gasification processes

2.5.1 The high-temperature hydrothermal gasification process

In the high-temperature process, the hydrothermal reaction requires temperatures of 550-700 °C in the gasifier in order to be able to effectively convert the fluid into renewable and low-carbon gas. Historically, among the majority of developers of this type of process, the fluid introduced into the gasifier still contains its solid components (with no upstream salt separator): the supercritical conditions result in the separation of the mineral salts by gravitational precipitation to the bottom of the gasifier, where they can be removed using an appropriate mechanism (see previous section). However, the current trend among developers is to implement a salt separator upstream of the gasifier so as to achieve the highest possible level of thermochemical conversion of the carbon-containing fluid.

The carbon-containing fluid that remains in the gasifier, which is primarily water, carbon and nitrogen, is then converted into the largest possible quantity of synthetic gas. Initially, its composition is approximately 30% methane (CH_4), 30% hydrogen (H_2), 30% carbon dioxide (CO_2) and 10% alkanes, primarily ethane (C_2H_6). The proportions of these four components can nonetheless vary to a certain extent based on the type of feedstock, the operating conditions and other parameters (see Table 2).

As conversion of the fluid to synthetic gas is not complete, some of the fluid remains, mainly composed of water and nitrogen, which requires the use of a gas/liquid separator to separate the water from the high-pressure synthetic gas.

After separation, the raw high-pressure synthetic gas can then be:

- **processed to maximise the production of synthetic methane** and bring it into compliance with the specifications required for injection into the gas grid. It can then be supplied to all standard consumers of natural gas without requiring any modifications to their appliances;
- **treated through purification** (separation of the various gas molecules) so the methane and alkanes can be recovered for use in the gas grid while the hydrogen is recovered separately;
- **directly consumed** on site without modification as a combustible gas;

The residual water primarily contains nitrogen and can, depending on the presence of other minor residual components, either be directly used for irrigation or treated to drinking water standards by separating out the nitrogen and impurities.

2.5.2 The catalytic hydrothermal gasification process

What makes this type of process unique is the presence of a catalyst at the entrance to the hydrothermal gasifier. This catalyst is currently typically composed of ruthenium, a rare metal, which offers a number of very appealing benefits, including:

- **Achieving an unrivalled carbon conversion rate** until 99%, which promotes the conversion of carbon into methane – which can account for up to 70% of the synthetic gas!
- **Reducing the reaction temperature in the gasifier to around 360-400 °C.** This reduction results in turn in a significant lowering of the heat input requirements for this process type and an increase in the overall energy efficiency of the facility to a minimum of 85%,
- **Indirectly generating clear residual water** of at least industrial quality, which can be used for irrigation purposes as a minimum, if a salt separator and sulfur capture device are installed.

- **Simplifying gas processing:** the high proportion of methane and the relatively low proportion of hydrogen (5-10%), with the remaining amount being carbon dioxide, means that only simple purification is required. This solution is comparable to the practices used in anaerobic digestion, with the difference being that in hydrothermal gasification, the gas pressure during processing is much higher (≈ 80 bar versus ⩽ 10 bar), significantly improving its efficiency. This benefit compensates for the increased cost of the solution as the gas can be injected into the high-pressure grid via simple expansion (thus avoiding any need for compression).

However, it also results in several limitations:

- If the feedstocks contain sulfur (a catalyst poison), the facility must be equipped with a salt separator and sulfur capture system upstream of the reactor and the catalyst. These systems eliminate almost all of the sulfur (down to a few parts per million).
- As the catalyst loses its effectiveness over time, the sulfur capture system must be replenished periodically as it is continuously consumed. These limitations have a relatively high impact on the system operating cost. However, there are also two positive points to mention:
  - > Both systems combined reduce the risk of corrosion of the gasifier and all the other equipment exposed to supercritical conditions downstream of the salt separator.
  - > Despite an additional initial setup cost, the presence of a catalyst capture system is strongly recommended as it allows recovery of up to 75% of the catalyst, reducing the need for catalyst replenishment purchases and keeping operating costs to a minimum.

2.5.3 Summary of hydrothermal gasification technologies

Table 3 below summarises the range of operating conditions and the approximate initial composition of the synthetic gas produced in the gasifier for each type of technology.

In summary, whether a high-temperature or catalytic hydrothermal gasification process is used, and whether or not the system is fitted with a salt separator, the overall hydrothermal gasification value chain is broadly the same and always involves the same steps (Figure 5).

Currently, given the low number of projects in existence (see Chapter 4), hydrothermal gasification stakeholders cannot predict what market share each of the two hydrothermal gasification process types will be capable of achieving in the future.

Each has its strengths and weaknesses:

► Catalytic hydrothermal gasification

- **increased CAPEX** as a result of the rare metal catalyst, salt separator and sulfur capture system is **offset by the potential savings** on gas processing systems and heat input systems, which are much simpler than those required by high-temperature technology,
- **increased OPEX** as a result of replenishing the catalyst and sulfur capture system **can be at least partially offset** by the relatively low heat input requirements and other potential savings as a result of simpler processing of the synthetic gas and the residual water, which require little or no processing in order to meet minimum standards.

Table 3: Summary of hydrothermal gasification technologies (GRTgaz).

Type of Hydrothermal Gasification technology	Operating conditions		Synthetic gas composition (%vol)			
	T (°C)	P (bar)	CH_4 (%vol)	H_2 (%vol)	CO_2 (%vol)	C_xH_y (%vol)
Catalytic	360–450	210–300	60–70	0–10	20–35	-
High-temperature	550–700	250–350	20–40	20–50	20–30	6–12*

C_xH_y = a mix of ethane (C_2H_6), propane (C_3H_8) and/or butane (C_4H_{10}): also found in natural gas

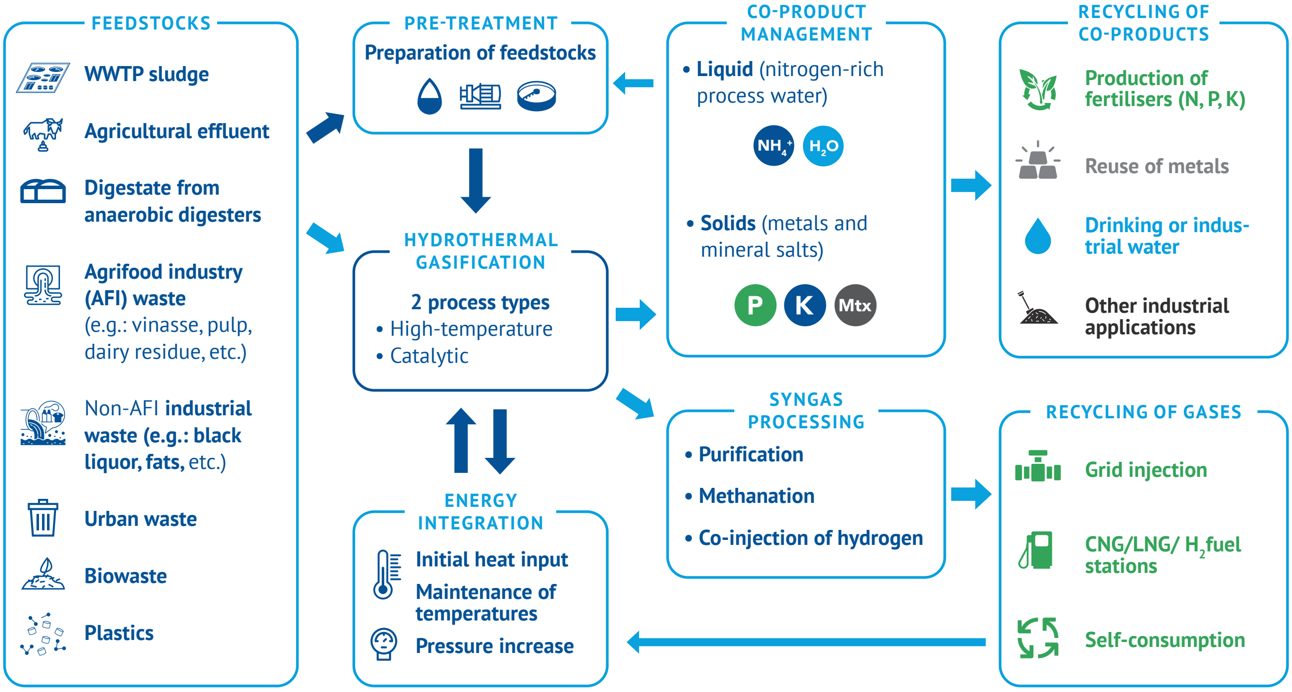

Figure 5: Diagram of the hydrothermal gasification value chain, Hydrothermal Gasification Working Group, 2021 (Source: Cerema/GRTgaz).

► High-temperature hydrothermal gasification

- **Potentially lower initial CAPEX** but this may **increase** depending on the gas processing system chosen, whether or not the feedstock contains sulfur and the desired quality of the residual water produced, which requires at least a minimum level of treatment before it can be reused,
- OPEX is necessarily higher as a result of the relatively high temperatures used, requiring greater energy input. Depending on the gas processing system chosen, the operating cost and energy requirements can increase or reduce this cost.
- Overall, gas processing CAPEX and OPEX are at least equal to if not higher than the catalytic process.
- As the synthetic gas produced can contain relatively high volumes of hydrogen (up to ≈ 50%) alongside methane and heavier hydrocarbons (totalling around 30-35%), this technology type has many assets allowing it to adapt to changing methane and hydrogen markets.

Finally, other criteria can also affect the choice of one or the other technology for a specific project: the baseline circumstances; the local context; the types of feedstock, whether segregated or mixed; whether a salt separator is required, and so on.

2.6 Separating gaseous, liquid and nitrogen flows after the gasifier

2.6.1 The gas-liquid separator

Because the carbon-containing fluid has a relatively short residence time in the gasifier, it does not fully convert into synthetic gas, and as such some liquid remains upon exiting the gasifier. This liquid is primarily water, nitrogen and any other components that must be separated from the gaseous flow, all of which are still in a supercritical state. So the synthetic gas can be used downstream, the liquid must be separated off through a gas-liquid separator, also called a flash drum, to collect two components:

- The high-pressure synthetic gas, which includes almost all of the methane, hydrogen and any other hydrocarbons (C_xH_y) and a fraction of the carbon dioxide;
- And the liquid residue, which primarily contains ammonium and potentially traces of other elements. This liquid is also saturated with carbon dioxide and can contain traces of hydrogen and methane.

a) Processing and use of the gaseous phase

To be compliant with the grid injection requirements, it must be processed using any of a number of different techniques whose performance and suitability varies based on the composition of the gas to be processed.

In short, there are two main potential approaches for processing synthetic gas, which, for reasons of energy efficiency, must take place at relatively high pressure (80-120 bar) to allow the injection of the synthetic methane[a] into the medium- and high-pressure gas grid (16-67.7 bar) through simple expansion:

1. **Purification:** This technique is the standard approach for catalytic hydrothermal gasification. It primarily uses membrane separation to isolate the methane (CH_4) contained in the gas from the hydrogen (H_2) and carbon dioxide (CO_2).

   Purification can also be used to separate the synthetic gas produced using high-temperature hydrothermal gasification if the aim is to inject the methane and any hydrocarbons with a longer carbon chain (C_XH_Y) into the natural gas grid while recovering the hydrogen for use elsewhere.

2. **Methanation:** this is the standard approach used for high-temperature hydrothermal gasification. Methanation is a chemical or biochemical reaction in which methane is synthesised from carbon monoxide (CO) and/or carbon dioxide (CO_2) using dihydrogen (H_2). There are currently three options for methanation:

   a. **Catalytic methanation:** a catalyst, most commonly nickel-based, is used to facilitate the desired reaction. The catalyser is vulnerable to sulfur, which reduces its effectiveness and lifespan, and so must be protected upstream via a desulfurisation process designed to eliminate any potential hydrogen sulfide (H_2S). As this reaction is exothermic (around 200 °C), the heat produced can be recovered for use in the process to improve its overall energy efficiency. As the synthetic gas does not generally contain enough hydrogen to react with all of the CO_2 it contains, the residual CO_2 must be separated from the synthetic gas (via a membrane process) before it is injected into the grid.

   b. **Biological methanation:** this methanation technology uses the same chemical processes as the catalytic approach, but the reactions are biochemical in nature. These

[a] processed gas that complies with natural gas standards

reactions are achieved through the use of methanogenic bacterial strains grown in aqueous environments in a dedicated reactor that receives a constant supply of nutrients. Any sulfur present is readily consumed by the bacteria and the surplus CO_2 produced is processed in the same way as for catalytic methanation.

c. **Plasma-catalytic methanation:** this is an innovative variant of catalytic methanation that is currently being developed by the French company Energo. It requires significantly less energy (-40%) by creating a plasma using an electric field that triggers a reaction among the targeted molecules. As in the previous two cases, the residual CO_2 must also be separated from the synthetic methane before injection. Currently, the technology works at near-atmospheric pressures only.

3. There is a third possible approach to gas treatment, called **'hydrogen co-injection[a]'**, which works by adding hydrogen from an external source with the aim of maximising methane production at the output of the hydrothermal gasification process. When present in excess, the hydrogen will react with the maximum possible quantity of carbon dioxide found in the synthetic gas. Depending on the type of hydrothermal gasification process, the hydrogen is added via one of two mechanisms:

- **Catalytic hydrothermal gasification:** the hydrogen is brought to the pressure and temperature of the fluid, then directly injected alongside the carbon-containing fluid in the gasifier. Tests carried out by the Paul Scherrer Institute in Switzerland have demonstrated that under these conditions, it is possible to create a synthetic gas composed of over 90% methane.
- **High-temperature hydrothermal gasification:** the hydrogen is injected directly into the methanation facility (whether catalytic, plasma catalytic or biological) where it reacts with all of the carbon monoxide and carbon dioxide contained in the synthetic gas. The aim at the output of the methanation process is to maximise methane production, to consume even entirely hydrogen and to minimise CO and CO_2 residue in the synthetic methane that is produced. The resulting synthetic methane is of sufficient quality that it meets standards without requiring any further processing before being injected into the gas grid.

With hydrogen co-injection, production of synthetic methane can be anything up to double that produced without the addition of hydrogen. With hydrogen costing less than €4/kg, this additional approach appears to be economically viable.

2.6.2 Treatment and recovery of the liquid phase and nitrogen

The liquid residue that exits the gas-liquid separator is formed of water that is fully saturated with carbon dioxide. If the initial feedstock contains nitrogen, this element will also be found in the liquid residue in the form of ammonium (NH_4^+). It is generally colourless but for some feedstocks, such as sludge, and when high-temperature hydrothermal gasification is used, it can take on a brownish colour (hence the term 'brown water') as a result of a few remaining traces of impurities.

Residual water from catalytic technology is **clear and transparent** and contains no or few impurities. This water can then be used almost as-is (after analysis) for agricultural irrigation or for watering green spaces in urban environments.

However, the residual water from high-temperature hydrothermal gasification requires specific filtration and purification systems to be put in place. For this reason, the Dutch developer SCW Systems has installed a treatment system in its first industrial plant, of 20 MW_{th}, allowing it to produce drinking-quality water.

Depending on the intended purpose of the residual water and its nitrogen content, specific ammonia separation or concentration processes should be considered (including stripping, ion exchange, precipitation, gas-liquid absorption, …).

[a] For catalytic hydrothermal gasification only.

2.7 The benefits of hydrothermal gasification

Hydrothermal gasification presents a number of specific advantages, as set out below (Figure 6):

These benefits make hydrothermal gasification a suitable alternative to the traditional processing and current management approaches used for a certain number of waste types within regions, allowing the development of local circular economy loops. Some key benefits of the technology are listed below:

► No need to dry the wet organic waste being recovered

As the hydrothermal gasification process is capable of valorising organic waste with relatively low concentrations of dry matter (≈ 15-20% as a minimum), it **does not require dewatering**, which can consume very large quantities of energy. This is in contrast to the need to use mechanical or thermal dewatering techniques to make the waste combustible (for example, for incineration). Because the energy output from waste combustion does not offset the energy input required for dewatering, this technological combination is particularly inefficient and expensive.

In addition, within the hydrothermal gasification process, once the inorganic components have been separated out and gasification is complete, the supercritical gas-liquid fluid is still at a very high temperature. Hydrothermal gasification technology developers are skilled at correctly sizing the heat exchangers to transfer as much of the heat in the fluid as possible to the new feedstock which enters the hydrothermal gasification system via the high-pressure pump. Developers have already demonstrated heat transfer efficiency rates of over 85%.

This level of energy performance is crucial to achieving an overall energy efficiency of greater than 75% with hydrothermal gasification.

► Recycling of the mineral elements, nitrogen and metals contained in the waste

Hydrothermal gasification falls squarely within the remit of the circular economy in that water resources are preserved and 'cleaned' of pathogens, viruses and microplastics of all kinds found in the feedstock. It also allows minerals (phosphorus, potassium, nitrogen, etc.) to be recycled, potentially being used as fertilisers after processing.

The ability to separate and recover metals, which are found in particular in many types of industrial waste, is another crucial asset because some of these metals, whether due to their volume or their scarcity (and thus high price), may offer an additional financial opportunity.

► A compact, modular design

Hydrothermal gasification converts waste to gas in a few minutes in a very compact facility in which the heat exchangers take up the majority of the space. The choice to take a modular approach to hydrothermal gasification facilities, defining the maximum processing capacity for each module at a level between 3 to 6 t/h, reflects developers' desire to keep the costs of certain sub-components as low as possible. This is because the cost of these components can increase significantly up to a certain size, as these parts need to withstand especially high pressures and also high temperatures. Standardising each module results in a certain flexibility and adaptability as well as limiting the costs from design to construction. Furthermore, during operation, the modularity of hydrothermal gasification means the plant can adapt more easily in response to fluctuations in the volume of waste to be processed.

The benefits of hydrothermal gasification

- Up to 100% feedstock recovery = up to 100% elimination of final waste
- Fast (some seconds to a few minutes) with a very high rate of carbon conversion (85-100%), including microplastics
- Pathogenic microorganisms and micropollutants eliminated
- No atmospheric pollutants
- Modular technology with very low footprint
- No noise pollution or unpleasant odours
- Thermal processing of feedstocks not required
- Recovery of minerals and metals
- Production of a gas that can be injected, stored, and used just like natural gas
- CH_4 / H_2 Technology that can produce methane and hydrogen as required
- Recovery of industrial-quality water that can be filtered to produce drinking water
- An eco-friendly alternative to incineration, burial and landfill

Figure 6: The benefits of hydrothermal gasification (Source: Cerema/GRTgaz).

03

THE POTENTIAL TO PRODUCE RENEWABLE AND LOW-CARBON GAS

An assessment of the potential for producing renewable and low-carbon gas through hydrothermal gasification was carried out by estimating the potential scale of mobilisation of certain waste types by 2050. This includes waste identified as relevant to the technology, which, for the most part, **is organic waste, whether it is of biomass or fossil origin.** The list of these feedstocks is growing as more precise information on specific industrial waste passes and technological developments take place.

In total, the overall annual quantity of organic biomass waste that is suitable for hydrothermal gasification has been estimated at more than **400 million tonnes, of which an estimated 150 million tonnes can be mobilised for HTG**.

However, these volumes are likely to increase, especially if fossil organic waste from industrial activities is to be integrated. With the growing use of anaerobic digestion, whose digestates – the final waste – cannot all be used locally in agriculture (due to a lack of available spreading surface), the stated quantities are likely to rise further in the years to come. Similarly, the volume of suitable fossil waste has probably been underestimated. As this type of waste comes primarily from industrial activities, and in particular the chemicals and petrochemicals sectors, little data is available. Furthermore, the volumes in question are even greater given that these industries produce as much waste as they do products, which themselves, once used or consumed, also become waste (for example, plastic packaging).

3.1 Hydrothermal gasification, a solution for recovering certain waste types

3.1.1 The limits on land application for certain biogenic waste

Some countries have chosen a radically different approach compared to the French position by banning the practice of returning certain waste types to the soil. For example, this is the case for sludge from wastewater treatment plants in Switzerland, Denmark, the Netherlands and soon Germany (2029). The Netherlands is a particularly interesting case (Figure 9), as the country ban on using WWTP sludge in agriculture dates back to 1995 and is correlated with a significant decrease in their landfilling over the past 30 years as well as the rise in the use of alternative solutions.

Meanwhile, Switzerland illustrates the next step: all WWTP sludge, whether digested or not, is sent for incineration despite the negative impacts

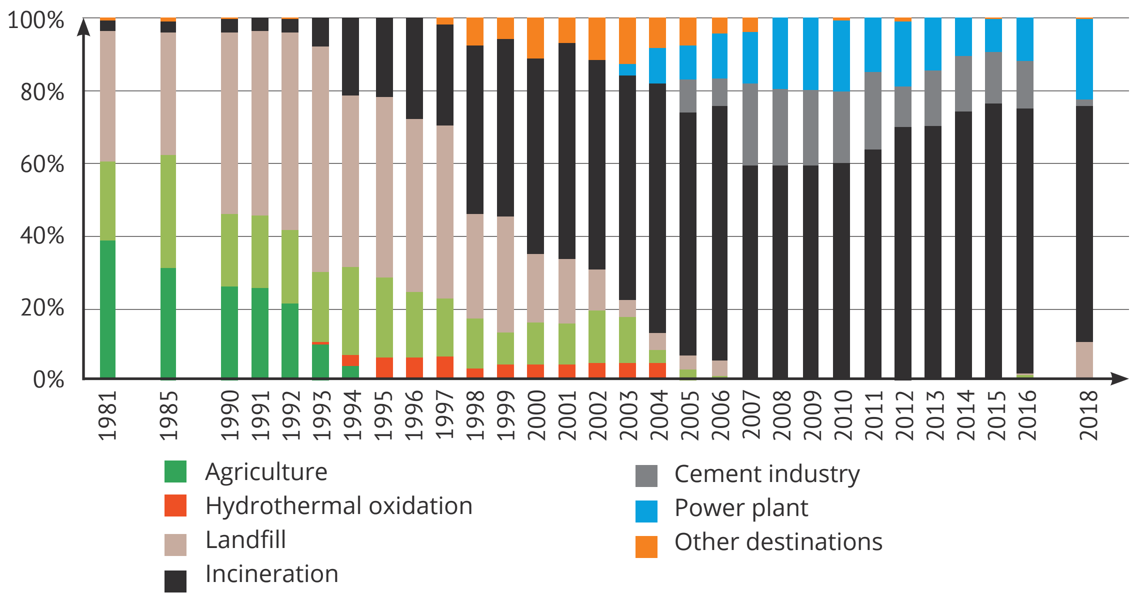

Figure 7: Changes to the final destination of WWTP sludge in the Netherlands since 1981 (Source: clo.nl).

(see Chapter 1), which has encouraged the development of hydrothermal gasification, with financial support from the Swiss government, as a relevant alternative that both recovers energy and protects valuable resources. The fact that hydrothermal gasification can produce a range of co-products of agricultural and economic value, such as phosphorus, nitrogen and other minerals as well as a number of metals, has also helped to secure the support of the Swiss Federal Office of Energy in order to provide a rapid alternative to incineration.

In France, local pollution phenomena are a common sight as a result of poor management of fertiliser products. For example, some composts produced using mechanical-biological treatment (MBT) can contain small quantities of microplastics which, as they are spread on agricultural land, leave permanent traces in the soil [8]. Spreading other organic effluent, such as slurry, sludge from water treatment plants or digestate, may result in thresholds for nitrogen, phosphorus or trace metal elements (TMEs) such as copper, iron, zinc and cadmium, among others, being breached.

Furthermore, these biomass streams are often unevenly distributed across the country, with a significant proportion being transported tens or even hundreds of kilometres for disposal. In addition to the inconvenience that this creates locally (noise, odours, traffic issues, etc.), it also results in high levels of GHG emissions as a result of the transport by lorry.

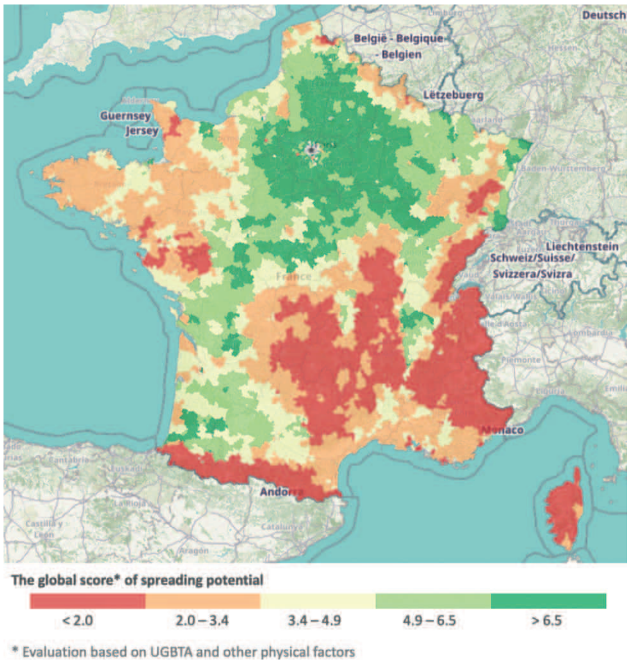

Figure 8: The difficulties involved in spreading on agricultural land in France (Source: ValorMap).

Finally, the ValorMap project has published a map of France showing the spreading limits in force across the country **based on physical criteria** (soil and river topography), **agronomic criteria** (crop/agriculture type) and **the presence of livestock farming**. Figure 8 shows that around **40% of France already has spreading limits in force**.

Hydrothermal gasification therefore presents a **relevant alternative for treating livestock farming effluent** that can no longer be returned to the soil as a result of local overproduction or overuse in agricultural activities and in agrifood industries.

3.1.2 A number of questions surrounding certain industrial waste types

In addition to biogenic organic waste for which material recovery is impossible or undesirable, as seen above, a number of waste types – whether they are rich in fossil carbon or not – do not always appear to undergo environmentally friendly recovery. Indeed, these waste streams, mainly of industrial origin, are poorly known, quantified and/or mapped despite the significant economic activity and high production volumes of the French industrial sector.

As such, multiple questions remain regarding the quantities, composition, management methods and export volumes of certain types of industry waste, in particular in the chemicals and petrochemicals sectors.

Similarly, there is a high volume of plastic-rich waste (packaging and various plastic products, whether segregated, soiled or mixed with other waste), and again there is little in the way of information about its composition, volume and management methods.

For these waste types, it is highly likely that hydrothermal gasification could be an appropriate solution to avoid export, landfilling and incineration.

3.2 The potential to produce at least 63 TWh of renewable and low-carbon gas in 2050

Methodology

Assessing and estimating the potential to produce renewable and low-carbon gas using hydrothermal gasification relies on a number of parameters, such as the nature and composition of waste streams, their availability, their regional distribution and how they are managed. The methodology used for this assessment involved several stages:

1. Identifying families and types of waste streams (of biogenic origin only).
2. Identifying their distribution and volumes.
3. Identifying the management processes (if any) put in place.
4. Assessing the energy potential of each stream.
5. Estimating the mobilisation rate of the identified streams.
6. Estimating the realistic potential for renewable and low-carbon gas production via hydrothermal gasification (inspired by the method proposed by Louw *et al.*, 2014 [9][a]).

This new assessment, carried out in 2022, is partly based on the initial work conducted by ENEA Consulting, published by GRTgaz in October 2019 [10]. It takes account of a comprehensive data set from other publications by renowned stakeholders (see below for example sources), which were supplemented in part by searching for geolocated data using algorithms in an attempt to fill the information gaps that exist in terms of publicly accessible data.

Limits of the exercise

In France, it is very difficult to obtain publicly accessible data and accurate estimates covering organic waste volumes as well as the distribution of the various waste streams and suitable organic matter across the country. However, there are several accessible public databases and publications, which the Hydrothermal Gasification Working Group used to identify accessible streams that could be mobilised, then calculate the sector potential gas production. To present the most complete and consistent figures possible, the Hydrothermal Gasification Working Group focused on the **18 organic waste streams of biogenic origin** that exist in the greatest quantities and are best represented in the databases available (Figure 9).

In particular, organic waste of industrial origin is poorly documented and lacks precision, meaning proper statistical use of this data is impossible. As hydrothermal gasification requires certain details to assess the potential of a waste stream, such as the dry matter and organic matter levels of the raw tonnage figures provided, it is difficult to accurately determine the true volumes of suitable existing waste that could be converted into gas using the technology. For example, data on waste volumes from the petrochemicals industry cannot be located. As such, it is perhaps no surprise that it is sometimes almost impossible to determine the fossil proportion of certain organic waste generated by a number of industry sector stakeholders.

The main resources used during this study are primarily from open databases, public studies and private sources from the industries themselves:

- **Public databases:** assainissement.developpement-durable.gouv.fr, Insee, Agreste, etc.
- **Reports and publications:** Réséda survey on waste streams and recycling of co-products from agro-industry [11], the assessment of agricultural and agrifood resources by the ONRB [12], studies by ADEME [13][14] and Cerema [15] and other scientific publications [16][17].

[a] To determine this potential, the Hydrothermal Gasification Working Group built on the work presented in the study by Louw *et al.* (2014), which indicates that $HCV_{gas}(kWh/kg_{biomass}) \approx 90\% \times HCV_{biomass}(kWh/kg_{biomass})$. To more accurately reflect the results of the first experimental tests conducted using pilot projects, the Hydrothermal Gasification Working Group agreed on a conservative conversion rate of 85% for conversion calculations.

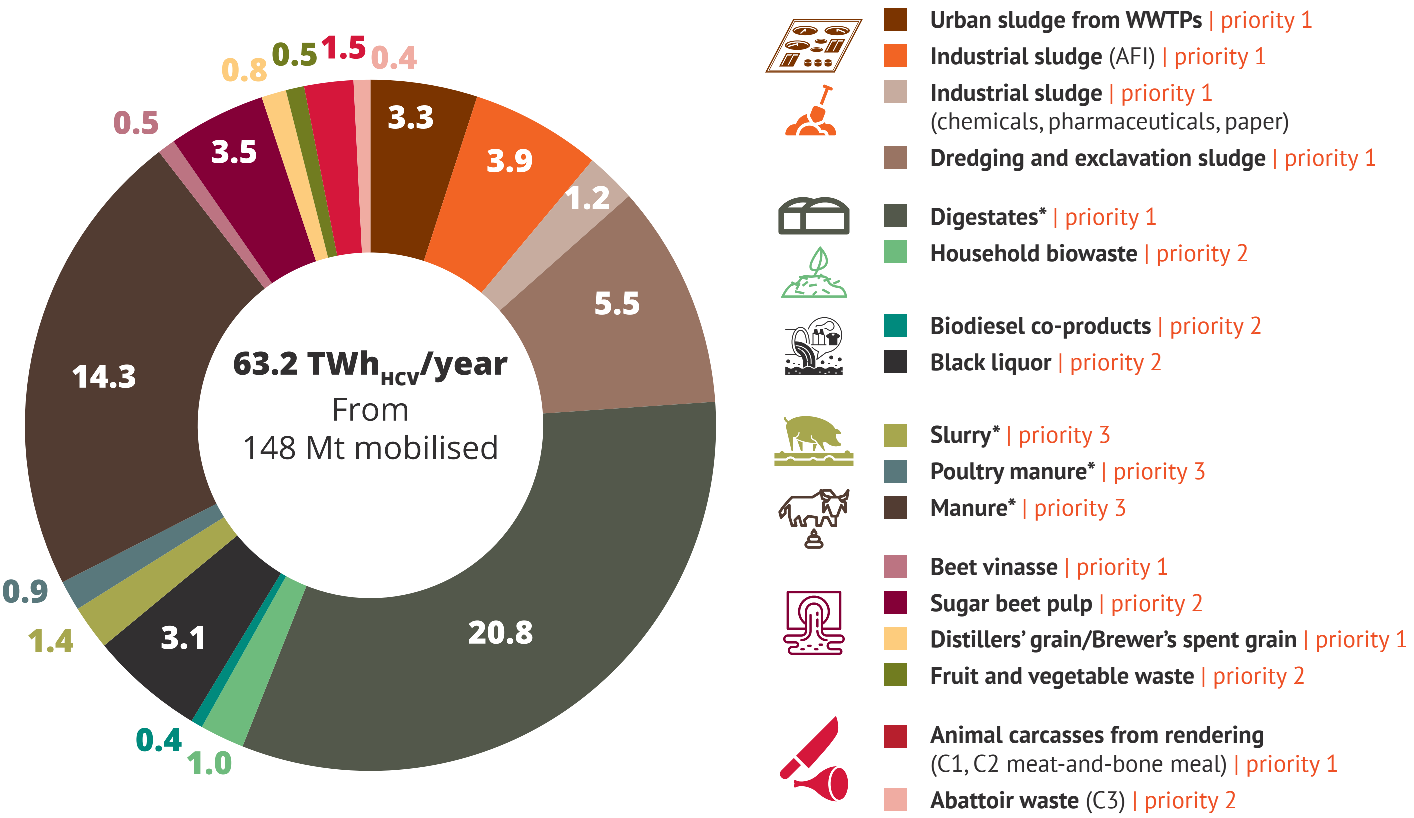

Figure 9: Estimated injectable gas production via HTG for the 18 major feedstocks of biogenic origin by 2050 (63.2 TWh/year) – **estimates for 2050.*

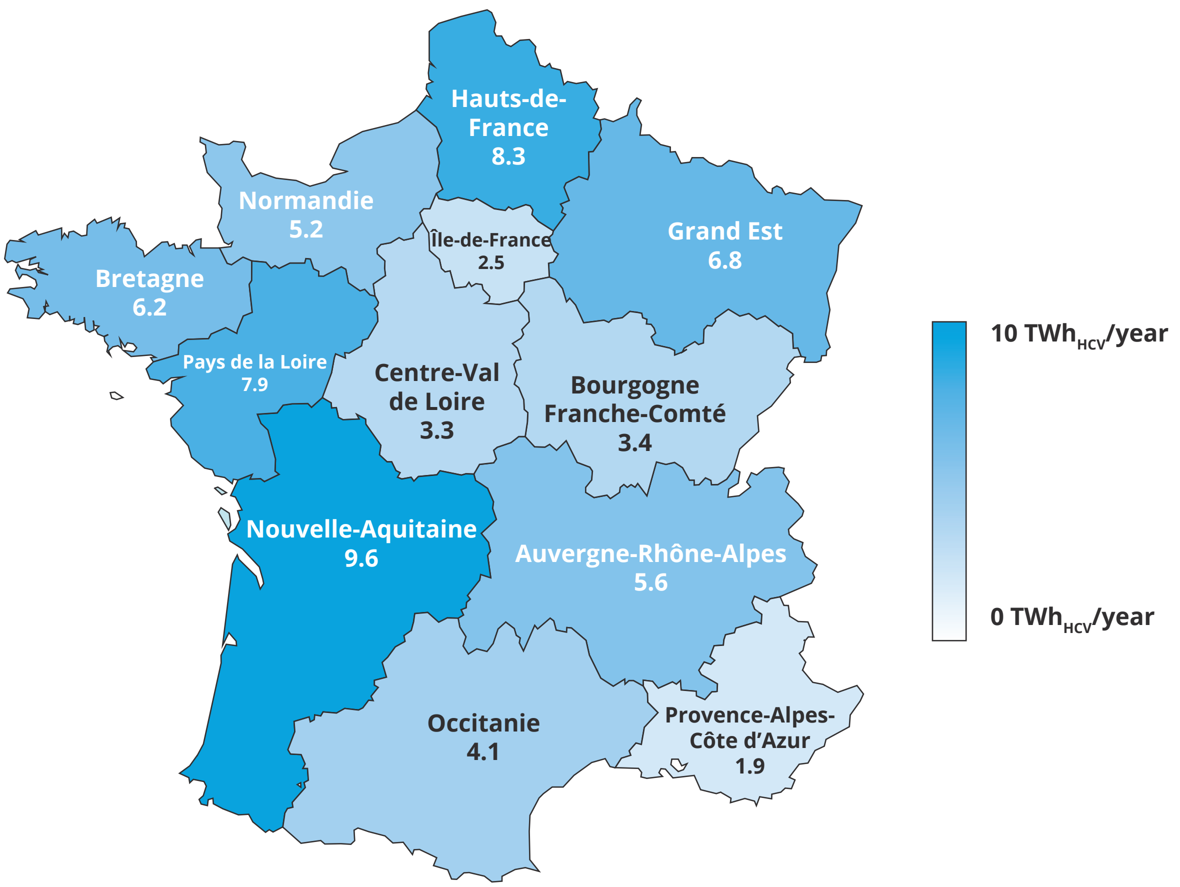

Figure 10: Estimated injectable gas production via HTG by region in 2050 (63.2 TWh/year).

Because of the imprecision that arises from the use of different types of data sources, making comparisons difficult or even impossible, the results presented are semi-quantitative and are not intended to provide an accurate or definitive estimate or presentation of the potential gas production via the hydrothermal gasification sector by 2050. **The resulting work, summarised in Figure 9 and Figure 10, should be understood as the closest possible estimate based on the best information currently available, taking into account – to the greatest possible extent – likely developments to specific volumes as forecast by certain experts** (for example: Solagro data that forecasts a significant drop in livestock effluent streams by 2050 compared to 2018, which was taken into account in the ENEA Consulting study).

This initial approach indicates a realistic scenario with a **gas production potential of around 63 TWh/year by 2050** through hydrothermal gasification, taking into account the mobilisation of livestock farming effluent and certain organic waste that is not necessarily 100% biogenic in origin (polluted by the presence of fossil-origin waste such as plastics or from certain specific industries, such as the chemical industry).

3.2.1 The priority feedstock types for hydrothermal gasification

There are a number of feedstock types that meet the technical specifications required for hydrothermal gasification and for which recovery options are currently limited or non-existent (such as dredging sludge). These waste types can result in tensions at the local level but also have real potential for use in hydrothermal gasification processes:

- **Urban WWTP sludge and industrial sludge** (from the agrifood, chemicals, pharmaceuticals and paper industries, etc.): increasing regulatory constraints regarding returning sludge to the soil by 2027 and the aim to reduce the use of incineration[a], which is inefficient for feedstocks that contain more than 70% water, should allow hydrothermal gasification to capture the vast majority of this waste stream by 2050. For urban sludge, 65% of volume (conurbations of> 50,000 PE[b]) should ultimately be available for hydrothermal gasification, even if a few anaerobic digestion plants remain. Industrial sludge from the AFI, chemicals, pharmaceuticals and paper sectors represent a very significant overall resource and are more abundant than urban sludge. Furthermore, they are often richer in carbon.
  > **Potential renewable and low-carbon gas production in 2050: 8.4 TWh/year**
- **Dredging and cleaning sludge**: regulations are tightening and in 2025, ocean disposal of polluted sludge will be banned. Despite a low proportion of organic matter (6-30% depending on the origin – for example, estuaries, rivers, ports, etc.), due to the volumes in which they exist (50 Mt/year), dredging sludge could have potential as a feedstock for hydrothermal gasification technology provided that separating the organic matter from the inorganic matter (sand) becomes technically and economically feasible.
  > **Potential renewable and low-carbon gas production in 2050: 5.5 TWh/year**
- **Digestate from anaerobic digesters where spreading limits apply**: currently, where possible, digestate is returned to the soil via strictly managed processes in line with the local context and seasonal limits on spreading (depending on the crops grown). Hydrothermal gasification could therefore become a permanent outlet for a growing volume of digestate in response to current constraints, some of which could be strengthened. In this way, hydrothermal gasification could help to overcome the local constraints of digestate spreading for anaerobic digestion projects in a number of regions that already have limitations in place, such as the Sud, Bretagne, Hauts-de-France, Grand-Est and Île-de-France regions.

[a] In France, 20% of sludge is currently incinerated.
[b] Population equivalent

> **Potential renewable and low-carbon gas production in 2050: 20.8 TWh/year**

- **Vinasse and spent grain (beet, cereals) from breweries and distilleries**: with these waste types generated in ten or more production sites in France, industry stakeholders in this sector are looking to make better use of these feedstocks than through spreading, which offers little benefit to the soil.

  > **Potential renewable and low-carbon gas production in 2050: 1.3 TWh/year**

- **Animal by-products (animal carcasses from abattoirs)**: The use and recycling of category 1 animal by-products is currently limited by regulations[a] governing their use in energy recovery (excluding fats in biofuels). Through recovery of the residual solid (mineral) and liquid (water) matter, hydrothermal gasification could provide a far superior recovery rate compared to incineration (the only method currently permitted), while also eliminating all health risks due to the high-pressure, high-temperature conditions. The technology could provide an alternative recovery option for category 2 animal by-products, which present a lower risk to public health and which can be used for purposes other than animal feed (slurry and manure, for example).

  > **Potential renewable and low-carbon gas production in 2050: 1.5 TWh/year**

3.2.2 Priority 2 and 3 feedstock types for hydrothermal gasification

Priority 2 & 3 waste streams are currently fully valorised but have **evolving valorisation paths**, which may mean it will be possible to mobilise them for hydrothermal gasification depending on the local context:

- **Sugar beet pulp**: currently primarily used as animal feed[b] and in anaerobic digestion. Sugar producers are looking for alternative uses for pulp as livestock numbers fall while sugar production is set to remain more or less stable.

  > **Potential renewable and low-carbon gas production in 2050: 3.5 TWh/year**

- **Other feedstocks (grape pomace, biowaste, fruit and vegetable waste, biodiesel co-products and black liquor)**: for these types of waste, which are often generated in specific locations, there is often already a recycling method in place. Depending on the local context, hydrothermal gasification can provide an alternative solution with even greater overall technical and economic added value for stakeholders.

  > **Potential renewable and low-carbon gas production in 2050: 5.6 TWh/year**

Finally, as mentioned in the previous section, while some agricultural resources have already the possibilities to be valorised in the form of energy, their concentration and regulatory changes may lead to considering them as potential feedstocks for hydrothermal gasification:

- **Agricultural livestock effluent**: currently spread directly or after anaerobic digestion, local concentration of volumes[c] results in difficulties with recycling and excess nitrogen in certain regions (Bretagne, Pays-de-Loire, etc.)

  > **Potential renewable and low-carbon gas production in 2050: 16.6 TWh/year**

[a] Under European regulation (EC) 1069/2009, category 1 covers animal by-products that present a significant risk to public health, including: risk of transmissible spongiform encephalopathies (TSEs) or specified risk material (SRM), risk of prohibited substances or environmental contaminants, emerging health risks, etc.

[b] 50% as compressed pulp recovered during the harvest and 50% as dried pulp the rest of the year.

[c] The total potential takes into account a significant drop in overall livestock numbers by 2050.

04

TECHNOLOGICAL MATURITY AND OVERVIEW OF PROJECTS IN EUROPE

The first experiments involving hydrothermal processes were performed in 1913, with the hydrothermal carbonisation of cellulose to produce a material similar to coal. Work on these processes was also carried out in the 1970s and 1980s by the Pittsburgh Energy Research Center (USA), the Royal Institute of Technology in Stockholm (Sweden) and the University of Toronto (Canada). In general, research into hydrothermal processes has accelerated since the mid-2000s.

And as for hydrothermal gasification, it was at MIT (Massachusetts Institute of Technology), a highly renowned research institute and university in the United States, that the first experiment with this biomass conversion technology was recorded [18]. Following this initial approach, the PNNL (Pacific Northwest National Laboratory in California) and the University of Hawaii began working on the topic, focusing in particular on high-temperature conversion. Following its efforts to master hydrothermal liquefaction, the PNNL turned its attention to developing a hydrothermal gasification solution with a catalyst in the gasifier. All of this work contributed to the thinking of researchers at the Karlsruhe Institute of Technology (KIT) in Germany, who were the first in the world to implement a high-temperature pre-industrial pilot project in 2004. Its Swiss equivalent, the Paul Scherrer Institute, later continued on from the PNNL's work on catalytic hydrothermal gasification and improved the process, eventually becoming the leading player in this type of HTG technology. In Japan, several stakeholders, including the universities of Tokyo, Hiroshima and Osaka, also worked in parallel on developing catalytic hydrothermal gasification. There are now more than ten developers of HTG technology in the academic world and, increasingly, the industrial sector, particularly in Europe.

4.1 Developers of hydrothermal gasification technology in Europe

As can be seen in Figure 11 below, in Europe, the majority of hydrothermal gasification technology developers have created facilities of various types:

- Prototype (TRL ⩽ 4): 1 - 10 kg/h,
- Pre-industrial pilot (TRL 4 - 6): 40 - 150 kg/h,
- Industrial demonstrator (TRL 7 - 9): 500 kg - 2 t/h,

Operating continuously, these hydrothermal gasification plants are concentrated in five countries: Germany, France, Spain, the Netherlands and Switzerland.

4.2 European developers (outside France)

4.2.1 The Karlsruhe Institute of Technology (KIT) and its VERENA pilot project (2004)

The KIT is both a centre of research excellence and the oldest and most widely renowned engineering university in Germany. In the 1990s, its researchers focused on high-temperature hydrothermal gasification. They laid the technology foundations in Europe and subsequently filed a wide range of patents. With the VERENA project in 2004, they successfully launched the world first pre-industrial pilot facility demonstrating the technology. In early 2021, to support the emergence of a dedicated hydrothermal gasification sector, Dr. Boukis, the scientist in charge of hydrothermal gasification research at the KIT, published a scientific article in the journal *Processes*, presenting an extensive overview of the lessons learned from the VERENA

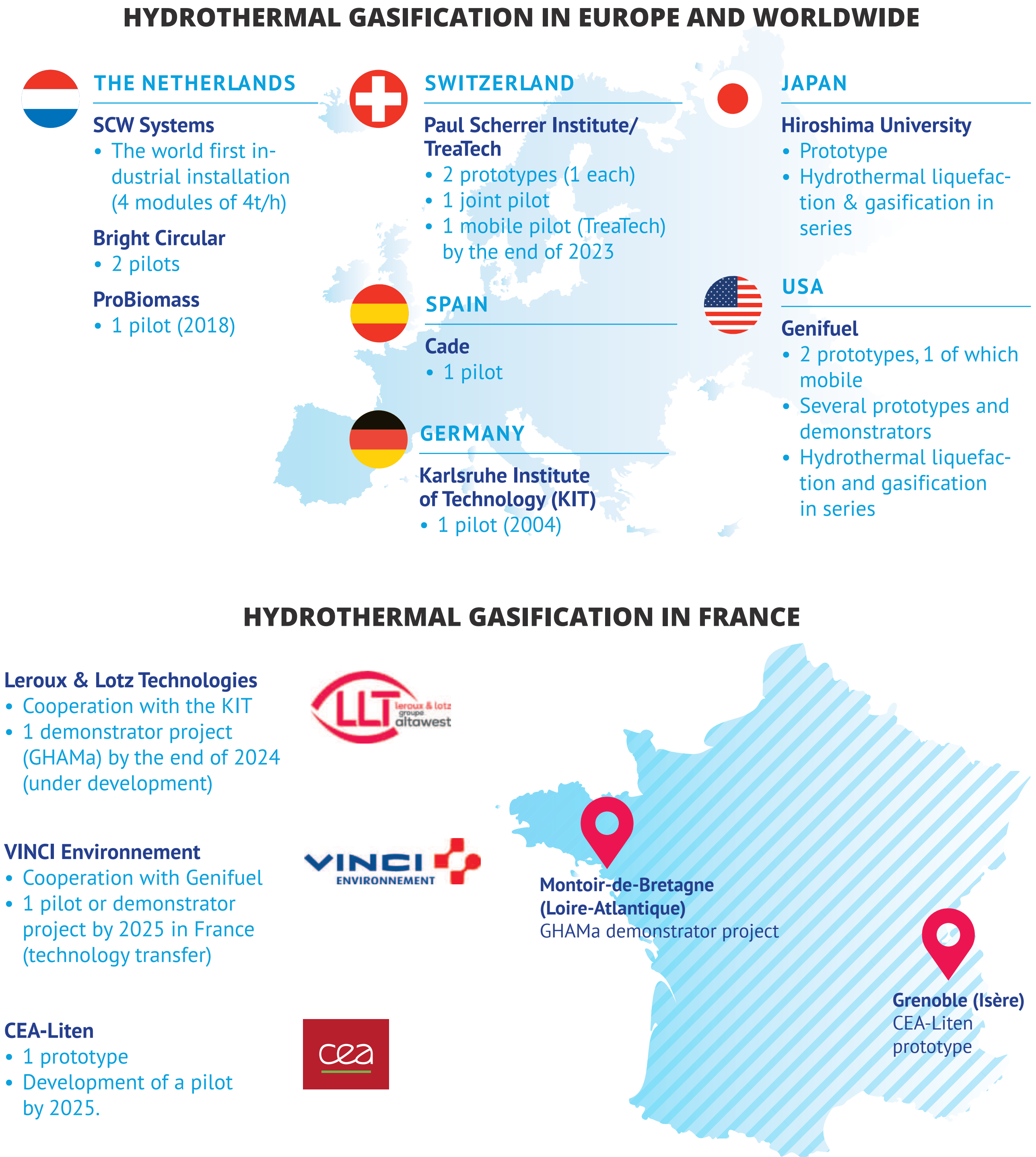

Figure 11: Map of current developers in Europe and worldwide (as of mid-2022) (Source: Cerema & GRTgaz).

pilot [19] since its creation in 2004 (details in Table 4).

The VERENA pilot works on the basic operating principle that continues to apply regardless of the technological developments that have been made to date: the feedstock, pre-processed if necessary (e.g. through grinding), is compressed as it is injected into the system, with the pressure rising from initial atmospheric levels to high pressure (in this case, 300 bar). The heat energy required to pre-heat the feedstock to supercritical conditions (at least 360 °C) is captured using a heat exchanger, which cools the flow exiting the gasifier to recover its energy. After passing through a salt separator (cyclone), the feedstock – with its mineral load removed – is gasified at a temperature of around 700 °C. The pre-heater and gasification reactor are supplied with heat by hot gases from a furnace. In the gasifier, the primary gases that form are methane, hydrogen, carbon dioxide and ethane.

The success of the VERENA pilot has led to several academic and industrial collaborations between the KIT and a range of partners. Of these partnerships, the most noteworthy are with the PSI (Paul Scherrer Institute in Switzerland) to test its first industrial-scale vertical salt separator and with two of the three main developers in the Netherlands, Pro Biomass BV and Bright Circular, the latter via the University of Delft. The third Dutch developer, SCW Systems, which is currently the most advanced worldwide, went through all its technological development stages – from a prototype (10 kg/h) to a demonstrator (2 t/h, and now an industrial facility of 16 t/h) – without any academic support. Currently, each of the three Dutch companies mentioned, alongside the PSI, has developed and produced at least a pilot facility (50-110 kg/h) or a demonstrator (2 t/h).

Table 4: Profile: the VERENA pilot. Sourced from public data.

Project name	VERENA
Project owner/partners	Karlsruhe Institute of Technology (KIT)
Location	Karlsruhe, Germany
Launch year	2004
Maximum capacity	100 kg/h, 20% DM
TRL	5
Technology type	High temperature with integrated cyclone salt separator
Operating conditions	600-700 °C, 250-300 bar
Feedstocks	WWTP sludge, maize silage, methanol, glycerol, plus around 10 further feedstocks
Gas recovery	High-pressure cylinders
Recycling of co-products	No (disposal via a WWTP)
Construction costs	CAPEX: ~ 2 M€*

**In 2004 - Webinar: NEW R&D ADVANCES IN HYDROTHERMAL GASIFICATION FOR BIOFUEL PRODUCTION 2021 (https://vimeo.com/510267625).*

4.2.2 PSI – TreaTech and HydroPilot (110 kg/h)

In Switzerland, the Paul Scherrer Institute (PSI), a research centre dedicated to energy, laid the groundwork for the development of hydrothermal gasification in the country (from the early 2000s). Unlike other developers, the PSI focuses on developing catalytic hydrothermal gasification, and its work was initially heavily inspired by that of the Pacific Northwest National Laboratory (PNNL), part of the US Department of Energy.

Building on the knowledge gained, an initial prototype facility (KONTI-C, 1-2 kg/h) was first constructed in 2014 as part of the SunCHem project. This presented an opportunity to simultaneously test and prove an initial design for a salt separator and a catalyst system. The first tests were conducted with the catalyst. Tests began using microalgae and glycerol before moving on to more complex feedstocks such as WWTP sludge. In parallel, the design of the salt separator was improved and industrial-scale equipment was produced then tested with support from the KIT through its VERENA pilot: this separator is now integrated into a pre-industrial pilot facility (see Figure 12) run by the PSI and TreaTech.

While a brine containing varying levels of nutrients (P, K, Ca, S, etc.) and metals is collected at the salt separator output, the aqueous effluent at the output of the catalytic process contains almost all of the nitrogen and a very low proportion of organic carbon. Up to 99% of the carbon from the initial feedstock is converted into syngas, a testament to the excellent conversion performance made possible thanks to the catalytic reactor.

Two Swiss trailblazers – Frédéric Juillard and Gaël Peng – became interested in industrialising the technology developed by the PSI, and in 2015 founded the start-up TreaTech. Both entities collaborated on the design and production of their first quasi-industrial pilot installation capable of processing up to 110 kg/h of feedstock (see Table 5 below). TreaTech also has its own prototype with a salt separator optimised for treating

WWTP sludge, a patented design that is very different from that developed by the PSI.

The PSI's scientific development work on catalytic hydrothermal gasification and the production of its joint pilot with TreaTech received significant support from the Swiss Federal Office of Energy. Initially, its primary motivation was to support the development of an alternative to incineration for WWTP sludge and sludge digestate. It should be noted that since spreading sludge on agricultural land was banned in 2006, incineration has been the only permitted disposal method in Switzerland.

This pilot project is also intended to offer a solution to the new Swiss federal regulation, applicable from 2026, that will require all WWTP operators to recover as much phosphorus as possible from the sludge they produce. As such, PSI and TreaTech are working with partners to identify and industrialise a technically and economically viable method to recover, process and recycle phosphorus into a marketable product.

As a priority, TreaTech is focusing on developing industrial units for operation from 2025, targeted at the treatment market for both WWTP sludge and organic waste from industry. It has begun work on its first pilot facility, which will be capable of deployment at a client site and available by early 2024. Its design incorporates the lessons learned from the joint pilot with the PSI. The company plans to deploy an industrial-scale demonstrator from 2025 on with feedstock treatment capacity which will be fixed between 2 and 4 t/h.

Table 5: Profile: the HydroPilot project.

Project name	Hydropilot
Project owner/partners	TreaTech/PSI, KASAG, Exergo, Afry
Location	Paul Scherrer Institute (Villigen, Switzerland)
Launch year	2020
Maximum capacity	110 kg/h, 20% DM
TRL	6
Technology type	Catalytic with integrated salt separator
Operating conditions	400-450 °C, 250-280 bar
Feedstocks	WWTP sludge and sludge digestate
Gas recovery	No; flared
Recycling of co-products	Research into phosphorus recycling in progress
Construction costs	CAPEX: ~ 2 M€

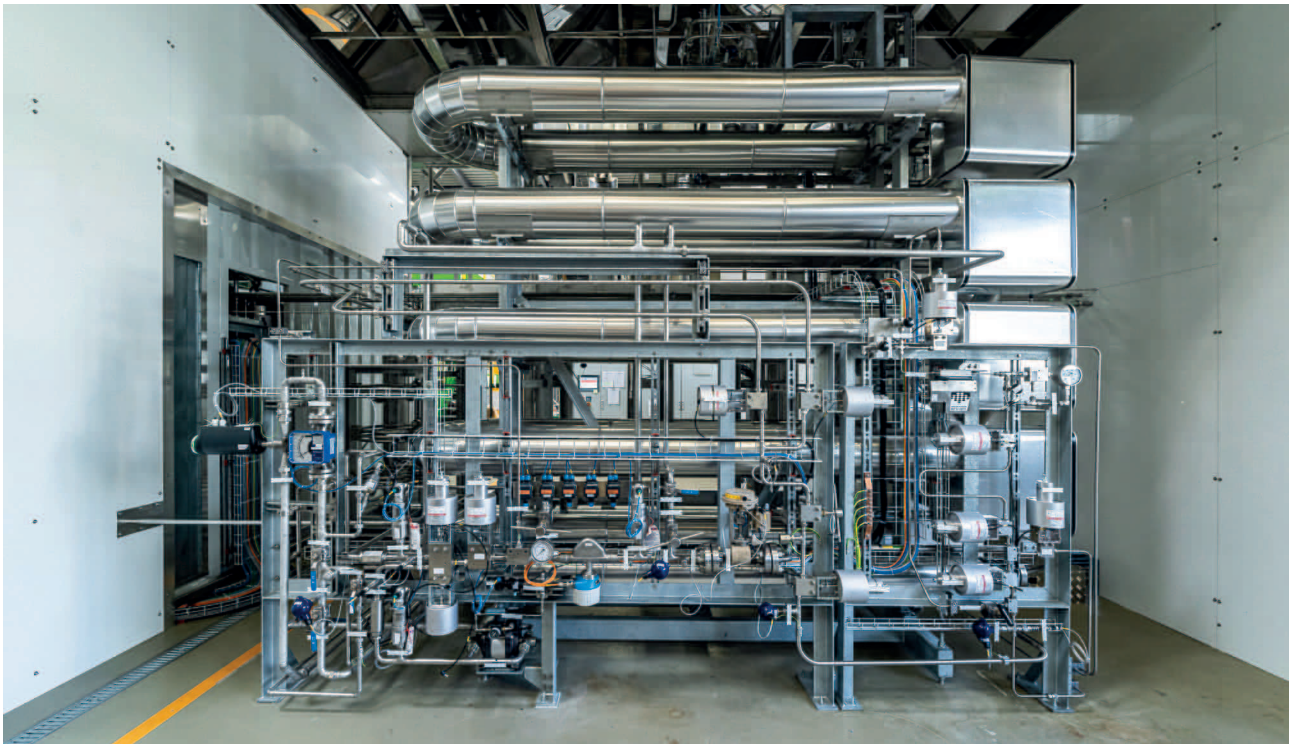

Figure 12: PSI photo of the 'Hydropilot' facility installed in 2020 in Villigen (Switzerland) in partnership with TreaTech (Source: M. Fischer, Paul Scherrer Institute, 2020).

The technology developed by both PSI and TreaTech is based on catalytic hydrothermal gasification, which allows a lower reactor temperature of around 400 °C and generates a syngas that is particularly high in methane (up to 70% without artificially adding hydrogen).

The waste introduced into the pilot plant is first compressed at 280 bar and then pre-heated using a heat exchanger to around 360 °C to optimise the use of the residual heat from the gasification reactor and limit system losses to the minimum possible level. The salt separator is heated to around 450 °C and is the first component to receive the feedstock, separating out the solid components (minerals and metals) from the carbon-containing fluid that will undergo hydrothermal gasification. After passing through a sulfur capture system that permanently removes all traces of sulfur, which poisons the catalyst, the carbon-containing fluid enters the catalytic gasification reactor, where it is converted into a mix of syngas and residual water that mainly contains nitrogen (ammonium). After the gaseous phase is separated from the liquid phase upon exiting the reactor, a syngas is obtained at high pressure, mainly composed of methane (CH_4: ≤ 70%), hydrogen (H_2: 0 to 10%) and carbon dioxide (CO_2: 30 to 35%). The carbon conversion efficiency achieves 85% to 99% depending on the complexity of the type of feedstock or mix of feedstocks being recycled. In addition, over 98% of the total organic carbon (TOC) contained in water treatment sludge is degraded, with a phosphorus and ammonium recovery rate of at least 80%.

Table 6: Example of mass flows for a commercial 6 t/h catalytic hydrothermal gasification facility (Source: TreaTech).

Feedstocks	Products, co-products and effluents	
Dry matter 20%m	Renewable gas	17%m*
	Phosphorus	0.4%m
	Ammonium	≈ 20 g/l
	Organic matter recycled in the process	1%m
	Final waste	7%m
Water 80%m	Water recycled in the process	11%m
	Process water	62%m

* *%m = mass percentage*

The table below (Table 6) gives an example of the breakdown of by-products produced using a catalytic hydrothermal gasification process with a commercial unit processing digested sludge at a rate of 6 t/h.

In a partnership built and realized in 2022 by Paul Scherrer Institut (PSI), TreaTech and GRTgaz testing the complete process chain of the Hydrothermal Gasification unit "Hydropilot", a complete syngas production analysis showed that his quality could be easily compliant with the European biomethane quality standard*** for its injection into the gas grid.**

*** Résumé de l'analyse en Annexe.*

**** EN 16726 ou EN 16723-1*

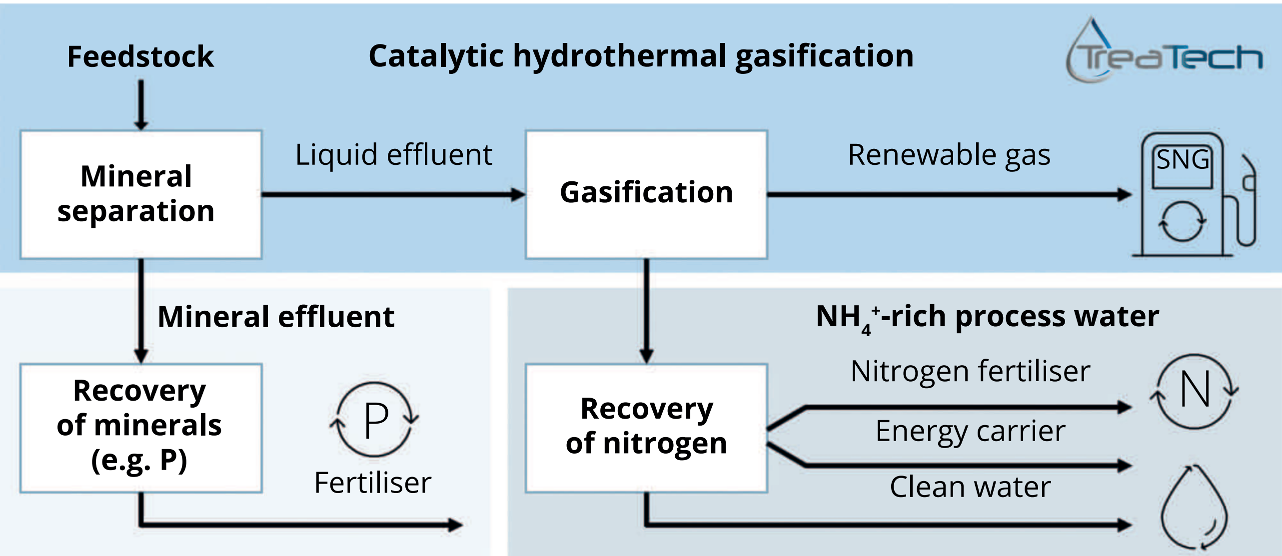

Figure 13: Diagram of the principle of the hydrothermal gasification pilot (Source: TreaTech).

4.3 Private developers

4.3.1 SCW Systems and the Alkmaar industrial plant (16 t/h)

SCW Systems is the world most advanced hydrothermal gasification company, which commissioned its first industrial installation in 2023. It is capable of continuously processing (≈ 7,500-8,000 h/year) up to 16 t/h of feedstock and has a total installed capacity of around 20 MW thermal (depending on the type of feedstock/mix of feedstocks and the concentration). The photo below shows the current facilities (Figure 14) and Table 7 gives technical details.

- SCW Systems began operations in 2014 with the development of an initial 100 l/h pilot using 10% glycerol, which was built in Alkmaar. Heat input was provided using an electric heater. A major obstacle to the process at that time was the removal of inorganic compounds from the system, primarily because of carbon and salt deposits. SCW Systems filed multiple patents with solutions to this obstacle (which have not yet been made public).

- This prototype underwent significant testing and improvement, following which, in 2016, SCW Systems began developing and constructing an industrial demonstrator project with a processing capacity of 2 t/h (≈ 2 MW_{th}), completed in 2018. To support the project, a partnership was signed with Gasunie New Energy, with 15 M€ of financial support providing the majority of the funding to cover the development and production

Table 7: Profile: the SCW Systems project.

Project name	Alkmaar 1 plant
Project owner/ partners	Joint project company between SCW Systems and Gasunie New Energy
Location	Alkmaar, the Netherlands
Launch year	Before end of 2022
Maximum capacity	16 t/h (4 modules of 4 t/h), 20 MW_{th}
TRL	8
Technology type	High-temperature (no catalyst)
Gas processing	A sequence of desulfurisation, catalytic methanation and CO_2 membrane separation
Recycling of co-products (liquid, gaseous, solid)	Residual water: treated to drinking quality CO_2: mineralisation (carbon-containing dust) Metals: intention to recover the most economically attractive metals (volume and/or value)
Operating conditions	Greater than 374 °C, 250-300 bar
Feedstocks	WWTP sludge, agricultural waste, agrifood waste, household waste, biowaste, industrial effluent, plastics.
Construction costs (estimate)	Demonstrator project CAPEX: ~ 15 M€ Alkmaar 1 project : ~45 to 55 M€

Figure 14: Aerial view of SCW Systems' Alkmaar site (Source: invest-nl.nl).

of the demonstrator project (increasing from TRL 6 to TRL 8). In late 2018, the first commissioning tests were conducted. In December 2019, the SCW Systems project became **the first hydrothermal gasification project worldwide to have successfully injected fully compliant high-pressure gas into the Gasunie grid**, the equivalent of GRTgaz in the Netherlands. During the testing and optimisation stage, the demonstrator underwent multiple improvements, with tests focusing both on the conversion of various feedstocks and subsequent injection of grid-compliant gas and on the strength of the materials used for the equipment. For one section of the demonstrator, the chosen alloy was reconsidered and replaced with stronger materials, which proved satisfactory after a new round of in-depth tests.

- In 2018, SCW Systems launched its first industrial hydrothermal gasification project (Alkmaar 1, with a processing capacity of 16 t/h (20 MW_{th}), see Table 7) as part of an annual call for proposals by the Dutch government, which financed experimental renewable energy generation projects. SCW Systems subsequently received guaranteed remuneration for its project over 12 years thanks to a subsidy worth €55/MWh_{HCV} and a sale price for the injected gas of €20/MWh_{HCV}. SCW Systems' Alkmaar 1 project is designed to operate continuously, and is predicted to receive a total of 112 M€ over the life of the contract.

Aiming to massify the manufacturing of its facilities, and with the goal of developing projects with an output in the dozens or even hundreds of megawatts per site, SCW Systems is also focusing on mineralisation of excess CO_2: it has developed and patented a specific process for transforming the gas into carbon powder[a]. Recycling of CO_2 is of great interest to the cement and paper industries, among others, for its carbon credit eligibility.

Finally, SCW Systems' ambition does not end there, and it has a dense roadmap for the years ahead:

- By 2024/2025, two other hydrothermal gasification projects – 40 MW_{th} each for a total power of 100 MW_{th} with a gas production capacity of around 0.5 TWh/year – are planned to be implemented. The first 40 MW_{th} project (Alkmaar 2A) received Dutch government approval in 2020 and is scheduled to be operating in 2024 at the latest.

In parallel, SCW Systems has already begun developing other sites in addition to Alkmaar which will add a further installed capacity of 100 MW_{th} by 2025: the company is focusing in particular on industrial sites located near major Dutch ports that are seeking to improve their waste recycling. By 2030, its aim is to develop a total installed thermal capacity of 650 MW_{th} in the major ports of Rotterdam and Eemshaven (near the German border). Together with the facilities at the Alkmaar site, SCW Systems forecasts that within the same timeframe, its industrial facilities will have a total base injectable gas production capacity of at least **10 TWh/year in the Netherlands and around 40 TWh/year across Europe**. For context, the Dutch government is targeting national production of around 11.2 TWh/year (or 40 PJ/year) of renewable and low-carbon gas by hydrothermal gasification in 2030, accounting for 57% of the global 2030 target for renewable and low-carbon gas production[b].

It should be noted that as SCW Systems has made very few details public, the majority of the information above is from the report '*BTG openbaar eindrapport vergassing 11 maart 2021*' [20], with additional information communicated orally by the company director of business development.

4.3.2 ProBiomass BV and the SUPERSLUDGE project

Based on technology from the KIT, ProBiomass designed an initial prototype (with a capacity of around 0.2 l/h) in 2011, which was developed and later used as part of the SUPERSLUDGE consortium (Table 8). The primary goal was to better understand the effects of converting wastewater treatment plant sludge using hydrothermal gasification. For this reason, the project has been heavily subsidised by the Dutch water agencies (the De Dommel and Aa en Maas agencies are involved in the project).

[a] COCOMINE-2 project (https://www.kansenvoorwest2.nl/en/projecten/cocomine-2).
[b] Kamerbrief Routekaart Groen Gas (Dutch parliamentary archive, accessed on 12/01/2022)

Supplemented with two pilot-scale tests (with a capacity of 50 l/h) using wastewater treatment sludge at the KIT VERENA facility, a preliminary design for the final implementation of a demonstrator capable of processing 1 t/h of sludge was in development until 2016.

For economic reasons, the decision was made to begin by constructing a low-budget (0.7 M€) pre-industrial pilot facility with a capacity of 150 kg/h, which was completed in early 2018 with the launch of a pilot preparation stage. This stage was followed by two years of operational testing to optimise the process. The aim was to arrive at a final design basis to launch a 1 t/h demonstrator project as the final stage in the development of the process.

The consortium has used a cyclone salt separator, modifying the way it is managed to optimise salt separation and thus limiting the loss of organic matter from the fluid to be converted into gas in the gasifier [20].

For the syngas processing module, ProBiomass contacted the German equipment manufacturer MicrobEnergy, which specialises in biological methanation [21]. The German company then developed a proof of concept demonstrating that it could adapt its methanation process in order to bring the syngas produced by ProBiomass's hydrothermal gasification system into compliance with gas injection requirements.

In 2020, ProBiomass assessed the average total CAPEX[a] of a future industrial project using its technology as follows, depending on size (due to economies of scale):

- 5.5 M€ for a 1 t/h hydrothermal gasification facility

Table 8: Profile: the SUPERSLUDGE project.

Project name	SUPERSLUDGE
Project owner/ partners	ProBiomass/Aa en Maas and Dommel water agencies along with SNB and Glaesum
Location	The Netherlands
Launch year	2018
Maximum capacity	150 kg/h, ⩾ 17% DM
TRL	6
Technology type	High temperature (Non-catalytic)
Operating conditions	650 °C, 350 bar
Feedstocks	WWTP sludge
Gas recovery	No (flared) + R&D partnership with MicrobEnergy (Germany) – since acquired by Pietro Fiorentini Group (Italy) – to work on a biological methanation syngas processing concept.
Recycling of co-products	NA
Construction costs	0.7 M€

- 7.3 M€ for a 1.5 t/h hydrothermal gasification facility
- 17.9 M€ for a 5 t/h hydrothermal gasification facility
- Similarly, ProBiomass has varied certain parameters to determine their impact on the CAPEX and profitability of potential projects operating using WWTP sludge:
- An operating time of 8,000 h/year coupled with a thermal efficiency of 88%, a conversion rate of 95%, an HCV of 21.6 MJ/kg DM and a feedstock dryness level of at least 17% gave the best results.

4.4 French developers

4.4.1 CEA-Liten and the Gaseau prototype

In France, CEA-Liten in Grenoble has been focusing on high-temperature hydrothermal gasification since the early 2010s, with its work leading to the implementation in 2016 of an initial prototype capable of processing up to 10 kg/h of feedstock. In 2019, work began to design a pilot

[a] Pro-Biomass presentation sent to GRTgaz. The data is public but the presentation is confidential and thus cannot be attached to this study.

facility processing around 100 kg/h as part of the Cométha project in partnership with VINCI Environnement[a]. Since then, the initial prototype has been replaced by a new model, identical in size, which incorporates the improvements made to the process design. In spring 2022, CEA and GRDF joined forces to boost and try to finalise work to develop the hydrothermal gasification process with the aim of completing the planned pre-industrial pilot as soon as possible, with one industry stakeholder involved.

The Gaseau prototype is a continuously operating test reactor with input rates ranging from 1 kg/h to a maximum of 10 kg/h. The heat energy required for the process is provided externally via electric heating, with no heat recovery in place.

Inorganic compounds are separated via gravity settling within the gasifier, with a cold area in which these compounds are trapped. CEA has tested more than a dozen feedstocks, including black liquor, algae, digestate, sludge and sludge digestate, vinasse and more.

According to CEA, the main technological barriers to overcome to develop hydrothermal gasification are energy management (and heat recovery), salt management (with or without a dedicated salt separator), equipment corrosion and mechanical strength, proper conversion of the carbon stored in the organic matter, and finally recycling of outputs (ammonium-rich water and solids such as minerals and metals).

Table 9: Profile: the Gaseau prototype.

Project name	GASEAU
Project owner/ partners	CEA-LITEN
Location	Grenoble, France
Launch year	2016/2021
Maximum capacity	10 kg/h, 10% (continuous prototype)
TRL	4
Technology type	High-temperature
Operating conditions	600-700 °C, 250-300 bar
Feedstocks	WWTP sludge and sludge digestate, black liquor, microalgae, etc.
Gas recovery	No (flared)
Recycling of co-products	No
Construction costs	NA

4.4.2 Leroux & Lotz Technologies, the first French equipment manufacturer to focus on developing HTG technology

The latest French specialist in biomass and waste-to-energy conversion, Leroux & Lotz Technologies is a Nantes-based company with around 90 employees that belongs to the Altawest group. With over 35 years of experience, Leroux & Lotz Technologies designs, produces and commissions facilities capable of converting (including boiler combustion, thermal gasification and hydrothermal oxidation) and recycling different types of renewable and/or fossil feedstocks (biomass, SRF, urban and industrial waste, etc.) into energy (heat, electricity and gas).

With a background in biomass boilers, Leroux & Lotz Technologies has expanded its focus in recent years with thermal gasification and hydrothermal oxidation (HTO), two innovative new technologies

Figure 15: Hydrothermal oxidation demonstrator produced by Leroux & Lotz Technologies as part of the Leanships H2020 project.

[a] Cométha Technical Morning – 21 Sept 2018 (https://www.syctom-paris.fr/fileadmin/mediatheque/documentation/cometha/Cometha_Dossier-information.pdf)

for different types of markets, both in France and abroad. It was no major leap for the company to include hydrothermal gasification in its innovation strategy, which it did in 2019 by taking part in the first GHAMa demonstrator project (2 t/h, ≈ 2 MW_{th}) in Saint-Nazaire, firstly as an integrator of hydrothermal gasification technology. In late 2021, Leroux & Lotz Technologies decided to go one step further by launching the development of its own technology (high-temperature hydrothermal gasification) through a partnership with the KIT in Germany, the leading scientific developer of the technology in Europe (see section 4.2.1).

Leroux & Lotz Technologies' aim is to roll out this technology with an initial market date of 2025/2026 based on the lessons learned from the GHAMa demonstrator project. Just as it did for the other technologies, with hydrothermal gasification, Leroux & Lotz Technologies is positioning itself as a turnkey supplier of 'core process' equipment, targeting in particular those facilities that process between 4 to 8 t/h of organic waste from activities managed by regional authorities (WWTPs, household waste, biowaste), industry stakeholders and farmers.

4.4.3 VINCI Environnement, an integrator that is focusing on HTG technology

VINCI Environnement, a subsidiary of VINCI Construction Grands Projets, is a historic French stakeholder implementing industrial waste treatment and recovery projects. Its hundred employees rely on the multidisciplinary support functions working at the VINCI Group to successfully implement its projects, particularly those working in its hydraulic division (design/construction of wastewater treatment plants), but also, for the last several years, those focusing on anaerobic digestion facilities, an area in which VINCI Environnement has its own process (a dry digestion process).

Given the future challenges and opportunities of the renewable and low-carbon gas sector, including hydrogen, VINCI Environnement wants to expand its offering by fully playing its part in the future development and roll-out of hydrothermal gasification in France and across Europe.

To achieve these goals, it has signed a partnership agreement with **GENIFUEL CORPORATION**, a historic developer that is renowned for its hydrothermal gasification technology in the USA, and whose technological readiness level is sufficiently high to ultimately integrate this 'process module' into a turnkey facility.

The technology that has been developed is a two-step catalytic process that uses hydrothermal liquefaction and then hydrothermal gasification. A number of demonstration facilities (processing capacity: ≈ 0.5 t/h) using this process are currently in operation. In recent years, these facilities have also provided the opportunity to test many different feedstocks: the first facility has been processing algae since 2017, while among those that are currently being developed, GENIFUEL is also working on other feedstocks such as different WWTP sludge types (from WWTPs in Vancouver and

Figure 16: GENIFUEL mobile facility.

Florida). The facilities are installed in containers, meaning they can be easily transported between sites, allowing the system to be tested with different prospects and feedstocks (Figure 16).

4.5 The main challenges to overcome to successfully move to the industrial scale

All developers of hydrothermal gasification have to meet the very specific (supercritical) operating conditions the technology requires. There are several technological barriers that each stakeholder must overcome to develop and industrialise the technology:

- Optimising the input and management of heat energy in the process;
- Optimising management of corrosion and the mechanical strength of the materials used;
- Optimising the separation of solids (mineral salts, metals, etc.);
- Optimising the carbon conversion rate for each type or mix of feedstocks;
- Optimising the recovery of outputs (in gaseous, liquid and solid form).

4.5.1 Optimising the recovery and management of heat in the process

There are two criteria on which the energy efficiency of the hydrothermal gasification process can be assessed:

$$\textbf{Energy conversion efficiency} = \frac{\text{Energy from collected gases}}{\text{Energy contained in the feedstock}}$$

$$\textbf{Overall energy efficiency} = \frac{\text{Energy from collected gases - Energy consumption}}{\text{Energy contained in the feedstock}}$$

For the system energy consumption and the overall energy efficiency calculation, a distinction must be made between two stages:

1. The start-up or heating stage of the HTG unit: this is the stage that involves the highest energy consumption, almost all of which is thermal energy used to pre-heat the HTG system from ambient temperature to nominal system temperature required for continuous operation. The need for electrical energy is very limited and is essentially required to operate the high-pressure pump (as well as a few other sources of low electric power consumption, such as valves, probes, etc.) which compresses the feedstock in the liquid stage. By default, compressing a liquid does not require much energy.
2. The continuous operation stage: while the electrical energy requirements remain unchanged, the majority of thermal energy consumption is due to the need to offset heat loss from the system component with the highest temperature requirements, either the salt separator (catalytic hydrothermal gasification) or the gasifier (high-temperature hydrothermal gasification). Other minor thermal losses occur via the solid and liquid residue generated at the output of the salt separator and the liquid/gas phase separator.

A high heat exchanger efficiency (> 85%!) is essential to achieve the high overall energy efficiency targeted for industrial facilities (> 70-75% as a minimum).

Because the high-temperature process takes place at temperatures of 550 to 700 °C, it necessarily requires more significant thermal energy input than the catalytic process, which operates at 360 to 400 °C. This means that optimising the design and efficiency of heat exchangers and choosing the most suitable technologies of thermal production are central to the different designs used by developers of this technology.

In the joint PSI/TreaTech Hydropilot pilot system, the efficiency of the heat exchangers installed has been measured at 88%, meaning that the cooling equipment installed (as a precaution) on the main output flow from the hydrothermal gasification gasifier is not required.

In catalytic hydrothermal gasification, the salt separator is the component that is heated to and maintained at the highest temperature (around 450 °C in the TreaTech system), while all other components in the process (the gasifier and the feedstock pre-heating system) are exclusively supplied with thermal energy by the heat exchanger. As such, the heat requirements can be met, both during the start-up phase and during continuous operation, by a single heat production unit, which can use any available type of primary energy (gas, wood, electricity, solar power, etc.).

For high-temperature hydrothermal gasification processes, the gasifier is the hottest component and the salt separator and other components are supplied with heat by one or more (cascading) heat exchangers. For the heat supply, it may be wise to make a distinction between a heat production technology only for the start-up phase and another technology with more precise control (electrical resistance, for example) to manage and adjust the temperature in the gasifier (high-temperature HTG) or in the salt separator (catalytic HTG).

The energy content of the synthetic gas generated is directly linked to the conversion rate of the hydrothermal gasification process used (pressure, temperature, residence time) and to the energy content of the feedstock, which depends on its organic matter content, and in particular its carbon content.

At a given tonnage, the higher the energy content of the feedstock, the higher the gas flow and the higher its energy content, while the hydrothermal gasification system energy consumption will remain almost constant. **As a result, the more energy-rich the feedstock, the greater its production of syngas and overall energy efficiency.**

- By increasing the dry matter content of segregated or mixed organic waste, its carbon content is increased, resulting in a proportional increase of the feedstock and an indirect increase of the synthetic gas gross calorific value. Note that the energy conversion rate is generally between 85% and 99% depending on the ash/mineral content of the feedstock
- In current pilots, heat exchangers have achieved thermal efficiency of over 85%

The Dry Matter content in the feedstock (including its OM and carbon content) and its associated calorific value are therefore two key elements in the system energy efficiency. However, increasing the DM proportion can have consequences:

- **Greater difficulty handling feedstocks:** some of the targeted resources behave 'like water' up to a dry matter content of around 20%, but others become much more difficult to handle and introduce to the reactor. The rheology of these products can make pressurisation of the feedstock difficult. There are no high-flow, high-pressure pumps available on the market. However, there are many feedstocks with dryness levels of much greater than 20% that can be converted and for which a range of suitable pumps exist. It should be noted that the viscosity can be improved by pre-heating the feedstock before it enters the pump, or certain feedstocks can be injected together with water in the gasifier or the salt separator, depending on the type of hydrothermal gasification technology used.

  The DM content can be raised for example to 35% for a mix of glycerol, WWTP sludge and plastics, and up to 80% and more for specific feedstocks like plastics, monomers, polymers, etc. For some feedstocks like solvents water must be specifically added to assure that the HTG system works.

The hydrothermal gasification process can be made more reliable through the following optimisation levers:

- Heat exchanger efficiency
- Energy input efficiency (heat production methods chosen based on the target temperature)
- The efficiency of heat recovery from the outgoing liquids and solids

In the catalytic hydrothermal gasification process, which allows the use of lower temperatures (360 to 450 °C), the energy requirements are less significant but nonetheless remain crucial. Several parameters must be taken into account to ensure the efficiency of the technology:

- **The nature of the catalyst**
- **Catalyst regeneration and upstream sulfur capture:** excessive sulfur concentrations will significantly shorten the lifespan and efficiency of the catalyst. It must be removed or separated upstream of the catalytic gasifier. High levels of mineral separation and sulfur capture (> 90%) are essential for proper long-term operation.

The capture of sulfur upstream of the catalyst, as well as the recycling and replacement of the catalyst, generate induced costs that impact OPEX's budgets. A catalyst recycling rate of > 75% substantially reduces the recurring cost of replacing the catalyst.

4.5.2 Optimising the separation of inorganic matter (mineral salts and metals) to facilitate gasification of the organic matter

A number of feedstocks in hydrothermal gasification – and WWTP sludge is an excellent example – contain a significant fraction of mineral material, which may or may not be dissolved in water. Under supercritical conditions, the solubility of these minerals falls drastically and precipitates them down the salt separator (or gasifier). According to the literature, there are two different types of salt:

- **Type 1 salts** characterised by the existence of a dense liquid phase above the critical point of water. In principle, these salts do not pose any problem.
- **Type 2 salts** characterised by the fact that they precipitate as the critical point of water is approached. They form a 'sticky' phase on the walls. These salts cause clogging and clumping problems in the reactors.

There are three solutions to resolve these clogging and clumping issues:

1. Remove the salts upstream of the reactor, for example through chemical treatment.
2. Manage the salts by installing a salt separator upstream of the reactor (TreaTech technology).
3. Manage the salts by installing a cyclone separation system upstream of the reactor (KIT technology).

4.5.3 Optimising the choice of steel alloys depending on the location of mechanical stresses and corrosion risks

The mechanical strength of reactors under supercritical conditions (a temperature of over 500 °C) is affected by corrosion due to the combined aggressiveness of supercritical water and the minerals contained in the feedstock.

Note that it is worth conducting long-term testing of sample alloys in order to find the most suitable material for designing the high-pressure equipment (reactor, heat exchanger, salt separator, ...) with the best long-term processing capacity.

To establish the reaction required for the hydrothermal gasification process, the feedstock must be provided with energy, contain or be mixed with water. By heating the feedstock externally (for example, through a wall), the outside of the reactor will be hotter than the feedstock contained within it. This temperature difference will result in significant mechanical stresses that can limit the lifespan of the reactor. In addition, if heating takes place within the reactor through oxidation of a portion of the feedstock, the energy efficiency can be affected.

4.5.4 Optimising carbon conversion: determining the best operating parameters

The rate of conversion of carbon into synthetic methane is one of the criteria used to assess the performance of a hydrothermal gasification process given that the aim is to produce a synthetic gas that is as rich as possible in CH_4, H_2 and potentially other hydrocarbons (C_xH_y).

The breakdown of the elements that form biochar is a key factor in reactor sizing. Certain carbon-containing molecules are very easily converted (e.g. ethanol, glucose), while the process is more difficult for others (e.g. lignin).

4.5.5 Optimising the recovery of outputs: determining the best operating parameters

Hydrothermal gasification generates outputs in each of the 3 potential phases, each of which has its own challenges and limitations:

- Gaseous phase outputs: the high-energy molecules (CH_4 + C_xH_y) produced are of the greatest interest because they have the greatest economic value. All other molecules (CO, CO_2, H_2S, etc.) must be separated (CO_2, H_2S) or converted (CO).
- Liquid and solid phase outputs: in addition to the liquid residue from the process containing mainly ammonium, the solid inorganic residues (minerals and metals) may carry molecules of interest that deserve to be valorised downstream, and for which the waste status should no longer apply after transformation into a marketable product. It is therefore beneficial to implement processes that allow an optimal valorisation of the liquid residue as well as separating and recovering a very high proportion of the solids in the fluid introduced into the system. This allows optimum recycling of:
  - > Phosphate, potassium and/or ammonium molecules to produce fertilisers.
  - > Metals (iron, aluminium, rare metals, etc.) whose recovery and reuse as a valuable new resource is of particular interest because of their rarity and/or their relatively high economic value (unit cost or absolute volume).

In the examples given above, the overall recovery and separation rate of these molecules is an important component in any assessment of the technical and economic viability of the series of processes put in place to enable commercial valorisation.

In summary, every developer of hydrothermal gasification technology must overcome broadly the same types of challenges to optimise the operation, profitability and energy balance of their hydrothermal gasification process. Their success is dependent both on research, studies and specific developments, which are often highly innovative, and on relevant partnerships with specialists from other sectors capable of adapting solutions that have already been tried and tested successfully under similar conditions.

05

A TECHNOLOGY AT THE HEART OF THE CIRCULAR ECONOMY

5.1 A circular economic model that benefits regions

The hydrothermal gasification sector offers an industrial model based on the thermochemical transformation of a wide range of feedstocks into various co-products that are recycled locally wherever possible. As well as producing a renewable or low-carbon gas with varying levels of methane and hydrogen, the technology also recovers solid and liquid residues that, after processing, become co-products that further increase the overall recovery rate of a given feedstock input.

Building on these benefits, hydrothermal gasification aims to be part of a local (bio-) economy that, bolstered by the deployment of compact modular units, leads to the emergence of several additional positive externalities.

5.1.1 Types of co-products

ADEME defines a 'co-product' as a material created during a product manufacturing process, whether intentionally or not. Hydrothermal gasification produces two types of co-products depending on their final use:

- **Energy co-products**: renewable and low-carbon gas.
- **Material co-products** (solid and liquid) generated after processing the residual solids and liquids collected downstream of the hydrothermal process.

Each co-product has an economic value normally determined by specific markets, like any other product. As these markets are generally based on a fossil benchmark that is often very cheap, co-products of biogenic origin often require financial and regulatory support from public authorities in order to exist and to allow the emergence of the technologies required to generate them.

To overcome this additional obstacle during the emergence stage, the first hydrothermal gasification business models are primarily based on energy production (the gas co-product that is made grid-injectable) to ensure the first industrial projects achieve the minimum level of profitability.

5.1.2 Energy co-products

a) Production of synthetic methane (> 95% CH_4)

As has often been mentioned in this white paper, the hydrothermal gasification process produces, depending on the type of feedstock, a synthetic gas that is either renewable or low-carbon based on the composition of the biogenic and fossil portion of the initial feedstock. After passing through a number of different treatment processes (gas-liquid separation, purification or methanation), the synthetic gas is processed and upgraded in synthetic methane, meeting natural gas standards[a] allowing its injection into the gas grid. After processing, it is made up almost exclusively (> 95%) of methane and higher hydrocarbons (C_xH_y).

Against a backdrop energy self-sufficiency – in terms of both gas and electricity – is becoming a major challenge around the country: the development of local renewable and low-carbon gas production capacities with the same qualities and composition as natural gas is a strategic benefit of hydrothermal gasification, both regionally and nationally.

[a] Standards: the composition of the injected gas must comply with the gas grid standards for natural gas.

b) Production of carbon dioxide (CO_2)

Hydrothermal gasification generates a synthetic gas with a very high carbon conversion rate (85 to 99%). It still contains carbon dioxide (in both catalytic and high-temperature hydrothermal gasification). The proportion depends on the feedstocks, the facility conversion parameters, and its operation.

After separation of the gaseous and liquid phases, a significant portion of the carbon dioxide contained in the syngas is captured and stored until saturation in the liquid residue. The proportion of carbon dioxide that remains in the gaseous phase is processed downstream with the other gaseous molecules (methane, hydrogen, etc.).

The syngas, with its carbon dioxide content reduced, then undergoes purification or methanation treatment and is separated from its residual carbon dioxide content, making it into a gas suitable for grid injection, synthetic methane. The residual carbon dioxide can be valorised, more or less directly, in a variety of ways depending on its purity (use in agricultural greenhouses, synthetic carbon sinks through mineralisation or sequestration in soil, power-to-gas projects, etc.).

However, there is an alternative that avoids the need for syngas treatment/processing as described above: if hydrogen is deliberately added to the hydrothermal gasification process, either directly into the gasifier (catalyst process) or into the methanation equipment (high-temperature process), the carbon dioxide is 'consumed' by the injected hydrogen for generating methane. Doing so not only significantly increases methane production (up to double the normal flow) but also permits to almost achieve a synthetic methane composition suitable for injection.

As shown in the previous chapters, regardless of the technology type or techniques used, CO_2 is a gaseous co-product that accounts for a significant proportion (20 to 35% in terms of gas quantity) of the outputs. Valorisation or recycling of CO_2 is necessary because doing so encourages the emergence of new closed loops within the circular economy, reducing the total emissions of the process while also meeting national and European climate targets.

CO_2 can potentially be recycled in three ways, with varying requirements in terms of purity levels:

1. **Recycling without processing:** enhanced hydrocarbons recovery, deep geothermal, in the food or pharmaceutical industry, etc.
2. **Recycling with chemical processing:** organic synthesis, mineralisation, methanation, etc.
3. **Recycling with biological processing** for energy use: for example, growing microalgae.

Some recycling methods have been identified as promising options (Table 10), for example, use in deep geothermal, methanation and methanol production, because they involve either long-term CO_2 storage or direct use of the final product, reducing the environmental impacts of the process. It should be noted that these impacts can be substantially mitigated if the energy required by these processes is provided by the synthetic gas produced directly via hydrothermal gasification.

Table 10: Summary of CO_2 recycling processes by minimum purity required, maturity of the recycling technologies, and the quantity of output produced from a tonne of CO_2 (Source: GRTgaz).

Process	Minimum purity required	Quantity produced per tonne of CO_2 recycled	Maturity (TRL)
Deep geothermal	⩾ 95%	1 MWh of electricity	6–8
Production of polycarbonates	⩾ 20%	10 t of carbonate	9
Methanation	⩾ 10%	0.36 t of methane	6–9
Hydrogenation (methanol)	⩾ 70%	0.73 t of methanol	7
Ex situ **mineralisation**	⩾ 20%	2.64 t of carbonate minerals	7–9
Microalgae cultivation	⩾ 20%	0.20 t of algae fuel	7–9

In Europe, the two lead developers of hydrothermal gasification technology, TreaTech and SCW Systems, have focused on the question of recycling the residual carbon dioxide, with interesting results. As part of the CoCoMine[a] project, SCW Systems has developed a mineralisation process in which the carbon dioxide is reacted with olivine, a common mineral, converting it to solid carbon. Called 'Clean-Up', SCW Systems is currently making the process into a product and a trademark. An initial industrial-scale facility was launched in 2022 at the Alkmaar site, which will capture at least 10,000 tonnes of CO_2/year. This demonstrates the accelerator effect that European support can bring to these sectors and to related recycling technologies.

c) Production of hydrogen (H_2)

In both Europe and France, the production of decarbonised hydrogen is strongly supported and keenly expected as part of efforts to support the energy transition and meet carbon neutrality targets. Hydrothermal gasification produces a synthetic gas with varying levels of hydrogen (anywhere from 0 to ⩾ 50% by volume) depending on the type of HTG process and the technological parameters used.

After separating the hydrogen produced from the initial synthetic gaseous flow, it can be valorised more or less directly depending on its purity and the tolerance level of the equipment in which it will be used.

Thanks to hydrothermal gasification versatility, its gaseous production can be adjusted to produce more or less quantities of methane or hydrogen. This means that future project owners will be able, in a certain range, to adapt production to meet market requirements.

5.1.3 Material co-products

a) Minerals, in particular phosphorus (P) and potassium (K)

The supercritical water conditions used in the process lead to the precipitation of the minerals in the form of salts into the bottom of the reactor, allowing them to be separated from the carbon-containing fluid. To prevent this phenomenon from occurring in the gasifier itself and potentially disrupting its operation, more and more hydrothermal gasification developers are installing a specific salt separator upstream of the gasifier for this task. Of particular interest due to their essential role in plant growth, the recovering of phosphorus (P) and potassium (K) allows, along with the nitrogen (N) collected downstream in the process water (see the section below), to produce fertilisers for use in agriculture after processing. Recovering and recycling phosphorus in a usable form for crops is not a direct process. As explained below (Chapter 6 on the business model), any potential recycling and sale of this mineral on the market is reliant on overcoming regulatory constraints (authorisation) and economic constraints (profitability of production and the existence of a dedicated market).

b) Metals

Depending on the composition of the organic waste being converted, certain metals can be found among the minerals. Some waste, mainly from industrial activities, can contain precious metals with a certain economic value due to their rarity or, for more common metals (iron, aluminium, etc.), due to their relatively large quantities.

A joint publication by Inrae, INSA, Deep, Agence de l'eau Rhône méditerranée and Reseed [22]

[a] Continuous mineralisation of CO_2 for negative emissions.

Table 11: Metals of interest for recovery for each matrix (concentration) (Varennes E. *et al.*, 2020).

Raw wastewater	Treated water	Sludge	Ash
Copper, Titanium, Barium	Boron Rubidium Lithium	**Iron** **Manganese** **Copper** **Zinc** **Phosphorus***	**Aluminium**

*phosphorus: added by the Hydrothermal Gasification Working Group

Table 12: Categorisation of metals by financial potential per 1 million PE (Varennes E. *et al.*, 2020).

> €10^6/year €1/PE.year	> €10^5/year €1/PE.year	> €10^4/year €1/PE.year	> €10^3/year €1/PE.year	< €10^3/year €1/PE.year
Barium	Aluminium	Copper	Boron	Antimony
Calcium	Hafnium	Gallium	Chrome	Silver
Caesium	Gold	Germanium	Tin	Arsenic
Magnesium	Palladium	Lithium	Iron	Bismuth
Rubidium	Platinum	Manganese	Molybdenum	Cadmium
	Potassium	Niobium	Nickel	Cobalt
	Silicon	Rhodium	Tungsten	Indium
	Sodium	Titanium	Vanadium	Mercury
		Zinc	Phosphorus	Lead

presented the economic potential of the various metals that can commonly be found in domestic wastewater (Table 11).

As demonstrated, hydrothermal gasification is able to recover the metals contained not only in urban and industrial WWTP sludge but also in a number of specific types of industrial organic waste. Table 12 shows the economic value of these metals in proportion to facility size (population equivalent – PE).

However, the gross market values shown do not lead to the conclusion that recovering all of these metals is economically viable. Some require one or more successive steps, which vary in cost, before they can be reused.

c) Water (H_2O) and nitrogen (N)

Nitrogen is present in the form of ammonium (NH_4^+), diluted in the process water which is collected at low pressure (≈ 5-10 bar) at the output of the gas-liquid separator. Depending on the type of feedstock, these two residues can account for up to 75-80% of the residual mass at the output of the process.

By separating out the nitrogen using suitable technology (membrane stripping, for example), purified water can be produced. The water can even be used without removing the nitrogen in the microalgae industry or for irrigating agricultural land. Wastewater treatment and reuse (WWTR) projects are also an option that could be investigated following the publication of the decree of 10 March 2022 in France on the use and conditions of reuse of treated wastewater.

Nitrogen – in particular as ammonium – is an essential element for the growth of all plants and is found in many fertilisers. As fertilisation and nitrogen fertiliser costs have increased in the current economical situation, having a local supply capacity of biogenic nitrogen would be a real asset for all stakeholders in the value chain.

d) Conclusion

Finally, hydrothermal gasification also offers, in addition to its ability to recover energy from organic waste through gas production, the possibility of recovering all its solid and liquid residues by recycling them as complementary co-products. As such, it offers a global and economically attractive alternative solution for the recovery of organic waste capable of successfully competing with existing technologies.

5.2 Waste recovery techniques with positive impacts

The passing of the French AGEC anti-waste and circular economy law (*Loi Anti-Gaspillage pour une Économie Circulaire*) in 2022 made reusing materials a necessary practice in order to achieve local carbon neutrality targets. The development of hydrothermal gasification plays a part in this process by developing pathways through which its co-products can be recycled.

5.2.1 Co-products with high added value for French territories

As described in the previous paragraph, hydrothermal gasification process produces both energy and material co-products. The climate situation and the current circumstances surrounding the fossil fuel markets are putting particular pressure on the following co-products:

- **Mineral salts and nitrogen:** effects linked to climate change and the geopolitical context, which constantly raises the question of access to fossil resources, have a major impact on the agricultural sector, in turn resulting in major economic and environmental challenges. Recovering nitrogen, phosphorus and potassium through hydrothermal gasification would help to address these challenges, at least in part. After processing, it offers a local, short-loop source of fertiliser while helping to secure agricultural production. As such, a farmer can directly benefit from the technology on two levels: they can recycle their waste into gas while also recovering minerals, nitrogen and water at a sustainable and managed cost. These fertilisers would be an affordable alternative to the use of less virtuous chemical fertilisers for the soil.

- **Metals:** despite the technological progress that has been made, extracting metals often has a significant environmental impact. Its specific economic cost varies, for each metal, depending on the deposits that are depleted at varying speed, on respective market needs, and on the control exercised by certain key countries which dominate the exploitation of certain fossil resources. As metals are materials that, due to volume effects or cost (rarity), must necessarily be recycled (via a short loop) to the greatest possible extent, there are multiple recovery opportunities. These opportunities are also capable of responding to the economic and regulatory demands placed upon them. Therefore, where hydrothermal gasification plants process metal-containing feedstock, recovering these metals from the plant output helps to make these local industries more self-sufficient.

5.2.2 Creating or amplifying a local ecosystem of stakeholders to maximise the potential for growth

Recycling these co-products can only take place if committed local stakeholders come together to create or amplify local recycling streams for these materials while ensuring economic balance for future consumers (industry, agriculture, etc.).

Recovery of co-products will not be possible without regional investment in new recycling processes (such as chemical or biological processes) in order to achieve the economic optimum that will allow these products to be recycled locally.

Hydrothermal gasification acts as a catalyst for this recycling and circular economy dynamics, but it must be supported by all regional stakeholders in the co-products value chain to materialize the various valorisation pathways. Finally, public support will be a key factor in mobilising these ecosystems.

5.2.3 A generator of positive externalities

Implementing these new circular ecosystems will benefit local areas in multiple ways, in particular through the creation of direct and indirect sustainable jobs that require qualifications of all levels and that cannot be relocated:

- Supplying organic waste and resources;
- Designing, building and operating the sites housing the technology;
- Generating and/or recycling the gaseous, solid and liquid co-products, either locally or regionally.

A precise estimate of the number of jobs that could be created by the sector is yet to be determined, and the Hydrothermal Gasification Working Group will play its part in this process.

Other than jobs, other positive externalities with a tangible intrinsic value for the local community, as well as the surrounding region and the country as a whole, could emerge.

However, these remain to be quantified and expressed in financial terms:

- Public health: lower NO_x emissions released into the atmosphere during combustion of waste-water treatment plant sludge and improperly controlled spreading;
- Environment: very significant reduction in GHG emissions and a reduced ground footprint compared to conventional solutions;
- Helping to establish positive energy regions and clean local mobility;
- Trade balance: reduced natural gas imports.

Hydrothermal gasification also offers development and leadership opportunities for French micro-enterprises and SMEs that are at the cutting edge of innovative components of the value chain and are currently contributing as part of the national Working Group.

As a summary, the figure below (Figure 17) presents the positive externalities and benefits linked to hydrothermal gasification technology. This representation is not exhaustive and illustrates the initial results obtained by a subgroup of the national Working Group. As stated above, it remains difficult, for the moment, to quantify these externalities in financial terms. Doing so will require specific studies. By incorporating more approaches based on the sustainable development goals within existing markets, their long-term micro- and macroeconomic value will rise.

Environment

- **Captures and recycles minerals and nitrogen (avoiding the need for imports and creating closed bio-geo-chemical loops)**
- **A process that emits no atmospheric pollutants**
- **Treats and reduces final waste**
- **Produces fertiliser, limiting the risks of water eutrophication, soil acidification and air pollution**
- **Eliminates organic micropo-llutants and pathogens**
- Recovers and preserves water (irrigation)
- Low surface footprint
- Isolates heavy metals, limiting their environmental impact and facilitating their recycling

- For wastewater treatment plants (WWTPs), HTG can help to bring about overall optimisation
- Conversion of plastic microparticles into gas

Energy

- **Strengthens energy self-sufficiency through local, controllable and storable energy production**
- **Continuously produces a renewable and low-carbon gas (methane + H_2)**
- **Produces energy in a way that eliminates all biological, health and climate obstacles**
- High energy efficiency: 75 to ⩾ 85%
- A gas that is easy to store and distribute via the existing gas grid
- Very fast conversion time (1 to 5 min)
- Greater energy efficiency, using the high pressure of the gas produced for grid injection

HTG helps to reduce fossil fuel energy requirements

High carbon conversion (> 90%)

HTG plant can be shared between a variety of waste producers and process a wide range of feedstocks

- Regional decarbonisation (GHG reduction)
- An alternative solution to incineration or landfill
- Reduces non-GHG environmental impacts (noise, odour, logistics, etc.) through local processing of organic residue and waste
- Closes regions' bio-geo-chemical loops
- Managed recovery of co-products in the biofertiliser/soil amendment sector
- Coordinated recycling of CO_2 through other biological and thermochemical processes (mineralisation, electrolysis, etc.)
- Recycles carbon-containing residue from other technologies (anaerobic digestion, thermal gasification, etc.)
- Potential to redevelop brownfield sites
- Modular, flexible and compact solution

- Competitive cost of the renewable and low-carbon gas produced
- Improved local energy footprint
- Potential production of H_2 in addition to methane: industrial and transport uses
- Potential to recover waste heat

Economy

- **Substantially reduces waste processing costs (including final waste)**
- Generates socio-economic benefits, adding to the local value chain (sustainable jobs, new expertise and activities)
  » Creates sustainable jobs
  » Creates local expertise
  » Creates new activities (local production of co-products for use in industry, agriculture and the tertiary sector)
  » Improves trade balance (flow of energy, materials, waste, etc.)
- Improves traceability (circular economy)

Figure 17: Example of the positive externalities and benefits linked to a hydrothermal gasification (HTG) facility at the intersection between environmental, energy and economic issues (Source: HTG Working Group).

06

THE BUSINESS MODEL AND ECONOMIC POTENTIAL OF HYDROTHERMAL GASIFICATION

While the scientific principle of hydrothermal gasification or also called SuperCritical Water Gasification (SCWG) is not new[a], it was not until 2004 that the technology took its first step towards continuous operation and its future industrialisation: the commissioning of the world first pilot facility, the VERENA project (100 kg/h) from the Karlsruhe Institute of Technology (KIT) in Germany.

Since 2010, several other pre-industrial pilots and, later, the first quasi-industrial demonstrators (Osaka Gas in Japan, SCW Systems in the Netherlands, Genifuel in the USA, etc.) were produced and have helped to make significant technological developments in both catalytic and high-temperature technologies.

Finally, more recently, boosted by private developers who have been actively working on HTG in the last decade, the technology is now making the leap to the industrial level, as demonstrated by the commercial commissioning of the world first industrial project from SCW Systems (the Netherlands), 'Alkmaar 1' (20 MW_{th}), which is scheduled in 2023. For the company, it is the beginning of a series of three consecutive projects (along with 'Alkmaar 2A' and '2B', both with a capacity of 40 MW_{th}), which are scheduled to be installed at the same site by the end of 2025. The initially available information indicates that based on an injected gas price of around €75/MWh_{HCV} (taking into account price levels set between 2018 and 2020), the first two of the three planned projects should be able to cover their costs (CAPEX and OPEX) over a total facility lifespan of 12 years. It is currently still too early to have sufficient global experience feedback to build a true business model and give an accurate estimate of the technology economic potential. However, it is possible to identify an initial vision and the outlines of the potential development of the future hydrothermal gasification market in France.

Outside of confidential information shared by certain private developers, only a few scientific publications [23] have dared to make an estimate. Furthermore, the figures provided by certain stakeholders do not always cover the same scope, which has required the Working Group to fill in certain parameters (e.g. gas processing technology, CAPEX financing, etc.) and to take into account the specific characteristics linked to the type of hydrothermal gasification technology (catalytic or high-temperature) used.

Similarly, in addition to the full cost analysis of the technology (for the project as a whole), calculations of the potential revenue generated by a given project are currently limited to the injected gas only.

Depending on the type of waste recycled, additional economic value may be generated, for example through the waste processing service provided and/or through the ability to recycle the liquid and solid residue that is recovered during the process. These examples of revenues streams may be more or less significant, and, in many cases, are not applicable to other renewable and low-carbon gas production technologies. Assessing overall revenue is not a simple process, and so a case-by-case approach is preferred while simultaneously taking into account the baseline circumstances, which can have varying levels of impact on the profitability of a given project.

[a] The first research was published by MIT (Massachusetts Institute of Technology, USA) in the 1970s, https://bit.ly/3OR897r.

6.1 Assessing the technology CAPEX and OPEX

Facilities of all sizes exist worldwide and/or are currently being built in Europe:

- Pilots and little demonstrators of a few hundred kg/h:
  - > KIT (Germany), TreaTech (Switzerland) + ProBiomass (Netherlands): 100-150 kg/h,
  - > Osaka Gas (Japan): 350 kg/h and Genifuel (USA): 500 kg/h
- Demonstrator and industrial installations measured in t/h (SCW Systems = the world first industrial hydrothermal gasification facility):
  - > Industrial demonstrator (2 MW_{th}): one module of 2 t/h optimised between 2018 and 2020,
  - > The world first industrial project (Alkmaar 1 (20 MW_{th})): 4 modules of 4 t/h (= standardised industrial module size),
    - → Project commercial operation scheduled in 2023 at the latest!
  - > Alkmaar 2A and 2B projects (40 MW_{th} each): 8 modules of 4 t/h,
    - → Commercial operation scheduled by the end of 2024 and 2025.

Such a diverse range of facilities makes it more difficult to analyse, compare and determine a business model, but tends to show the minimum size beyond which economic viability appears to be attainable.

A hydrothermal gasification project needs to contend with cost limitations that are directly linked to the module processing capacity:

- If it is too small, it will be faced with a cost ceiling regardless of its size.
  - > Below a size of 1 to 2 t/h (depending on the type of feedstock processed), for several sub-components, the manufacturing costs cannot be anymore reduced with the size.
- If the size is too large, it will be faced with an exponential increase in costs for certain sub-components (taps and valves, for example). Due to the need to withstand supercritical conditions, increasing the diameter of these components quickly reaches the physical limits that must not be exceeded in order to keep costs to a competitive level.
  - > the maximum size of a module must therefore be between 4 t/h (the size chosen by SCW Systems) and 6 t/h; any project exceeding this feedstock processing capacity will be fitted with at least two modules of the same size.

Other elements also affect the costs and potential profitability of a facility sized for a given maximum gross flow (hourly tonnage) of waste: as the synthetic gas flow produced by the gasifier is directly dependent on the carbon content of the feedstock, the more concentrated and energy-rich (and therefore carbon-rich) it is, the higher the output of synthetic gas.

Similarly, the energy consumption of the hydrothermal gasification process depends almost entirely on the gross flow of waste for which the facility was sized: initially, this can be considered constant. So a more concentrated, more carbon-rich feedstock incurs no additional energy cost for the same gross feedstock flow rate!

The Dutch company SCW Systems has chosen to focus on individual large-capacity projects (at least 20 to 40 MWh) on production sites that can reach a total installed thermal capacity significantly in excess of 100 MW_{th} per site in the future. As its facilities require an abundant supply of organic waste all year round, SCW Systems primarily targets sites in the immediate vicinity of large sea ports or major industrial sites (Rotterdam, Alkmaar, Delfzijl, etc.) located near maritime or river transport networks to allow waste to be transported to hydrothermal gasification plants for processing and recovery at the lowest possible cost.

In France, given the very different geography and the more diversified location of large volumes of waste, stakeholders in the hydrothermal gasification sector believe that the majority of projects will have a waste processing capacity of 4 to 8 t/h. Given the large size of certain sites (water treatment plants in the biggest urban areas such as Paris, Marseille or Lyon and major industrial sites) and the presence of very large quantities of waste (> 25,000 tDM/year), there could be scope within France for a number of very large hydrothermal gasification projects of up to 40 MW_{th} or even more per project and per site.

6.1.1 CAPEX

The CAPEX figures available often cover slightly different scopes, making it difficult to compare them on an equal basis, and this is true both for figures in the scientific literature and for those communicated by private technology developers. Furthermore, because hydrothermal gasification is at the beginning of its industrialisation, it is expected that costs may fall further, either as a result of competition between stakeholders and/or through the series effect and standardisation in the industrial manufacturing of modules and the installation of hydrothermal gasification facilities as a whole. The most advanced developers believe that it will be possible to achieve economies of scale saving up to 30% within five years of commercial launch.

It should be understood that the figures gathered and set out below by the authors are merely a snapshot of a given moment in time (June 2022) and do not include any financial effects linked to inflation or disruptions to markets supplying specific materials or resources.

Despite the uncertainty in which hydrothermal gasification stakeholders operate, it is nonetheless possible to trace an initial CAPEX cost curve based on the facility processing capacity, taking into account both types of technology (catalytic and high-temperature) and based on the available sources (bibliographic data, scientific publications, etc.). Initial estimates have also been integrated for industrial projects from certain developers and figures have been gathered from the very first industrial projects that are currently being constructed or commissioned.

Additionally, on an individual unit basis, as shown in figure 19 above, to the left of the '2 t/h' threshold (indicated by a dotted red line), **CAPEX costs rise exponentially (from around 5.5 M€ to 13 M€ per t/h processed) for facilities with waste processing capacities below 2 t/h.** A hydrothermal gasification facility with a capacity of 2 t/h is currently at the maximum size threshold for an industrial

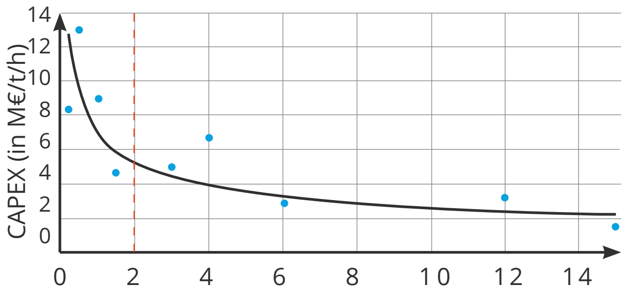

Figure 18: CAPEX (M€/t/h) for a hydrothermal gasification project plotted against waste processing capacity.

demonstrator project that allows a developer to optimise its technology and move from TRL 6-7 to TRL 8-9. At the same time, this is a representative size for a future marketable product (a 3 to 6 t/h module).

Moving in the opposite direction, by increasing the processing capacity of a facility, there is first a less significant reduction in costs from around 5.5 to 4 M€/t/h processed with an increase from 2 t/h to 4 t/h, and then a linear reduction in cost towards a lower threshold tangential to 2 M€ per t/h processed up to very high levels of processing capacity (> 14 t/h).

By varying the types of waste processed, it has been observed that a facility potential profitability threshold does not depend exclusively on its size, but that in fact, the type of waste or waste mix processed plays a non-negligible part. This means that the drier the organic waste (≥ 20% DM), the higher carbon content in the dry matter and significant energy value (> 20 MJ/kg DM), the higher the gas output flow rate generated at the outlet will be, while the system energy consumption remains constant at a constant gross flow rate. As such, the higher the energy content of a feedstock and the higher its gas production as a result, the lower the break-even point of a hydrothermal gasification facility. For example, a plant that processes 4 t/h of WWTP sludge with relatively low energy content may be less profitable than a plant processing 2 t/h of energy-dense waste.

Based on a purchase price for injected gas comparable to that in place when anaerobic digestion was first launched, simulations conducted by the members of the Hydrothermal Gasification Working Group have shown that it should be possible for the first hydrothermal gasification projects in France to be profitable with a processing capacity of over 4 t/h and with a CAPEX ratio of 4 M€ per t/h of waste processed.

For very large projects processing the most energy-dense waste, it appears that it will ultimately be possible to approach a CAPEX ratio of around 1 M€ per t/h.

The Dutch report 'BTG – The state of the art of gasification in the Netherlands and its outlooks, March 2021' [20] appears to confirm the estimates carried out in France, with **a cost ratio (CAPEX) per MW of gas injected of around ≈ 1.5 M€/MW$_{CH_4}$ for Dutch large-capacity gas facilities of slightly below 50 MW$_{CH_4}$.**

However, as the following section shows, the decisive factor is the comparison of operational expenditure (OPEX), including maintenance and depreciation, which gives a true image of the effective cost of sludge disposal, taking into account the income generated (sale of gas, mineral components, etc.).

Switzerland case study (CAPEX)

AFRY Suisse SA carried out a study in 2018 to analyse CAPEX in different sludge treatment sectors. The study considered the following scenarios and was based on a WWTP capacity of 200,000 population equivalent.

The baseline scenario in Switzerland (scenario 1a) for treating WWTP sludge is:

- On-site anaerobic digestion of sludge, with the resulting digestate thickened to 20-30% DM before being transported and incinerated (in Switzerland, sludge and sludge digestate must be incinerated and cannot be used or recycled for any purpose).

By comparing **the CAPEX for this benchmark with other scenarios**, the study shows that:

- **A combined solution, hydrothermal gasification after anaerobic digestion, is 40% more expensive (scenario 2a).**
- **However**, if anaerobic digestion of the sludge is entirely replaced **by hydrothermal gasification, processing the sludge directly (scenario 2b), <u>this solution is at least 20% less costly in terms of CAPEX than the benchmark scenario</u>.**
  → In fact, with hydrothermal gasification, this saving **could increase up to 40% or even 50%** (for WWTP sludge) due to the fact that it **eliminates the need for additional thermal pre-treating** (e.g. for thermal hydrolysis: 10 bar, 200 °C) required to make the sludge suitable for anaerobic digestion (80% of sludge in France), **eliminates the need for additional drying to reach a sufficient level of dryness** (~ 29%) to allow the digestate to be combusted in a special incinerator **and reduces or even eliminates transport requirements** (due to the significant reduction in the quantities of final residue to transport).

6.1.2 Assessing operating expenditure (OPEX)

There is little data available regarding the technology operating expenditure (OPEX); however, it is possible to determine the main elements. OPEX is primarily composed of the following (not including any potential feedstock cost):

- **Labour** (qualified staff providing remote monitoring as a minimum and a local rapid response team managing several projects. Except for the very first projects, it is not expected that specific technical personnel will need to be present on site).

- **The energy input** required by the process, primarily heat to bring the system up to temperature upon start-up and then to maintain the recommended gasifier temperature. However, pumping in the water-containing feedstock does not consume substantial amounts of energy.
- **Maintenance** of equipment, particularly equipment that is subject to high-pressure and relatively high-temperature conditions.
- **Consumables**: for example, in catalytic hydrothermal gasification, replenishing the catalyst (note that 75% of the catalyst material is recovered).
- **Administrative costs.**
- **The costs of financing** the project CAPEX.

Switzerland case study (OPEX)

The study by AFRY Suisse SA in 2018 shows that for CAPEX, hydrothermal gasification solutions are very competitive compared to the high costs of disposing of sludge via mono-incineration. As such, even in cases where hydrothermal gasification complements an anaerobic digestion facility (scenario 2a), the OPEX is slightly lower than the benchmark scenario while depreciation of assets is higher (see Figure 19).

In the event of direct processing of effluent with hydrothermal gasification, OPEX is almost halved!
Below is a brief description of each scenario:

- **Scenario 1a:** Off-site digestion and incineration, taking into account the additional costs involved in sludge transport. The energy from incinerating the sludge cannot be used on site.
- **Scenario 1b:** On-site digestion and incineration, which presents advantages in terms of transport and on-site energy integration.
- **Scenario 2a:** Digestion and SuperCritical Water Gasification (SCWG): the organic fraction of the sludge that remains after anaerobic digestion is gasified via hydrothermal gasification. This requires the two anaerobic digesters and the hydrothermal gasification plant to be constructed.
- **Scenario 2b:** Hydrothermal gasification only: this presents the advantage of avoiding expensive investments in the anaerobic digestion infrastructure.
- **Scenario 3:** Thermal hydrolysis process (THP) followed by anaerobic digestion and incineration.

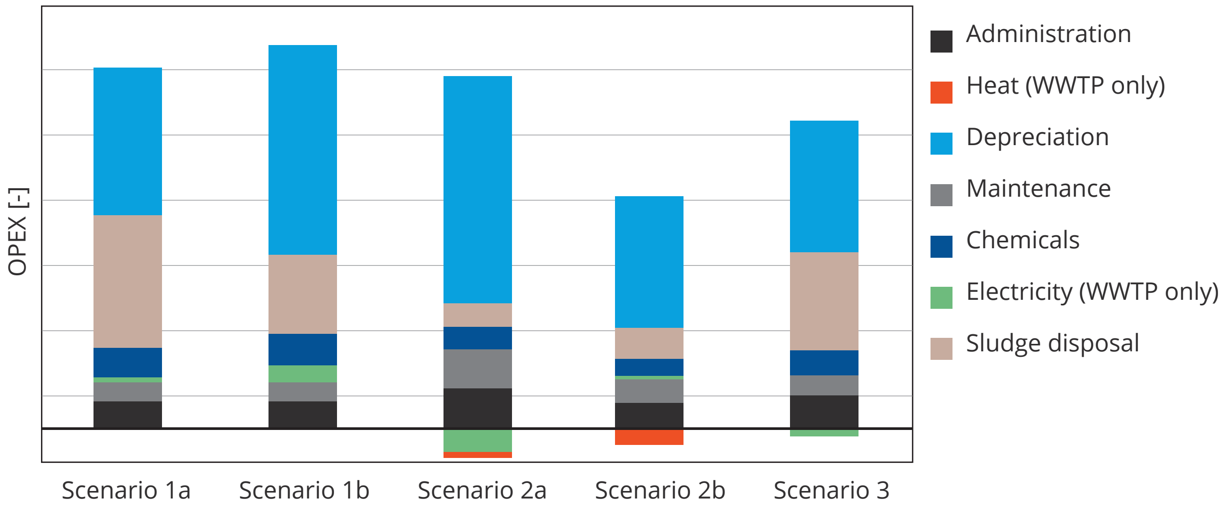

Figure 19: OPEX for various scenarios. Selling heat and electricity in the form of the biogas generated via hydrothermal gasification through cogeneration (scenario 2a) results in a significant reduction in OPEX.

6.2 A business model that changes over time

Because it can process and fully recycle organic waste, hydrothermal gasification avoids final waste processing costs such as incineration or landfill, produces an injectable, renewable or low-carbon gas, and recovers a large quantity of water, nitrogen, mineral salts and/or even metals.

As a result of these benefits, hydrothermal gasification can target a number of sectors, from agriculture, agrifood industries to local authorities, offering a relevant and economical solution for their waste alongside renewable energy generation. The diversity of feedstocks and technological solutions means that there is not **a single business model, but rather several, based on multiple criteria**, including the specific needs of demand-side stakeholders. In addition, as hydrothermal gasification is also incorporated into several related topics (decarbonisation, energy self-sufficiency, etc.), there are many changing variables that impact its business model.

These business models with their many driving factors can be built on a number of sources of remuneration, such as selling the renewable and low-carbon gas or recycling co-products.

6.2.1 The economic value of the gas produced

Remuneration for renewable and low-carbon gas production is a key element that enables the first projects to be constructed and helps to develop momentum. This remuneration should reflect the risks taken by the technology developers as well as the economic context (market price).

a) General regulatory framework governing the sale of the gas produced

- **Biomethane from an anaerobic digestion facility**:

  There are two financial mechanisms that currently support the development of biomethane injection.

  > Investment grants to facilitate project financing. The main provider of these grants in France is ADEME, but the country regions have local energy associations that can award grants, which generally do not exceed 15 to 20% of CAPEX.

  > A mandatory feed-in tariff, which guarantees that the producer can sell its biomethane at a fixed tariff for a period of 15 years. This 2022 tariff is between €64 and €139/MWh[a]. It includes the reference tariff as well as the feedstock bonus, which can vary from €5 to €39 per MWh depending on the type of feedstock and the installation flow rate.

  However, these mechanisms are changing:

  > Details of biomethane calls for tenders were published by the Ministry of Ecological Transition on 28/04/2022. These will take place in three stages, with a total capacity of 1.6 TWh/year. During the first stage, capacity of 500 GWh/year will be available for auction and tenders may be submitted up until December 2022. In particular, these calls for tender are required for large facilities that are no longer eligible for the feed-in tariff (> 25 GWh/year)

  > A decree[b] was published that paved the way for the establishment of biogas production certificates (CPB – *certificats de production de biogaz*), an extra-budgetary mechanism that gives natural gas suppliers the responsibility to obtain production certificates from producers as proof that they are incorporating sufficient biomethane into their energy mix.

- **Synthetic methane facilities such as thermal gasification or hydrothermal gasification plants:**

  Synthetic methane injection benefits from the same system of guarantee of origin as

[a] Theoretical range as this tariff is designed to fall by 2% each year, but due to high inflation in the first half of 2022, this figure could be revised upwards (see 2023 tariff evolution).
[b] Decree no. 2022-640 of 25 April 2022

biomethane as a result of decree no. 2021-1273 of 30 September 2021 but without the associated feed-in tariff system.

To obtain additional remuneration for the gas produced, project owners in these new sectors will be able to use a new mechanism introduced as part of the Climate and Resilience law, 'experimental contracts'. These contracts were introduced by decree no. 2021-1280 of 1st October 2021 and calls for projects are set to take place in the months to come. Rapid implementation of these contracts would give visibility to project owners and support the sector development.

b) Initial assessment of the expected support

Estimating the remuneration paid for the gas produced by a hydrothermal gasification facility is complex because it involves a number of factors.

For hydrothermal gasification, it is expected that the level of public remuneration for the gas produced will be within the price range for anaerobic digestion. It will depend on the size and the type of feedstock processed. Once the first projects have emerged, the hydrothermal gasification sector may, in the medium term, be able to envisage a drop in production costs to around **€110/MWh**$_{HCV}$ (excluding inflation-related effects) thanks to the learning effect, economies of scale, standardisation and technological progress.

For example, the first hydrothermal gasification projects in **the Netherlands** are already competitive (excluding inflation-related effects) with a global gas remuneration set at **€75/MWh**.

The competitiveness of Dutch projects compared to injected biomethane in France is illustrated in the table on the next page (Table 13).

Table 13: Competitiveness of Dutch projects compared to injected biomethane in France.

Year subsidy approved	Project	Power (number of modules)	Subsidy (additional remuneration) (€/MWh)	Gas sale price (€/MWh)	Total
2018	Alkmaar 1	18.6 MW_{th} (4 modules of 4 t/h)	€55/MWh	€20/MWh	€75/MWh
2020	Alkmaar 2A	40 MW_{th}	€56/MWh	€16/MWh	€72/MWh

c) Recycling of mineral salts and nitrogen

i) Recovery of phosphorus

Phosphorus recovery is a major challenge for Europe, which is almost entirely dependent on fossil phosphorus imports[a] to ensure its food security. As such, recovery of this critical resource – which is present in much of our waste in abundance – is now a necessity.

One initial approach for phosphorus recovery is based on an exhaustive market study by the canton of Zurich in Switzerland. This showed that each kilogram of phosphorus recovered from ash from wastewater treatment sludge costs around €5 [24]. The market value of the primary phosphorus-based product can be used as a point of comparison. For phosphoric acid, this is around €2 to 3/kg of phosphorus.

However, as mentioned above, at the current time, phosphorus recovery prices are higher than the market price. Nevertheless, it is important to take account of the fact that recycled phosphorus is more sustainable than conventional mined phosphorus.

[a] In Europe, the only active phosphorus mine is run by Yara in Finland. The main producers are China, Morocco, the USA and Russia.

ii) Recovery of nitrogen

The economic aspect of nitrogen recovery is still in its infancy. Unlike sludge incineration processes, hydrothermal gasification makes it possible to recover nitrogen from the liquid effluent. More than 95% of the nitrogen is found in the liquid effluent as NH_4^+ [25]. If sludge is incinerated [26], the nitrogen contained in the biomass is lost as NO_x or N_2. N_2O is a powerful greenhouse gas, with 300 times the impact of CO_2. Typically, for each Population Equivalent (PE), sludge incineration results in 0.025 kg of CO_2/PE/day being emitted. As an illustration, in Switzerland, wastewater treatment plants are able to produce ammonium sulfate at €20-45/t, but production costs exceed market prices. Currently, only the WWTPs at Yverdon-les-Bains and Altenrein operate nitrogen recovery plants.

As the final effluent following the hydrothermal gasification process is largely free of all organic matter and the nitrogen concentration is much higher than in the liquid effluent produced from sludge dewatering, lower recovery costs can be expected. However, with a view to creating a future circular economy, it is an additional opportunity to close nutrient loops.

d) Recovery of CO_2

As previously mentioned, one of the most promising results is the use of concentrated CO_2 flows in combination with renewable hydrogen, which makes this process an energy storage solution for renewable solar and wind power. This process, commonly called ‘power-to-gas’, is currently commercially available, with the main obstacle being the availability and affordability of concentrated CO_2 and renewable hydrogen. A commercial facility is in operation at a wastewater treatment plant in Switzerland[a].

6.2.2 The economic value of waste processing

Despite the fact that not all organic waste that is suitable for the technology necessarily has economic value and that the development of other renewable and low-carbon gas sectors results in a certain tension on these resources, hydrothermal gasification is the only technology that allows complete recycling of waste to produce renewable and low-carbon gas.

As such, any waste that cannot be recovered in situ via recycling or reuse will be processed via a dedicated process. As shown in Figure 2 of this white paper, hydrothermal gasification operates at the bottom of the waste processing hierarchy, but it has the benefit of being able to recycle a wide variety of waste types.

► Case study: the cost of managing WWTP sludge in France (AMORCE data)

In 2019, the French association AMORCE published a report that featured the costs of disposing of or recycling WWTP sludge (generally concentrated to 25-30% DM/TM*) via incineration, composting or spreading [27].

Table 14: Cost of disposal of wastewater sludge by treatment stream (AMORCE).

Stream	Cost (per ton TM)	Breakdown
Spreading (AMORCE survey)	€23 (€7-€45)	70-80%, with compost spreading accounting for 16%
Composting (AMORCE survey)	€53 (€40-€81)	
Incineration (standard values)	€90-€150	18% (2010 data)
Co-incineration with household waste (standard values)	€70-€120	

**Total Matter (TM) containing 25-30% Dry Matter (DM).*

[a] https://www.cng-mobility.ch/fr/article/la-technologie-power-to-gas-remporte-le-watt-dor-2020/

Table 14 shows that per tonne, the cost of sludge disposal ranges from €23 for spreading (35% of volume) up to €150 for incineration (≈ 26% of volume) [27]. Hydrothermal gasification could capture a large proportion of the waste volume that currently has the highest cost to local authorities.

The economic value of waste recovery via hydrothermal gasification is therefore the cost avoided by local authorities due to substantially lower spending on current waste recovery streams. Ultimately, hydrothermal gasification will demonstrate that it is capable of being competitive compared to the cheapest processing streams, such as composting, while continuing to meet the need to amend the soil through the introduction of organic matter.

In addition, as shown in the case study from Switzerland presented above, hydrothermal gasification could, in the future, become the preferred method of treatment for inbound effluent directly at the treatment site, with pre-treatment significantly reduced compared to the number of steps required in current facilities (clarification basins, thickening using chemical adjuvants, centrifugation, etc.), which use large quantities of energy and consumables.

6.3 With dynamic development opportunities

As part of discussions on the SFEC[a], the French gas sector – represented by GRTgaz, GRDF, France Gaz Renouvelables, the Hydrothermal Gasification Working Group and the ATEE Biogas, Thermal Gasification and Power-to-Gas Clubs – has published an analysis that estimates the potential production of renewable and low-carbon gas at 320 TWh/year in 2050, contributing to France's pathway towards decarbonisation. Of this potential, at least 50 TWh/year comes from hydrothermal gasification, a figure that could be significantly higher if much larger quantities of organic waste streams are directed to hydrothermal gasification (for example, livestock manure that cannot be spread locally).

To achieve this ambitious goal, the Hydrothermal Gasification Working Group has created a scenario setting out the annual development of future industrial hydrothermal gasification projects in France that inject the gas they produce into the gas grid:

1. The first commercial projects are commissioned from 2026.
2. Around 20 projects are launched by the end of 2028 with a total potential production capacity of 1 TWh/year of injectable gas.
3. In 2030, sixty or more projects are operational, injecting at least 2 TWh/year into the grid.
4. At the end of the first period of the Multi-Year Energy Programme (PPE) in 2033, the sector should have around 140 operational projects injecting at least 6.8 TWh_{HCV}/year of gas into the grid.

This ambition requires support mechanisms in the form of experimental contracts that take account of the specific characteristics of the sector and of hydrothermal gasification technology to enable the launch of the first industrial projects in 2026.

This initial outline highlights the importance of having an abundance of projects of variable size, beginning with an average thermal capacity of 4.5 MW_{th} per project, prioritising industrial and urban waste types whose benchmark processing costs are deemed too high. Then, as costs fall as technology improves and mass production of modules begins, larger projects processing a wider variety of waste types can be considered. This would allow the average thermal capacity of new projects to rise to 6 MW_{th} per project from 2030. These will be supplemented by one or more very large projects per year with an individual thermal capacity of up to 40 MW_{th} and beyond per project.

[a] French Strategy on Energy and Climate (*Stratégie Française sur l'Énergie et le Climat*)

These ambitious targets will not be met without:

- **Greater collaboration between all stakeholders in the hydrothermal gasification sector**, centred on French technology developers capable of competing with their international counterparts, who are also welcome.
- **Tailored support from public authorities to allow fair remuneration for the renewable and low-carbon gas injected into the grid** covering the risks taken by investors and stakeholders in the sector, particularly at its launch in France.
- **Movement in the gas market price (PEG[a])** in France, which will undoubtedly be the benchmark for the sector.
- In addition to the geopolitical and energy crises experienced on an unprecedented scale in 2022, **the price dynamics of methane and CO_2** are expected to be such that industry stakeholders can confidently anticipate cost recovery through a gas price remuneration scheme aligning with the expectations of economic actors in the French market.

[a] PEG: Gas exchange point

07

CONCLUSION & OUTLOOKS

Created based on all of the currently available data and the experiences that have been shared, this white paper summarises the main technical characteristics and benefits of hydrothermal gasification and its expected potential for 2050.

Positioning

Firstly, hydrothermal gasification is positioned as an environmentally friendly alternative to incineration and landfill for a number of organic waste types for which recycling is currently poor, insufficient or non-existent. The technology ability to produce renewable and low-carbon gases extremely efficiently while also offering the potential to recover and recycle water, mineral and metal co-products puts hydrothermal gasification at the heart of regional challenges such as **energy self-sufficiency, the circular economy and limiting the impact of climate change.**

It is aimed now not only at the treatment and valorization of a wide range of urban and agricultural organic waste, but increasingly also at other waste types generated by a large range of industrial sectors, which, to some extent, are not exclusively of biogenic origin. Since 2022, hydrothermal gasification has been the subject of much attention from a growing number of industry stakeholders, in particular from the chemical and petrochemical sectors. They see hydrothermal gasification as an appealing alternative with positive cumulative effects, including:

1. Improved processing capacity for their organic waste, which may be contaminated, at least partly, by various organic compounds (hydrocarbons, plastics, etc.), which require expensive processing in existing waste treatment processes,

2. Greater simplicity compared to the current administrative procedures – seen as complex or labour-intensive – is sought in relation to the obligation for waste treatment in domestic incinerators or abroad when suitable treatment facilities are not available in France,

3. Its benefits in terms of decarbonising their activities and the ability to transform their waste into resources that lower their overall processing costs due to much higher levels of recycling.

4. Substantially greater adaptability to future environmental constraints, which are constantly becoming stricter.

In essence, with its ability to process complex organic waste, whether segregated or mixed with other waste types, hydrothermal gasification could quickly become a waste recovery tool that is powerful, compact, relatively cheap and quick to put in place and that serves the interests of both public and private economic stakeholders that generate or manage waste and are looking for an efficient alternative to existing solutions.

The current situation and benefits of hydrothermal gasification

In terms of development, the strong dynamic in Europe and more specifically in the Netherlands and Switzerland has fostered the emergence of the first industrial demonstrators and helped to structure this new sector. In France, two industrial players have established a presence in the hydrothermal gasification sector (Leroux & Lotz Technologies and VINCI Environnement) and a large number of academic, institutional and private stakeholders are now working together to offer the best possible support to this sector in France.

In technological terms, hydrothermal gasification differs from other waste processing methods in that its operating principle is based on the power of supercritical water (374 °C and 221 bar). While reducing feedstock pre-treatment to an absolute minimum, these particular physico-chemical conditions optimise recycling of all of the organic matter contained within the waste in order to:

- **produce renewable and low-carbon gas that can be injected or used locally** (mobility and self-consumption), benefiting from the particularly high rate of conversion (85-99%) of carbon into gas,

While recovering and preserving

- **nitrogen and essential minerals** (phosphorus and potassium) for potential use in fertilisers (N, P, K),

- **metals** of varying quantity and/or economic value.

In addition, almost all organic pollutants (pesticides, detergents, medicinal residues, pathogenic microorganisms, etc.) and any microplastics are destroyed and/or converted into gas. In addition, a number of other positive externalities linked to the entire value chain can be expected, with long-term positive impacts on employment, the emergence of new co-product recycling sectors, industrial synergies, etc.

Finally, the technology presents a number of benefits that make it easy to integrate into a wide range of settings: a total conversion time of just a few minutes, its small size (requiring very little space), modular technology, no atmospheric pollution and very little noise pollution and odour, to name just the most significant.

The potential to produce renewable and low-carbon gas

An initial projection limited to around 20 types of biogenic feedstocks available in large quantities reveals that the production potential – based on conservative assumptions regarding mobilisation – is estimated to be **at least 63 TWh/year by 2050** (with just 50 TWh/year as the chosen target).

However, given that certain industrial waste is at least partly fossil in origin and has therefore not been taken into account, and in light of the potential for changes to regulations governing the return of certain waste types to the soil in the near future, **new streams for hydrothermal gasification could quickly become available for mobilisation** in France, further increasing its estimated potential for injectable gas production.

Development opportunities

In terms of industrialisation, the outlines of a very promising business model are emerging for hydrothermal gasification. However, a precise assessment is difficult in light of the wide range of feedstocks and co-products, the technological developments that are taking place and the potential involved in increasing the scale of production. As such, the approach taken is likely to change based on case studies.

As a result of progress made in certain other European countries, the French HTG sector is currently capable to accelerate the rolling out of industrial demonstrators across the country to help to develop **highly efficient operational industrial plants from 2026 on.** These initial demonstrators will be used to carry out life cycle analyses (LCAs), construct viable business models and test a number of technical optimisations that are currently being developed.

With the shared goal of enabling and achieving national targets for 2050 for decarbonisation, energy sovereignty and the development of the circular economy, the Hydrothermal Gasification Working Group has confirmed the feasibility of reaching **an estimated 50 TWh/year of potential renewable and low-carbon gas production from hydrothermal gasification within this timeframe.** This capacity would cover around 15% of France's total renewable and low-carbon gas production (320 TWh/year), according to gas sector estimates.

To achieve this goal, several short- and medium-term milestones have been set out:

- **By 2026:** assembly, construction and commercial commissioning of the first industrial projects.
- **By 2030:** production and injection of at least 2 TWh/year of renewable and low-carbon gas into the gas grid with around 60 hydrothermal gasification projects in operation.
- **By 2033:** production and injection of at least 6.8 TWh/year of renewable and low-carbon gas into the gas grid with around 140 hydrothermal gasification projects in operation.

The technological progress that has already been achieved by the most advanced developers, most of which are foreign, confirms the technology suitability as a solution for recovering a wide range of organic waste and producing renewable and low-carbon gas within France. However, the emergence of an industrial hydrothermal gasification sector in France will not be possible without the involvement of all stakeholders working towards ecological and energy transition. Public authorities must play a crucial role by providing a minimum level of decisive support to French developers of hydrothermal gasification technology and pioneering investors, assisting the launch of the first industrial projects by minimising their risks.

Public support must be supplemented with other mechanisms, the absence of which has been identified by the sector as hindering or even preventing potential technological development and the involvement of stakeholders working to encourage its emergence in France. These mechanisms include:

- public funding designed as financing for industrial demonstrators, allowing the two or three French developers of the technology to perform essential optimisations before moving to the final commercial stage;
- a wide range of support mechanisms in the form of remuneration for injectable renewable and low-carbon gas (e.g.: biogas purchase agreements, certificates of origin for renewable or low-carbon gas production, experimental synthetic methane contracts tailored to the sector, etc.);
- a regulatory and administrative ICPE (French environmental protection classification) framework that is tailored to the type of HTG process and simplifies the act of establishing industrial projects;
- specific financial mechanisms designed to support research and development by industry stakeholders investing in hydrothermal gasification technology and to allow them to reach the level of their foreign counterparts. These support mechanisms may also be necessary to develop technological modules located upstream (e.g. pre-treatments) or downstream (treatment of synthetic gas to make it suitable for grid injection, processes for converting solid and liquid residues into marketable products, processes for sustainable CO_2 recycling or for decarbonisation, etc.).

Finally, regarding the work objectives set by the Hydrothermal Gasification Working Group, which represents sector stakeholders in France, its members anticipate that the requests for support discussed above will be subject to specific studies. In particular, these will aim to provide public authorities – as soon as possible – with the necessary elements to:

- remove these obstacles and offer optimum support to the first industrial projects and
- to take hydrothermal gasification into account in legal texts (SFEC, PPE, etc.) to ensure that its potential in the future French energy roadmap can be fully acknowledged and to allow it to contribute to efforts to achieve carbon neutrality by 2050.

ANNEX

HYDROPILOT

Results of the measurement campaign conducted by RICE at Paul Scherrer Institute in December 2022

Available data concerning the detailed quality of gas produced by hydrothermal gasification are rare and incomplete. Paul Scherrer Institute (PSI), TreaTech and GRTgaz built a partnership focused on testing the complete process chain of the HydroPilot unit and performing deep analyses on the gas after phases separation. HydroPilot is a catalytic hydrothermal gasification unit with a converting capacity of 110 kg/h biomass or fossil origin waste located at PSI (Switzerland). In December 2022, the pilot was tested with food waste and plastic packaging. A sampling campaign was conducted with the collaboration of PSI and TreaTech, for later analyses at RICE's laboratories (Research & Innovation Center for Energy, part of GRTgaz). This campaign aimed at enhancing our knowledge of gases produced through this thermal-chemical process.

The results of the analyses show that the quality of the produced syngas could be easily compliant with the European biomethane quality standard for its injection into the gas grid.

The analyses show a good conversion of the carbon contained in the organic matter into methane. The measured concentrations of the major compounds are similar to those expected by PSI and TreaTech, as well as to the ones reported in the literature. As expected for a not upgraded gas, the quality of the raw syngas gas does not presently meet the European standards (EN 16726 and/or EN 16723-1) for its injection in the gas grid (table 1 above), because of the concentrations of CO_2 and H2. However, this syngas could easily be compliant thanks to existing purification systems. The significant amount of N2 (9,3 %) came from the purge of the system at the beginning of the test. It should be completely flushed with a continuous operation of the pilot.

The screening of VOCs shows the **preponderance of hydrocarbons** in the raw syngas, mostly between C6 and C10, which helps to increase the calorific value of the gas. Based on RICE's experience, the distribution of these concentrations seems to be very **similar to the one of natural gas**, but 5 times lower. **Consequently, this gas composition regarding VOCs do not seem to be an issue for its purification, injection, transmission, or use.**

Concentrations of the targeted compounds in the raw syngas produced by the HydroPilot (December 2022) and compliance with European standards :

Compound/ parameter	Raw syngas 14th December 2022	French technical prescriptions	European standards EN 16726[1] & EN 16723-1[2]	Compliance with standards
CH_4	**65,9 %**	-	> 60 %	**Compliant**
CO_2	**18,5 %**	⩽ 2,5 %	⩽ 2,5 or 4 %	**Not compliant****
CO	**0,02 %**	⩽ 2 % Spec. ⩽ 0,1 %*	⩽ 0,1 %	**Compliant**
O_2	**0,0025 %**	⩽ 0,75 % [2]	⩽ 0,001 or 1 %	**Compliant**
H_2	**6,0 %**	⩽ 6 % Spec. ⩽ 2 %*	⩽ 6 %	**Not compliant****
C_2H_6	0,19 %	-	-	-
C_3H_8	0,05 %	-	-	-
iC_4H_{10}	0,02 %	-	-	-
nC_4H_{10}	0,03 %	-	-	-
$neoC_5H_{12}$	4,4 ppm	-	-	-
iC_5H_{12}	0,01 %	-	-	-
nC_5H_{12}	0,01 %	-	-	-
iC_6H_{14}	23 ppm	-	-	-
nC_6H_{14}	28 ppm	-	-	-
Other C_{5+} (equivalent to. nC_6)	85 ppm	-	-	-
H_2S + COS	**< 3 mgS/Nm³**	⩽ 6 mgS/Nm³	-	**Compliant**
Mercaptic sulphur	**< 2 mgS/Nm³**	⩽ 6 mgS/Nm³	-	**Compliant**
Total sulphur without odorant	**< 5 mgS/ Nm³**	⩽ 20 mgS/Nm³	⩽ 20 mgS/Nm³	**Compliant**
NH_3	**< 0,94 mg/Nm³**	⩽ 3 mg/Nm³	⩽ 10 mg/Nm³	**Compliant**
Screening of VOCs at trace level	255 detected VOCs 229 identified VOCs Eq. à 200 mg/m³	-	-	***

[1]EN 16726 : Gas infrastructure - Quality of gas - Group H.

[2]EN 16723-1 : Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network - Part 1: specifications for biomethane for injection in the natural gas network.

*New specifications for the injection of synthetic methane.

** Could be compliant with the specification after adapted gas treatment

*** Volatile organic compounds from the same chemical families are also present in natural gas and with higher concentrations. This gas composition is thus not an issue for its purification, injection, transmission, or use.

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AFI	Agrifood industry
AGEC	French law: 'Anti-waste for a circular economy' (*Loi Anti-Gaspillage pour une Économie Circulaire*)
CAPEX	Capital expenditure
CEA	French Alternative Energies and Atomic Energy Commission (*Commissariat à l'Énergie Atomique et aux énergies alternatives*)
DM	Dry matter
HCV	Higher calorific value
HTG	Hydrothermal gasification
ICPE	Installation Classified for the Protection of the Environment: a facility requiring environmental impact assessment (*Installation Classée pour la Protection de l'Environnement*)
KIT	*Karlsruhe Institute of Technology*
LCV	Lower calorific value
LPEC	Energy and Climate Planning Law (*Loi de Programmation Energie Climat*)
MWI	Municipal waste incinerator
MW_{th}	Megawatt thermal
NGV (CNG + LNG)	Natural gas for vehicles
OFHW	Organic fraction of household waste
OM	Organic matter
OPEX	Operational expenditure
PEG	Gas exchange point
PE	Population equivalent
PPE	Multi-Year Energy Programme (*Programmation Pluriannuelle de l'Énergie*)
PSI	Paul Scherrer Institute
SFEC	French Strategy on Energy and the Climate (*Stratégie Française sur l'Énergie et le Climat*)
SNBC	French National Low-Carbon Strategy (*Stratégie Nationale Bas Carbone*)
SRF	Solid recovered fuel
TME	Trace metal element
TM	Total matter
TRL	Technology readiness level
WDF	Waste disposal facility
WtE plant	Waste-to-energy plant
WWTP	Wastewater treatment plant
WWTR	Wastewater treatment and reuse